Engaging beyond the meter: Encouraging residential energy management using smart grid tools

by

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Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners. I understand that my thesis may be made electronically available to the public.

Statement of Contributions

The research contained within this thesis was conducted as part of a Social Sciences and Humanities Research Council of Canada (SSHRC) Canada Graduate-Doctoral Scholarship and an Energy Council of Canada Energy Policy Research Fellowship in partnership with the Waterloo Institute of Sustainable Energy. The results presented in Chapter 4 is a manuscript published September 2018 in *Energy, Sustainability and Society*. The results presented in Chapters 5 to 7 are the bases for manuscripts intended to be published in peer-reviewed journals. As a result, a number of co-authors have contributed to the work presented in Chapters 4-7. However, all data collection or analyses which were not performed by me were conducted either under my direct supervision or were coordinated by me. All analysis and synthesis of the results were performed by me. Although technical and editorial contributions were provided by my co-authors, each manuscript was written by me. The individual contributions from all co-authors are, in alphabetical order, as follows:

Gordon Stephen: co-developed the clustering and household consumption analysis and provided both technical and editorial feedback in the preparation of Chapter 6.
Prof. Ian Rowlands: supervised the development of the interview questions for Chapter 4 and provided editorial feedback in Chapter 4.
Prof. Jennifer Lynes: provided technical and editorial insight during development of the ENGAAGGE model in the preparation of Chapter 7.
Prof. Paul Parker: supervised all work completed in this thesis, including editorial and technical feedback for Chapters 4 through 7.

Abstract

With scientists around the world indicating a brief window of opportunity for reducing irreversible climate change impacts, the time has never been more pressing for sustainability transitions (IPCC, 2018). The role of energy is especially important in these developments, where anthropogenic forces have created a "… twin energy and climate nexus," (Van De Graaf, 2013, p. 42) as a result of the extraction, production, and consumption of energy resources. At a global scale, 78% of human-induced greenhouse gas (GHG) emissions are from energy production and consumption (Natural Resources Canada, 2018a). Therefore, clean energy developments are an essential element of international climate goals.

A key element of clean energy developments is energy conservation and demand management. With Canada having one of the world's largest per capita electricity consumption rates, increased end-use management is essential to reduce system-level pressures within clean energy developments (International Energy Agency, 2018). Significant opportunities for electricity management exist in the residential sector, which contributes to 27% of international electricity consumption (International Energy Agency, 2017). This is especially the case in Canada, where the residential sector contributes to 34% of national electricity use, emitting 21.4 Mt of CO_2e (Natural Resources Canada, 2019b, 2019a). Therefore, there is a strong need to transform Canada's residential consumption management and practices to benefit national climate change objectives.

Technological innovations in the modern energy grid deliver new opportunities for clean energy developments. Specifically, the smart grid creates two-way flows of both data and energy, thereby transforming technological capabilities and end-user roles. Beginning in 2004, the Province of Ontario facilitated large-scale smart metering implementation to enable a 'conservation culture,' consequently, becoming a prominent testing ground for residential smart grid development. Although the smart grid offers new technological potential, investigating 'beyond' the meter and into end-user engagement is critical for making these large-scale shifts. Social science research applications have previously remained underrepresented in energy literature and deliver novel opportunities for studying smart grid engagement. The holistic and scalable energy cultures framework presents a comprehensive approach to study the complexity of residential energy management, with substantial opportunities for applications in smart grid research (Stephenson et al., 2010).

This dissertation, entitled *'Engaging beyond the meter: Encouraging residential energy management using smart grid tools,'* delivers novel contributions to residential smart grid and

engagement research for developing insights on household engagement and energy management. Drawing from the literatures on smart grid interventions, social science energy research, and consumer engagement, this dissertation utilizes two Ontario residential smart grid case studies to assess the potential of smart grid technologies to facilitate consumption changes. Additionally, this dissertation incorporates a comprehensive review of existing approaches for intervention design and proposes a novel integrated engagement model for shifting consumer cultures towards sustainability. This dissertation research is presented in four distinct yet interrelated manuscripts.

Chapter 4 investigates the impacts of smart grid interventions on household energy cultures during a multi-year residential smart grid case study, following participant interviews. The energy cultures framework is applied to identify the nuances surrounding household energy management, specifically the changes in norms, practices, and materials. Additionally, qualitative feedback on the effectiveness of these smart grid engagement mechanisms for household energy management is collected. The results identify the challenges surrounding household energy management in relation to smart grid developments and present a novel application of the energy cultures framework within the Canadian residential smart grid.

Chapter 5 further examines the impact of two smart grid interventions (electricity report and mobile tablet) to re-engage consumers over the multi-year residential smart grid project. This study examines whole-house and appliance-level consumption data alongside participant interviews. As a result, this study determines whether re-engagement influenced consumption, highlights contributing energy management practices (e.g., cooking, laundry, entertaining, air conditioning, dishwashing), and determines underlying factors influencing energy management. Significant conservation and peak shifting in laundry consumption were identified during a 10-week autumn period. User experience interviews highlighted the preference for weekly reports over a tablet for re-engagement. Therefore, this chapter provides unique perspectives for long-term engagement and re-engagement in the smart grid for the promotion of lasting residential energy management.

Chapter 6 assesses the influence of a large-scale introduction of in-home displays (IHDs) to central Ontario homes. Two years of hourly consumption data for IHD recipients (n=5274) are analyzed and compared to a control group (n=3020) to determine changes in conjunction with IHD feedback at population and cohort levels. Consumer segments incorporating behavioural (load-shape) and thermal consumption patterns were identified. Following an impact assessment, no significant impacts were experienced in the general population; however, specific consumer segments responded favourably by conservation or peak shifting. These notable segments only represented 12% of the

IHD recipients and had evening peak and heating thermal consumption profiles. This study emphasizes the importance of effective program design that utilizes comprehensive datasets, user-centred approaches, consumer targeting, and multiple mechanisms extending 'beyond feedback.' This chapter also highlights opportunities for utilizing 'big' smart metering data to understand consumers and their energy practices using quantitative methods.

Chapter 7 presents a novel model for intervention design for sustainability as an outcome of a conceptual review. The proposed ENGAAGGE model presents an integrated model for intervention design that bridges the limitations from the current disciplinary silos for collective change. The paper provides a comprehensive review of existing intervention approaches (social marketing, community based social marketing, social practice theory, and design thinking), highlights the key elements for intervention design, and proposes the ENGAAGGE model that incorporates the strengths of existing approaches, while addressing their respective limitations. Therefore, the outcomes of this chapter provide innovative opportunities for application in future research and practice for collective change.

This dissertation research brings novel contributions to theory and practice. First, this research provides an innovative application of the energy cultures framework to the residential smart grid and delivers a new framing for a smart and sustainable energy culture. The holistic understanding developed from applying this framework delivers insights for household smart grid engagement applicable to future program design. Second, the IHD segmentation analysis extends research on smart grid-enabled feedback and consumer response by the combination of a large-scale cohort and consumer segmentation. The research outcomes deliver critical recommendations for future programming to include consumer targeting and user-centred design. Third, the longevity and mixed-methods approach of the EHMS study provides novel and detailed contributions to smart grid energy cultures and engagement research to test with broader audiences. These outcomes provide insights for consumer engagement for long-term engagement and re-engagement relevant for residential smart grid programming. Fourth, the conceptual review and integrated model presented in Chapter 7 bring critical contributions to the sustainability engagement literature and provide substantial opportunities for application in future research and practice. In conclusion, this dissertation research delivers novel contributions to smart grid research for engaging consumers beyond the meter.

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Dedication

To my parents Kathryn and Brian Lazowski. Without your inspiration, I would have never attended the University of Waterloo all of those years ago. Your influential encouragement both initiated and supported this incredible journey. I am forever grateful.

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Table 62 IHD effect on thermo-behavioural clusters, TOU consumption, (estimate in hourly kWh). * is significant where *p*<0.05 320

List of Abbreviations

AMI: Advanced metering infrastructure

CBSM: Community based social marketing

CDD: Cooling degree day

CDM: Conservation and demand management

DR: Demand response

DSM: Demand-side management

DSR: Demand-side response

DT: Design thinking

ECF: Energy cultures framework

EHMS: Energy Hub Management System – Name of the study in Chapters 4 and 5

ENGAAGGE: name of the conceptual model outlined in Chapter 7

FIT: Feedback intervention theory

GHG: Greenhouse gas

HEM: Home energy management

HDD: Heating degree day

ICT: Information and communication technologies

IDEO: Global design and innovation company that specializes in design thinking

IESO: Independent Electricity System Operator

IHD: In-home display

kW: Kilowatt

kWh: Kilowatt hour

NRCan: Natural Resources Canada

P-TIPP: Practice-theoretical intervention planning process

SGCC: Smart Grid Consumer Coalition

SM: Social Marketing

SPT: Social Practice Theory

TOU: Time-of-use

1. Chapter 1 – Introduction

This chapter provides an introduction to the dissertation entitled *'Engaging beyond the meter: Encouraging residential energy management using smart grid tools.'* This chapter includes the rationale and research background, followed by the empirical context of the dissertation research, the gaps in the literature, the research purpose, and objectives, followed by the conceptual framing, and dissertation outline.

1.1 Rationale and research background

Fundamentally tied to societal and economic development, energy is considered "… the lifeblood of all societies" (Homer-Dixon, 2006, p. 26). Energy is embedded in the necessities of livelihoods and there has been a high correlation between energy consumption levels and the quality of life (Manners, 1971; Solomon, Pasqualetti, & Luchsinger, 2003). This dependency on energy for social and economic development has led to large-scale environmental impacts, while at the same time advancing the quality of life (e.g., facilitating certain medical procedures, thereby reducing mortality rates). Human impacts have likely caused 1.0°C planetary warming beyond pre-industrial levels (IPCC, 2018). The population-consumption-technology-nexus has raised concerns regarding the planet's limits to growth and the levels of unsustainable resource extraction, increasing the severity of climate change effects (IPCC, 2014). These concerns have remained important since Meadows, Meadows, Randers, and Behrens' (1972) seminal piece on the limits to growth and has progressed into the investigation of earth system limits within planetary (Rockström et al., 2009) and social scales (Dearing et al., 2014; Raworth, 2012). As a consequence of these anthropogenic forces, "the world is facing a twin energy and climate crisis," of energy access issues and climate change impacts (Van De Graaf, 2013, p. 42). Energy is a considerable influence on international climate goals. This 'twin crisis' is particularly the case in Canada, and evident in the country's Paris Agreement goals[1] and related policies (Government of Canada, 2015).

Energy conservation and demand management (CDM)[2] policies provide crucial pathways for clean energy transitions. The management of energy consumption is intertwined in socio-spatial

[1] Canada's Paris Agreement climate commitment is to reduce greenhouse gas (GHG) emissions 30% below 2005 levels by 2030 (Government of Canada, 2015).
[2] This dissertation recognizes that conservation and demand management do not yield the same outcomes. These concepts have been placed together in this dissertation to align with the policy objectives set by the jurisdiction of focus, Ontario, which promoted both conservation and demand management through the introduction of smart grid technologies for both reducing consumption and shifting to non-peak periods.

identities from macro- (international and national scales) to micro-scales (regional, community and household), resulting in complex issues for effective energy management (Calvert, 2015). Thus, decarbonizing the energy system is a sizable socio-technical challenge (Eyre, Darby, Grünewald, McKenna, & Ford, 2016). Society is faced with an urgent challenge to break this cycle by enabling social and economic development while achieving reductions in carbon emissions.

Contributing to 27% of global electricity consumption, significant opportunities for consumption management exist at the residential scale (International Energy Agency, 2017; Parker, Rowlands, & Scott, 2003). Residential energy studies traditionally fall under either technical or social knowledge areas, where technical studies focus on engineering elements and social studies investigate the barriers and benefits of programs (D. Scott, Rowlands, & Parker, 2001). Consequently, research can become focused on either human-specific or technologically-specific solutions, without interconnections between the two, resulting in disjointed silos of solutions and research. Multidisciplinary methods for studying user interaction with smart grid technologies can bring detailed insights into technological adoption (Karlin et al., 2017). However, due to the complexity of this human-environment relationship, a multidisciplinary approach is crucial to enable the comprehensive study of the patterns, factors and approaches influencing the consumption landscape, and to investigate opportunities for innovative and sustainable energy shifts (Stephenson, 2018).

Another major challenge of the energy system is the 'triad of anonymity,' among utilities, consumers, and embedded energy practices where consumers and their practices hold a large role in system efficiencies (Bigerna, Bollino, & Micheli, 2016; Sintov & Schultz, 2015; Summerton, 2004; Verbong, Beemsterboer, & Sengers, 2013). Smart grid technologies offer new capabilities for residential energy management and renewable micro-generation; however, the sustainable energy transition requires more than technology, it requires the creation of a culture of engaged consumers (Eyre et al., 2016; Hargreaves, 2018; Lazowski, Parker, & Rowlands, 2018; Yang, Liu, Gaterell, & Wang, 2017). At the residential scale, the smart grid requires user-centred design of technologies and interventions to shift households towards both a smart and sustainable energy culture[3] through the acceptance of new efficiency measures and smart technologies, shifts in energy actions, and changes in expectations surrounding energy management (Karlin et al., 2017; Lazowski et al., 2018; Stephenson, Barton, et al., 2015; Stephenson et al., 2010). The comprehensive energy cultures

[3] Elements of the smart and sustainable energy culture are discussed in more detail in Section 1.2.5 and Chapters 2 and 4. The tensions between the terms smart and sustainable are acknowledged and detailed references are made in Sections 2.8 and 2.10.

framework poses opportunities for new research to gain insights on residential energy shifts towards a smart and sustainable energy culture.

Energy studies incorporating social and technical knowledge areas study patterns of consumption, highlight issues surrounding future energy scenarios and identify mechanisms for management and reduction. Opportunities for further incorporation of social and technical knowledge areas in residential energy research are evident in the literature (Parker et al., 2003; Sovacool et al., 2015), and further detailed in the following sections (Chapter 2 – Literature Review). The emergence of innovative technologies (e.g., smart technologies,[4] clean technologies[5]) introduces opportunities to 'green' the energy system (Auld, Mallett, Burlica, Nolan-Poupart, & Slater, 2014); however, there is a lack of comprehensive knowledge for facilitating and developing a more sustainable energy culture. The diversity of the contemporary discipline of human geography combines a range of theories and approaches (Herod, 2009; R. Johnson, 2009) and provides a favourable lens to investigate the scale, sustainability, governance and consumption of energy. Overall, the integrated capabilities within human geography research provide a lens for understanding patterns of consumption and identifying opportunities for CDM.

A significant opportunity for clean energy shifts is evident within Canada's energy system. Increased electricity end-use management is essential for these system shifts, especially considering Canada has one of the world's largest per capita electricity consumption rates (International Energy Agency, 2018). Substantial opportunities exist at the residential scale. Residential electricity consumption contributed to 34% of Canada's national electricity use, emitting 21.4 Mt of CO_2e (Natural Resources Canada, 2019b, 2019a). At the household level, electricity contributed to 45.2% of residential energy consumption in 2015 (Natural Resources Canada, 2017b). Therefore, Canada has a significant responsibility for shifting consumption intensities at the residential scale. Although not equally distributed across provinces, this presents a substantial challenge for shifting towards a 'sustainable' energy culture that aligns with federal climate change objectives.

Household energy consumption is multifaceted and influenced by a multitude of social and technical factors (Kowsari & Zerriffi, 2011). Therefore, understanding the underlying impacts alongside this technological adoption is crucial for understanding how and why consumers can shift

[4] 'Smart' technologies refer to devices with the ability to connect to a network (e.g., WIFI, 3G, Bluetooth) to share and interact (e.g., between users, operators, other devices) remotely, facilitated by information and communication technologies.
[5] Clean technologies are defined by Natural Resources Canada (2017a) as "any process, product, or service that reduces environmental impacts providing a critical pathway to maintain and enhance competitiveness."

their energy consumption. Current energy research approaches focusing on studying human-induced impacts remain within disciplinary silos, with technical research dominating major energy research publications (Sovacool, 2014; Sovacool et al., 2015). Similarly, in smart grid research, studies primarily focus on the technical, or the social aspects, without integration (Froehlich, 2009). Multidisciplinary approaches are crucial for reducing the disciplinary silos for engagement approaches (Creutzig et al., 2018; Sovacool & Hess, 2017; Steg, Perlaviciute, & van der Werff, 2015; Vlek & Steg, 2007). Multidisciplinary approaches can be applied to smart grid research to identify opportunities for successful grid transitions.

Technological innovation in the residential energy system, particularly with smart grid advancements, can deliver potential opportunities for improved household energy management (Hiscock, 2014; Stephens, Wilson, & Peterson, 2015; Winfield & Weiler, 2018). The introduction of information and communication technologies (ICT) into the electricity grid brings substantial opportunities for two-way flows of both energy and information between utilities and consumers (Office of the Auditor General of Ontario, 2014). Facilitated through the introduction of smart meters[6], these advancements can create consumer opportunities in the smart grid (Anda & Temmen, 2014). Within Canada, Ontario made large advances in smart grid infrastructure developments compared to other provinces (Hiscock, 2014). Technologies bring opportunities to improve residential energy management; however, habits, routines, and related behaviours have a strong influence over the efficient use of technologies, contributing to two-thirds of energy use compared to technical components (Dietz, Gardner, Gilligan, Stern, & Vandenbergh, 2009; Lutzenhiser, Hu, Moezzi, Levenda, & Woods, 2012; Mills & Schleich, 2012). Additionally, energy consumption in households with identical features can differ up to 200%, with household behaviours contributing to this variability (Chen, Delmas, Kaiser, & Locke, 2015; Dietz et al., 2009; Lutzenhiser, 1993; Mills & Schleich, 2012). Studies have identified savings opportunities of upwards to 25% from conservation behaviour; therefore, emphasizing the significance of behavioural 'wedges' to improve energy management (Dietz et al., 2009; Granade et al., 2009; Karlin & Ford, 2013; Lutzenhiser, 1993). Equally, the importance of engaging end-users in smart grid transformations has been identified (Anda & Temmen, 2014; Goulden, Bedwell, Rennick-Egglestone, Rodden, & Spence, 2014). Therefore, these factors present substantial opportunities for studying consumer engagement and

[6]Smart meters are electricity meters that log the quantity of electricity use by time of day and connect to the electricity grid (Lysyk, 2014). Smart meters can also record power quality, disturbances and events and provide aggregate stored mechanical meter data logs (O'Malley, 2014).

demand response in conjunction with these socio-technical transformations in household energy management.

The development of the smart grid brings additional opportunities for applying mixed-methods and social science research approaches (Karlin et al., 2017). In recent decades, social science approaches in energy research remain underrepresented in leading scientific journals (Sovacool, 2014). Consumer-centred approaches are integral in developing mixed-methods research to the smart grid (Karlin et al., 2017). Thus, a significant opportunity exists to incorporate social science approaches to smart grid research. Novel social science research frameworks bring opportunities to study these shifts, consumer adoption, and engagement in the smart grid. In particular, the energy cultures framework (Stephenson, 2018; Stephenson, Barton, et al., 2015; Stephenson et al., 2010) presents a comprehensive approach to study the complexities of the smart grid, understand the underlying factors influencing household energy consumption, and to study the potential for smart grid technologies to shift household energy cultures within the smart grid transition. Therefore, four key elements brought together a strong opportunity for pursuing research on smart grid consumer engagement for home energy management: 1) the proliferation of smart grid technologies for residential energy management; 2) the strong development of smart metering infrastructure in Ontario's electricity grid; 3) the development of the Energy Cultures framework for holistic understanding of factors influencing home energy management; and 4) the acknowledgement for increased applications of social science and multidisciplinary research methods within contemporary energy studies.

This dissertation research, entitled *'Engaging beyond the meter: Encouraging residential energy management using smart grid tools'* provides methodological and conceptual contributions to the literature by four manuscripts which examine two case studies on residential smart grid engagement within Ontario (Chapters 4-6) while also proposing a new integrated model for intervention design (Chapter 7). The following sections present the empirical context, the contributions to the literature, and the conceptual and organizational structure of the dissertation.

1.2 Empirical context

This dissertation incorporates two case studies and a conceptual review within four research chapters (Chapters 4–7). The following sections present the empirical context for each chapter.

1.2.1 Ontario smart grid development

The Canadian energy system presents a significant opportunity to study household engagement within the smart grid. The province of Ontario has enacted substantial changes in technology, policy, and market rules to establish strong leadership in smart grid development among Canadian provinces, beginning with the province's *Electricity Act, 1998* (Lysyk, 2014; Mallinson, 2013; Winfield & Weiler, 2018). As a result of the Smart Meter Initiative in 2004, Ontario installed over 4.8 million smart meters across homes and small businesses by 2014 (Lysyk, 2014). This facilitated time-of-use (TOU) pricing for encouraging Off-Peak consumption. Consequently, this investment in energy infrastructure led to Ontario's Canadian leadership in smart grid research and development with 47 types of projects established across the province in 2014, including: a fully operationalized AMI; new rate options (TOU pricing); demand response for load shifting or ancillary services; distributed energy storage for peak shaving; self-healing grids; microgrids, and; voltage reactive power control (Hiscock, 2014).

Energy systems involve a multitude of actors from generation and distribution to consumption. Within Ontario, Local Distribution Companies (LDCs) facilitate the interaction of the smart grid between the utility and the consumer, and in particular, standardized electricity data are accessible to approximately two-thirds of Ontario customers for better management and understanding of energy consumption (Hiscock, 2014; Winfield & Weiler, 2018). Ontario's commitment towards a 'Conservation First' Policy, involving consumer engagement through smart meter demand response, brought significant opportunities to study the potential for these technologies as the province aims to achieve its CDM targets. Opportunities remain to examine details regarding how these externalities can shape residential energy cultures.

Although Ontario is a leader in the introduction of smart grid and advanced metering technology in the Canadian context, the related CDM benefits of these technologies has been limited. As identified by Lysyk (2016) the introduction of the smart metering technology did not achieve anticipated CDM targets. Although price difference between On- and Off-Peak periods was introduced to shift behaviour, as of 2016, the CDM objectives established by the Ontario Ministry of Energy were not met. As identified by Auditor General Lysyk (2016), the TOU rates were not significant enough to achieve CDM objectives. Therefore, it is crucial to study the nuances surrounding household energy management to identify *how* to shift consumers to both a smart and sustainable energy culture, aligning with CDM goals.

User-centred approaches for research design can bring new insights into human-technological interactions. As identified by Karlin et al. (2017) multiple methods can be applied for user-centred design in energy research, including literature reviews, ethnography, content analysis, focus groups, interviews, surveys, eye tracking, user testing, and experimental design. Social science approaches and mixed methods analysis can bring additional insights for understanding household energy management and the acceptance of new technologies. As a result of the large-scale implementation of advanced metering infrastructure (AMI) within Ontario, and the relevant opportunities for engaging household consumers, this dissertation research focuses on two Ontario smart grid case studies to explore residential engagement within the smart grid, thereby producing prospective insights for implementation in other jurisdictions. In particular, since Ontario had widespread implementation of smart metering infrastructure by 2014, this facilitated the study of long-term residential engagement and re-engagement in a multi-year residential case study, as well as influences from smart meter-enabled feedback in a large-scale implementation of in-home displays. Therefore, two case studies, as well as a conceptual review, are utilized within this dissertation research to develop detailed understanding on the factors influencing household energy cultures, consumer engagement with smart grid technologies, and engagement approaches for societal shifts. The following sections outline the related dissertation research.

1.2.2 Outline of EHMS case study

The University of Waterloo's Energy Hub Management System (EHMS) project established a long-term residential smart grid pilot and equipped 25 households with smart panel technology. During the multi-year project, a series of project-led interventions[7] were distributed to the households, including surveys, web portal activation, scheduling, goal setting, reminders, thermostat control functions, weekly feedback, and a tablet. During the study, high-resolution (hourly) electricity consumption data were collected per household, allowing access to whole-house and appliance-level data. This study provides an investigation into long-term engagement, re-engagement, and respective consumption analysis; therefore, enabling detailed analysis of the consumption changes over a multi-year case study. Additionally, this study conducted two phases of participant interviews. The first stage of interviews took place from September to December 2014 with 15 participants to gain further

[7] This dissertation has applied the term intervention, similar to Wilson and Dowlatabadi (2007) who define interventions as any instrument with the objective to change behaviour (e.g., policy, program, regulation, activity).

insight on their reactions to project elements and on the effectiveness of the project interventions introduced. Follow-up interviews were completed in December 2016 with 12 tablet recipients to further assess their shifts in energy practices, norms, and adoption of efficiency upgrades as a result of long-term project participation and re-engagement. The availability of comprehensive qualitative and quantitative data presented a strong opportunity to assess the interventions' impacts on re-engagement. Overall, these data delivered substantial opportunities to assess the changes in residential energy culture, as well as to identify the nuances and factors influencing the energy management within participating homes.

This case study provides insights on how smart grid interventions can influence long-term electricity consumption and energy cultures of participating households. These insights are delivered from an analysis of user experience feedback on intervention effectiveness and household dynamics influencing 'smart' home energy management. Additionally, this involves an assessment of consumption patterns in conjunction with the implementation of interventions later in the project (electricity reports and a tablet) to assess the ability of smart home energy management technologies to re-engage households in home energy management. In comparison to existing studies, this analysis of long-term engagement and re-engagement provides contributions to the literature in terms of smart grid implementation, participant engagement and re-engagement, as well as consumption changes at whole-house and appliance levels.

Two research papers (Chapters 4 and 5) deliver this case study research. The first paper (Chapter 4), focuses on qualitative participant insights. This paper aims to: (1) determine whether the project influenced the participants' energy culture, and; (2) determine what factors influenced 'smart' energy management and project engagement. This study focuses on the agency of the individual and utilizes the energy cultures framework to gain a detailed understanding of the complexity and the nuances surrounding residential energy behaviours.

The second paper (Chapter 5), integrates both electricity consumption data and qualitative participant insights. This paper aims to: (1) identify whether energy feedback via reports and a mobile tablet influenced re-engagement in household energy management; (2) highlight the specific energy practices contributing to shifts in energy management, and; (3) present underlying factors contributing to household energy management and user-experience with re-engagement mechanisms (electricity report and tablet) within a multi-year residential case study.

1.2.3 Outline of IHD case study

Multiple smart meter-enabled feedback programs were developed in Ontario as a result of infrastructure developments. In once such program, smart meter in-home displays (IHDs) were provided to 5274 Central Ontario[8] homes. This IHD facilitated knowledge transfer to participating households on electricity consumption by communicating directly with the smart meter. The IHD provided smart meter-enabled electricity usage and cost information to the consumer through a digital display and a light display. Two years of hourly utility consumption data were collected and analyzed (September 2012 - September 2014) to assess the impact of the IHD on residential electricity patterns in comparison to a control group who did not receive an IHD (n=3020). To develop a detailed understanding of the electricity consumption for the homes in question, load shape profiles and thermal consumption responses were utilized to categorize and cluster households into 78 consumer segments. One dissertation research paper delivers this case study research (Chapter 6). This study aims to: (1) analyze the influence of the IHD on the general population of participating homes; (2) assess whether different consumer cohorts responded differently to real-time feedback, and; (3) determine whether segmentation of households offers insights for smart grid consumer engagement.

1.2.4 Outline of engagement model paper

The aforementioned case studies highlight the challenges of engaging consumers with the smart grid and stress the importance of effective user-centred intervention design for the development of these programs. Smart grid implementation and related research requires an extensive collection of disciplinary knowledge and approaches for research (Ghiani et al., 2018; Ogie, Perez, & Dignum, 2017). Therefore, the next phase of this dissertation research warranted a review of existing approaches for intervention design in well-regarded fields followed by proposing a novel model for effective engagement design.

Forces influencing collective shifts towards idealized sustainability practices are complex. Often, current approaches to shift these forces towards sustainability remain within disciplinary-specific silos (e.g., technological, behavioural, marketing and design fields). The fourth dissertation paper provides a thorough review of the existing disciplinary approaches to intervention design, identifies critical elements for intervention design, and then proposes a novel engagement model to incorporate the strengths of the existing models and to address their respective limitations. To address

[8] The partnering organization and location of the study remain undisclosed for non-disclosure agreement purposes.

these aforementioned disciplinary challenges, the dissertation paper on engagement methods (Chapter 7) aims to: (1) provide an overview of existing intervention design elements; (2) examine the intervention design approaches of social marketing (SM), community based social marketing (CBSM), social practice theory (SPT), and design thinking (DT); (3) identify their key intervention design elements, and to review each approach for its respective strengths and limitations, and; (4) propose an integrated approach to intervention design.

1.2.5 Energy cultures framework

A multitude of factors influence energy consumption, therefore, utilizing holistic frameworks to assess changes and forces influencing energy consumption can develop a detailed understanding of energy consumption and management (Kowsari & Zerriffi, 2011; Stephenson, Barton, et al., 2015; Stephenson et al., 2010). Frameworks integrating technical and social elements, while also acknowledging the complexity of external systemic forces, can provide valuable insights in energy research (Wilson & Dowlatabadi, 2007). The energy cultures framework provides a comprehensive perspective into energy behaviours, shifts, and influencing factors related to energy consumption at multiple scales (Barton et al., 2013; Stephenson et al., 2010). In particular, this scalable framework can deliver an organized assessment of household energy management by investigating the interrelationships among material culture (technological and built environment efficiencies); practices and skills (routinized and one-off energy actions and the skills required to manage energy consumption), and; related norms and aspirations (the personalized and societal standards surrounding energy consumption) (Stephenson, 2018; Stephenson et al., 2010). This framework supports the knowledge development of transformations related to these interrelated elements and the underlying factors influencing these aspirational shifts (Walton, Doering, Gabriel, & Ford, 2014). Thus, the energy cultures framework provides an ideal organizing framework for the outcomes of this dissertation research.

Applied to the smart grid, the energy cultures framework can deliver insights on the interrelated socio-technical elements of home energy management with smart grid tools. In particular, this framework highlights the interrelationships between technologies, energy practices, norms and aspirations, as well external forces influencing the adoption and use of smart grid technologies for home energy management (Figure 1). Described in detail within Sections 2.7 – 2.10, the energy cultures framework facilitates multidisciplinary approaches to studying these socio-technical influences on home energy management within the smart grid. Framed in this dissertation as the smart and sustainable energy culture, which is further articulated in Chapters 2 and 4, this incorporates a tri-fold transition within technical and behavioural elements. In particular, this aspired energy culture involves: 1) a reorientation of material culture through the adoption and efficient use of energy efficient structural elements and appliances as well as smart grid technologies (e.g., smart thermostats); 2) a shift in energy practices and skills to conservation and peak shifting through the effective use of technologies for home energy management (e.g., maintenance, settings, optimization, and control), and; 3) a reframing of norms and aspirations surrounding energy use by increasing flexibility and changing standards for particular types of energy use (e.g., reducing thermostat use, shifting appliance use to non-peak periods). This dissertation acknowledges the tensions surrounding smart technologies and sustainable energy consumption patterns, where smart technologies have the capability to increase comfort and convenience, as well as require energy consumption for the production and operation of smart components (Tirado Herrero, Nicholls, & Strengers, 2018). However, this dissertation research applies the energy cultures framework for deeper understanding of the heterogeneous factors influencing the effective adoption of smart grid tools for managing residential energy use (Ford, Walton, et al., 2017; Stephenson, 2018).

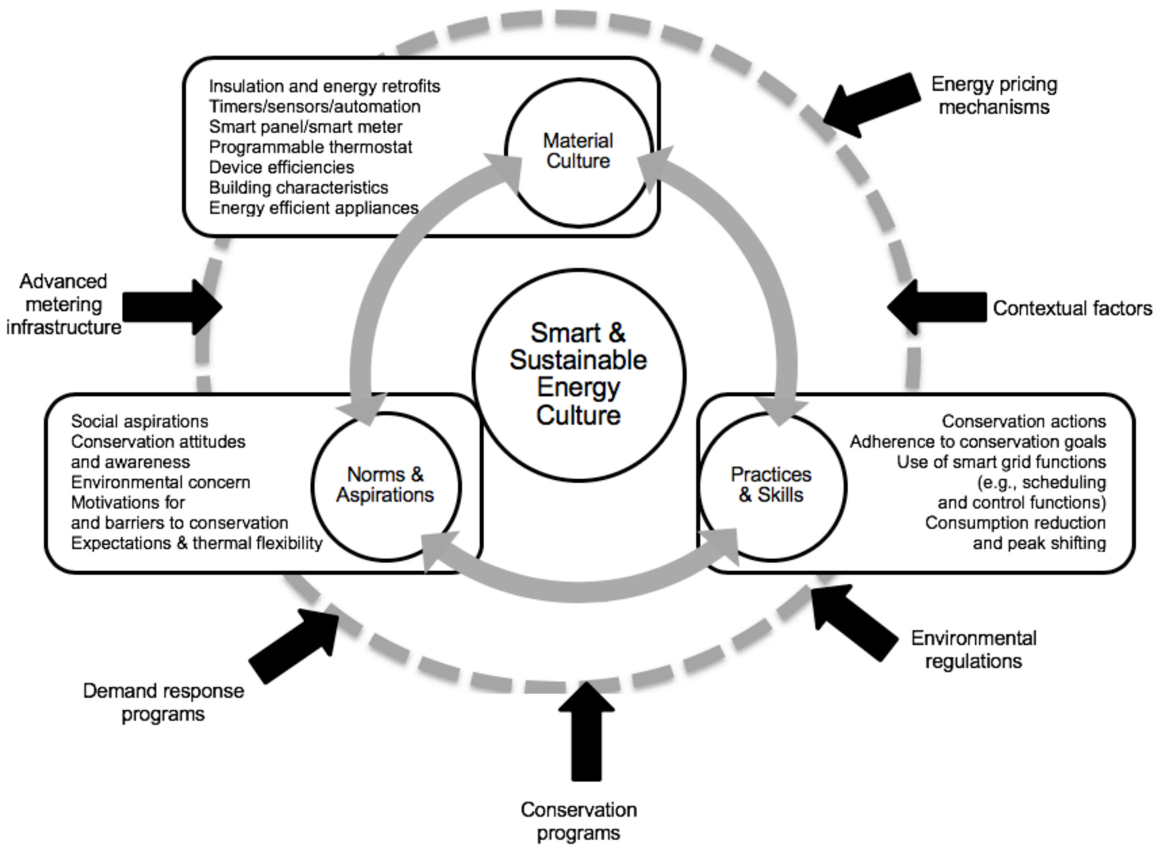

Figure 1 Smart and sustainable energy cultures framework, source: (Lazowski et al., 2018)

1.3 Contributions to the literature

The introduction of smart grid technologies provides opportunities to influence residential conservation and demand management (CDM); however, technology on its own will not transform society into the idealized 'smart utopia' (Strengers, 2013), especially considering there is no 'one-size-fits-all' approach to smart grid engagement programs (Rowlands, 2012). The incorporation of social and technical research through comprehensive conceptual frameworks is integral for the holistic understanding of household engagement within energy transitions, including the smart grid (M. G. Scott, Mccarthy, Ford, Stephenson, & Gorrie, 2016; Stephenson, 2018). In particular, perspectives from technical, engagement, design, marketing, as well as social and behavioural disciplines (e.g., social marketing, community based social marketing, social practice theory, design thinking) can offer support in this area of research. Utilizing multidisciplinary perspectives can support a thorough approach to addressing consumer engagement and to developing detailed knowledge on energy consumption within the grid (Summerton, 2004). This dissertation aims to address five gaps within the existing residential smart grid and consumer engagement literature, as expressed in Chapter 2 (Literature Review), by implementing the following:

1. Facilitating social science approaches in residential smart grid engagement research

From 1999-2013, published energy research was predominantly technical where social science research was underrepresented in main energy journals (Sovacool, 2014). Since energy has an influential role in connecting and modifying ecosystems and social systems, the understanding of human-environment relationships and their associated behaviours is an important topic to pursue in social science research (Harper, 2012). Research approaches integrating social science methods can deliver comprehensive insights on energy and smart grid research (Gaye & Wallenborn, 2014; Ghiani et al., 2018; Ogie et al., 2017). With only 12.6% of research in top energy journals from 1999-2013 utilizing qualitative methodologies, this offers an opportunity to integrate qualitative and social science approaches in residential energy research (Sovacool, 2014). As an outcome of the literature review (Chapter 2), mixed-methods analyses of residential smart grid technologies have had limited application in smart grid research, and particularly, within the Canadian smart grid context. Applying qualitative and mixed-methods approaches in this dissertation research provide a thorough approach for understanding consumer engagement in the smart grid, as presented in Chapters 4 and 5, respectively.

2. Understanding smart grid consumer segments

Consumer segmentation and classification of users can bring detailed insights into policy and program development, especially within the smart grid. Typologies of smart grid users, such as Gaye and Wallenborn's (2015) typology, bring a detailed understanding of certain consumers' preferences and applications of smart grid technologies. Additionally, load shape profiles and consumer segmentation bring additional insights into energy program and policy opportunities (Frades, 2016; Kwac, Flora, & Rajagopal, 2014; Oracle, 2015). In Chapter 4, Gaye and Wallenborn's (2015) smart grid typology is applied to the EHMS participants to identify the role of motivations surrounding household energy management in the smart grid. In Chapter 6, load shape profiles and thermal consumption patterns are utilized to segment 5274 IHD recipients to gain a thorough understanding of consumer cohorts, and their responses to smart meter-enabled feedback.

3. Utilizing long-term analysis to study occupant behaviour and engagement in the residential smart grid

Utilizing a long-term[9] timeframe to study smart grid interaction allows for additional understanding of energy cultures transitions. Limited long-term studies of occupant behaviour and interaction with residential smart grid technologies have occurred, particularly in the Canadian context; therefore, resulting in reduced insights for long-term engagement and sustained CDM practices in the smart grid. This dissertation research provides a multi-year assessment of smart grid consumer engagement, specifically where the EHMS case study utilizes a multi-year period of up to four years of participant involvement, as identified in Chapters 4 and 5.

4. Applying the energy cultures framework to residential smart grid research

Prior to this dissertation research, the energy cultures framework had not been applied to the smart grid or the Canadian context. Therefore, this research extends the application of the framework both technologically, by its application to the residential smart grid, and geographically to the Canadian residential context. Additionally, the analysis of different consumer segments for household energy management had limited applications in the energy cultures literature. Therefore, this research further advances this area of literature to understand different types of smart grid consumers and to suggest future areas to develop smart grid and energy cultures research. This is explicitly articulated within Chapter 4, presenting the smart and sustainable energy culture, with avenues for future research presented in Chapters 5 and 6.

5. Investigating integrated approaches to intervention design

Multidisciplinary research methods are crucial for developing thorough solutions for climate change challenges (Creutzig et al., 2018; Sovacool & Hess, 2017; Steg et al., 2015; Vlek & Steg, 2007). Diverse approaches, extending beyond behaviours, allow for detailed understanding beyond the 'tip of the iceberg' (Strengers & Maller, 2015b). The use of diverse approaches is also important for smart grid interventions and research (Ghiani et al., 2018). Current disciplinary approaches for intervention design and sustainability shifts remain in topic-specific silos, where potential cross-fertilization of innovations remains limited; consequently, there is an opportunity to propose an integrated model for intervention design. In Chapter 7, the diverse approaches are studied, and an integrated approach for intervention design is proposed.

[9] This dissertation defines long-term as greater than one year.

1.4 Research overview and objectives

To facilitate a multidisciplinary approach to studying smart grid engagement utilizing social science approaches for consumer engagement, this dissertation asks: ***How can Ontario residential consumers be engaged and re-engaged in the smart grid for the shift towards a smart and sustainable energy culture?*** Within the four manuscripts, the overarching dissertation research question is addressed through five interrelated research objectives. The research manuscripts included in this dissertation address the aforementioned research objectives through the methodologies and the conceptual framing applied, as identified in Table 1, and further described in the following sections.

Table 1 Overview of research objectives and dissertation chapters

Main RQ: How can Ontario residential consumers be engaged and re-engaged in the smart grid for the shift towards a smart and sustainable energy culture?	
Research objective	**Chapter**
O1: To determine whether smart grid engagement mechanisms influenced household energy cultures within two distinct residential smart grid projects	Chapter 4 Chapter 5 Chapter 6
O2: To gain a detailed understanding of underlying factors influencing household energy management	Chapter 4
O3: To determine whether, and if so the extent to which, consumers re-engaged within a multi-year smart grid project	Chapter 5
O4: To assess consumer segments in a large-scale smart grid project and to identify types of consumers that may positively react to smart grid feedback at the residential scale	Chapter 6
O5: To review the disciplinary approaches for consumer engagement and to identify an integrated model for intervention design applicable to multiple sectors, including the energy system	Chapter 7

1.5 Conceptual framing and dissertation outline

Through two smart grid case studies and proposal of a novel intervention design model, this dissertation research applies five research objectives to address the aforementioned research gaps (Table 1). Stephenson et al.'s (2010) energy cultures framework is used to frame this research to gain insights on how to develop a smart and sustainable residential energy culture[10] through the adoption of smart grid tools to reorient material culture, shift energy practices, and reframe norms surrounding energy consumption (Figure 2). In particular: (1) the EHMS case study studies the internal and external nuances and the changes in residential energy cultures in response to the introduction of smart grid technologies in both engagement and re-engagement; (2) the IHD case study identifies different segments of residential consumers and assesses how these differences in energy patterns can influence smart grid engagement, and; (3) the conceptual engagement paper studies and proposes an integrated method for intervention design which could be applied for the establishment of a smart and sustainable energy culture.

The data collected and analyzed through both the EHMS and IHD case studies delivered abundant opportunities for studying residential energy cultures and the interaction between residential smart grid technologies for home energy management shifts. Additionally, the related disciplinary literature offered a significant opportunity to review existing intervention design approaches and to propose an integrated model for intervention design. The energy cultures framework presents a comprehensive approach to studying residential impacts of smart grid technologies and opportunities for policy development. In particular, this dissertation research aims to advance the understanding of smart grid tools for shifting consumers towards a smart and sustainable energy culture. The aforementioned research objectives and results are incorporated in four separate manuscripts, which are integrated within Chapters 4 – 7 of this dissertation (Figure 2 and Figure 3).

[10] As articulated in detail in Chapters 2 and 4, the shift towards a smarter and more sustainable energy culture involves the adoption of new technologies and efficiency measures, shifts in energy practices and changes in norms surrounding energy management.

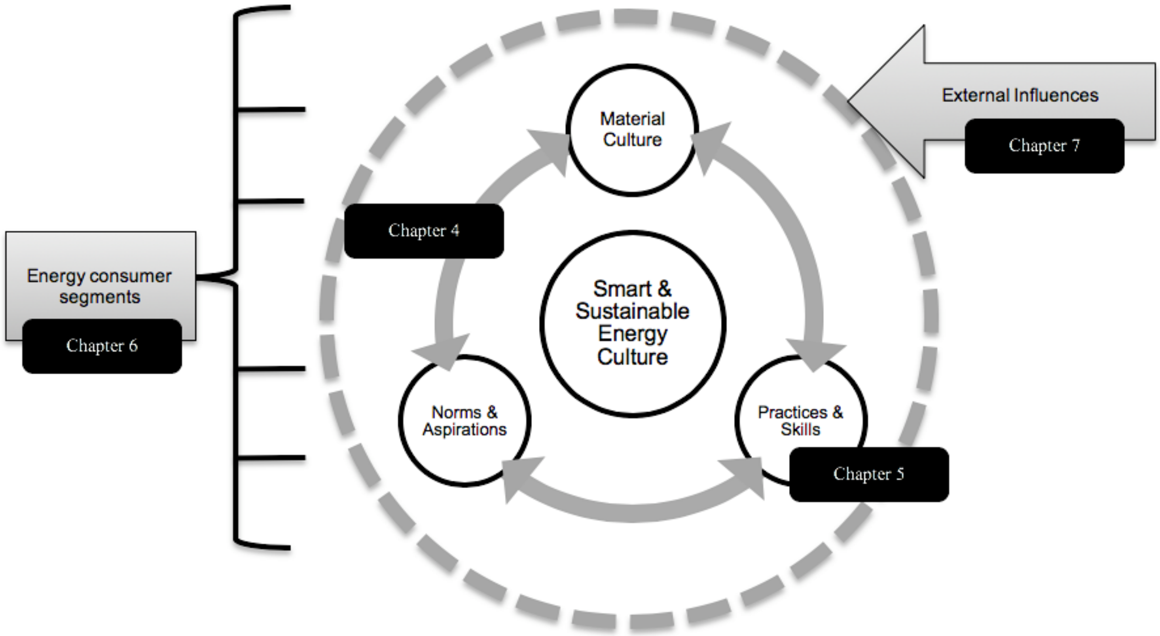

Figure 2 Applying the smart residential energy cultures framework to the dissertation research, adapted from (Lazowski et al., 2018; Stephenson, Barton, et al., 2015; Stephenson et al., 2010)

Several elements are brought together within the eight chapters of this dissertation. These chapters incorporate an overview of the research (Chapter 1), a review of the relevant literature (Chapter 2), a description of the methodology utilized throughout the dissertation research (Chapter 3), the research outcomes and respective insights in four manuscripts (Chapters 4–7), and a presentation of the conclusions and recommendations as an outcome of the dissertation research (Chapter 8) (Figure 3). In Chapters 4 and 5, the EHMS case study assesses both the internal and external influences, and related nuances, surrounding changes in residential energy cultures following smart grid program engagement. Specifically, Chapter 4 focuses on the nuances of energy cultures and household energy management changes during participants' involvement in the smart grid program. Chapter 5 concentrates on the capability of EHMS intervention mechanisms to re-engage participants in energy management practices. In Chapter 6, the IHD case study highlights types of consumer segments and how different types of consumers respond to smart meter-enabled energy feedback. In Chapter 7, the engagement model paper studies how to develop effective 'external influences' for more sustainable energy culture transitions by a review of the literature and a proposal for an integrated model for intervention design. Figure 3 outlines the chapters of the dissertation.

Together these research chapters present research results and insights for engaging residential smart grid consumers beyond the meter for household energy management.

Chapter 1: Introduction

Chapter 2: Literature review

Chapter 3: Methodology

Chapter 4: EHMS case study paper 1 - *Towards a smart and sustainable residential energy culture: assessing participant feedback from a long-term smart grid pilot project*

Chapter 5: EHMS case study paper 2 - *Re-engagement in a long-term smart grid study: Influences on household energy management practices*

Chapter 6: In-home display analysis paper - *Who's responding anyway? Assessing segment-specific responses to real-time energy displays*

Chapter 7: Engagement model paper - *ENGAAGGE: Towards an integrated model for collective change*

Chapter 8: Conclusions and recommendations

Figure 3 Overview of dissertation chapters

2. Chapter 2 – Literature Review

2.1 Introduction

To study consumer engagement with the smart grid a holistic approach to understanding the related literature was developed in alignment with the energy cultures framework utilized in this dissertation research (Figure 4). Consequently, this literature review, framed within the energy cultures framework covers five fundamental areas of literature. First, the smart grid technology literature provides an overview of both the internal and external material culture related to smart grid transitions. Second, the energy geography literature highlights the scales of energy cultures within energy landscapes. This literature ties together spatial scales (micro-to-macro) of consumption, innovation, governance, and engagement by studying energy consumption across space and time. Third, the energy policy and governance literature align with the contextual factors and design of external factors influencing energy cultures. This area of literature highlights the rules and structure for energy access, consumption, and sustainability, and identifies novel governance methods and key actors. Fourth, the socio-technical transitions literature aligns with the contextual factors and design of external factors influencing energy cultures. This area of literature develops how innovations in the energy landscape transform and how they are conceptualized. This topic area also highlights the roles of actors, artifacts, and systems in energy innovations. Fifth, the literature on energy behaviour, engagement, and design provides insights into the interconnections between materials, practices, and norms within energy cultures. This literature highlights factors of consumption, conceptualizes how society and individuals respond to interventions, and identifies intervention and technology design strategies to shape consumption. Overall, covering these areas of literature provides a holistic understanding of the nuances of energy cultures within the context of the smart grid.

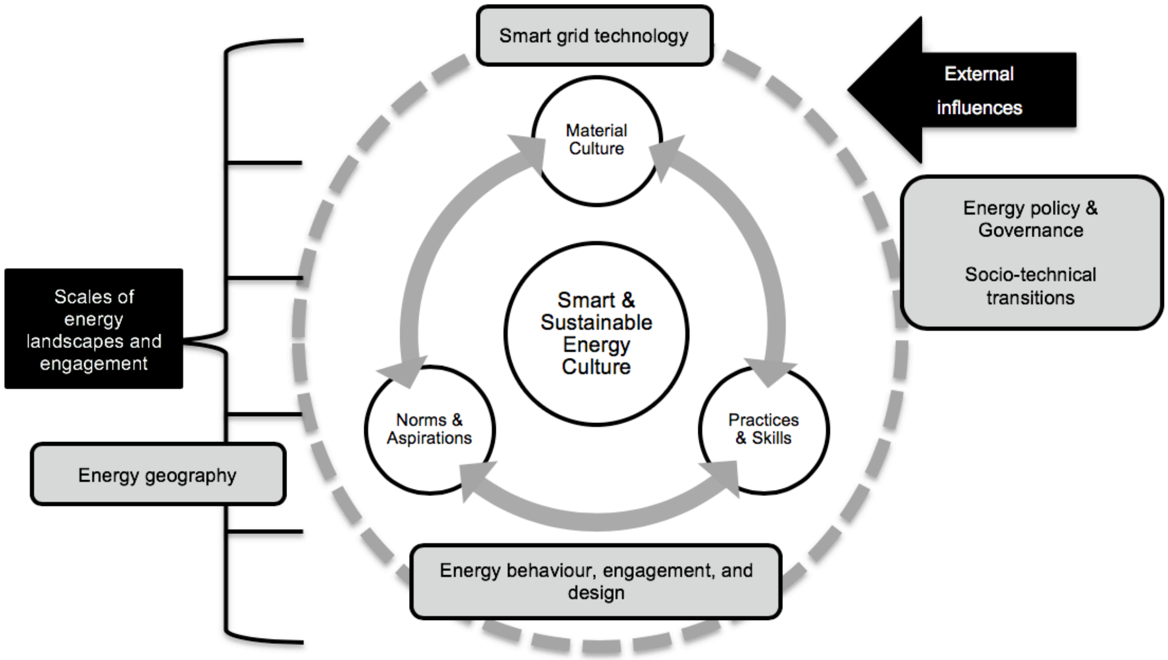

Figure 4 Conceptual framing of literature review

2.2 The smart grid: An introduction

Technological innovations in the form of smart grid technologies present several opportunities for managing household energy consumption. The smart grid applies modern communication infrastructure to the electricity grid and enables two-way communication between utilities and consumers (Depuru, Wang, & Devabhaktuni, 2011; Miler & Beauvais, 2012). Multiple stakeholders have defined the smart grid (e.g., policymakers, consumer groups, technology forums); however, the main elements incorporated in these definitions include renewable energy and storage integration, information and communication technologies, and increased grid capabilities that are secure, sustainable, and economic (CEA, 2017). In contrast, traditional centralized grids provide a one-way flow of communication where the utility operator is the primary collector and transmitter of information. As a result of the increased flows of both information and electricity, the smart grid 'connects consumers to control rooms' and consists of several elements, including smart meters/panels, monitoring and control mechanisms, communication infrastructure, and energy storage (Gelazanskas & Gamage, 2014; IESO, 2015). The smart grid is defined as an "…electric grid able to deliver electricity in a controlled, smart way from points of generation to consumers, which are considered as an integral part of the [grid] since they can modify their purchasing information, incentives and disincentives," (Siano, 2014, p. 462). Ultimately, this transformation with advanced metering technology introduces capabilities for increased energy feedback, dynamic pricing, distributed energy generation and CDM (Strengers, 2013). Smart grid policies, and related programs, have been introduced across several regions including the United Kingdom, the United States, the European Union, China, Australia, Japan, Canada (Ehrhardt-Martinez, Donnelly, & Latner, 2010; Faruqui, Sergici, & Sharif, 2010b; Pullinger, Lovell, & Webb, 2014; Sovacool, Kivimaa, Hielscher, & Jenkins, 2017; Yang et al., 2017). The widespread interest and application of the smart grid bring opportunities for studying the role of smart grid technologies for conservation and demand management and sustainable energy transitions.

2.2.1 Elements of the smart grid

The smart grid operates at different scales: the household level, the community level, and the main grid level (Figure 5)(Geelen, Reinders, & Keyson, 2013). Consequently, smart grid technologies are not just applicable to the macro-level, they consist of technologies available at the household-level and involve a range of product offerings, often including micro-generators, storage systems, smart appliances, smart meters, time-variable prices and contracts, energy monitoring, and control systems (Darby, 2008, 2010). Therefore, the smart grid incorporates flows of energy data alongside energy transmission. As a result of this potential for distributed generation and increased end-user participation, end-users become co-providers instead of passive consumers (Geelen et al., 2013).

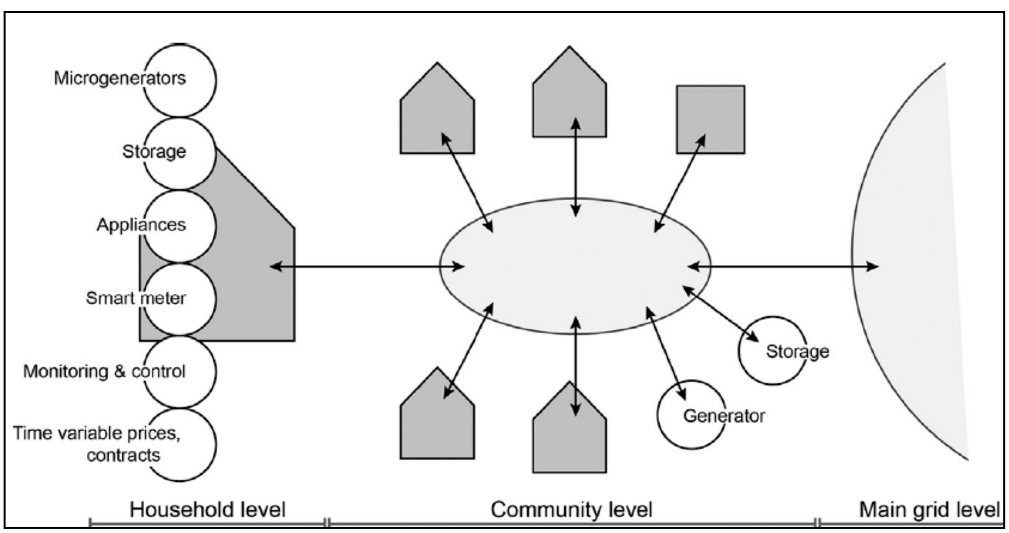

Figure 5 Schematic overview of the categories of products and services of a smart grid, source: (Geelen et al., 2013)

The main components that constitute a residential smart grid connection include a smart meter, communication infrastructure, smart home appliances and devices, and control devices for the optimization and automation of consumption. Smart meters measure consumption while providing additional services beyond that of a conventional meter (Darby, 2010; Sovacool et al., 2017). Smart meters can log the quantity of electricity use by time of day, enabling real-time data collection and feedback, and can also record power quality, disturbances and events within the electricity grid (Depuru et al., 2011; Lysyk, 2014; O'Malley, 2014). This capability can provide services for energy efficiency, security, as well as convenience, and comfort in the electricity grid (Yang et al., 2017). Whereas a conventional consumer only has a manual collection of consumption information, a smart meter system provides a gateway to more in-depth consumption information that may achieve consumption reductions within the household (Figure 6). The facilitation of increased control and feedback can enable 'demand-side intelligence,' allowing consumers to see real-time electricity cost and consumption information to reduce overall demand and shift consumption patterns, and thus the stress on the electricity system (ISGAN, 2012, p. 12). As household consumers are critical stakeholders in the residential electricity grid, incorporating their engagement with the smart grid system is essential for achieving the goals associated with smart grid implementation (Anda & Temmen, 2014). The human dimension of smart grid systems is a crucial aspect that must be incorporated to achieve effective CDM policy development.

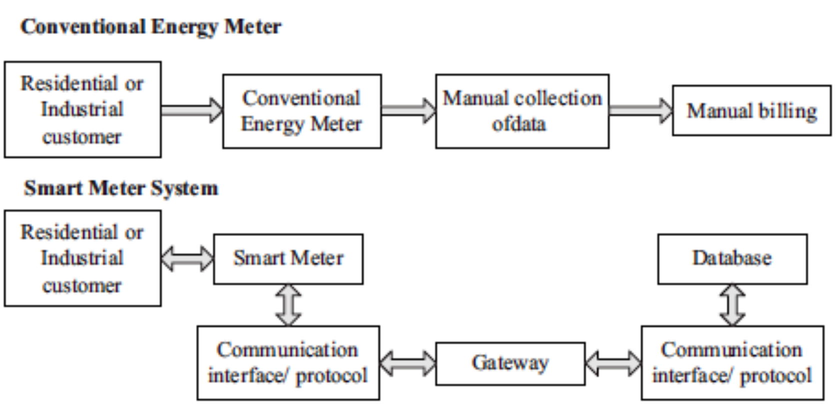

Figure 6 Metering architectures of conventional energy meters and smart meters, Source: (Depuru et al., 2011)

2.2.2 Smart home energy management: A new suite of 'tools'

The creation of the smart grid has resulted in the development of technologies for home energy management (HEM) a new classification of smart grid tools within the household exist, including those that are smart controlled and those that are user controlled. HEM technologies consist of a variety of products, with the main objectives of reducing peak demand, increased resource management, and increasing consumer benefit through increased control and reduced volatility (Ford, Stephenson, Brown, & Stiehler, 2014). Karlin, Ford & Squires (2013), developed a classification of smart grid technologies for residential energy feedback, consisting of nine categories: information platform, management platform, appliance monitor, load monitor, grid display, networked sensor, closed management network, and open management.

LaMarche et al. (2012) identify these smart devices in three categories. The first is control devices, which allow for consumer- or utility-controlled capabilities. This function can deliver control over multiple devices (centralized), for a single device (device-level), or incorporated within a specific device (onboard). Ford et al. (2014) further describe this as either 'smart' control, or user-centred control through the facilitation of appliance use scheduling; remote/autonomous load switching via utility signal; standby appliance automatic shutoff; smart appliance usage via external data (e.g., environment, utility load); user-enabled remote schedule/control, and; prompts for increased consumer management. The second category, user interfaces, can provide direct feedback or indirect feedback to the consumer. Enabling technologies, the third category, involve the sensors, communications and communications protocols facilitating the collection, transfer, and display of feedback (Karlin et al., 2013; Lamarche et al., 2012). At the household level, this includes a home control unit for communication with the appliance network, smart appliances, a display for feedback or control, as well as the ability to communicate within the network (Ford et al., 2014). These capabilities deliver smart control and user-centred control.

The progress of the smart grid, and HEM technologies transform the home from disconnected appliances and energy bills towards a smart home energy network. This technological ecosystem integrates a household 'hub' facilitating the control and automation of appliances, the connection to storage, electric vehicles, and opportunities for renewable micro-generation. Consequently, these HEM technologies provide opportunities for consumers to become 'prosumers' where they are active participants within the energy grid (e.g., managing, producing, and storing energy), transitioning the structure form top-down distribution, to a network of engaged players at different scales (Goulden et al., 2014; Leiva, Palacios, & Aguado, 2016; Yang et al., 2017). In particular, this shapes a new kind of consumer. According to the SGCC (2016a), in comparison to five years ago, consumers have a stronger sense of value towards the smart grid's ability to increase renewable integration and are increasingly eager to adopt new technologies.

2.2.3 Smart grid opportunities

The importance of smart grid infrastructure as a component to enable electricity efficiency is widely proclaimed in the literature, with benefits for consumers, utilities, and society (Darby, 2010; Römer, Reichhart, Kranz, & Picot, 2012; Sovacool et al., 2017). Particular residential smart devices installed in conjunction with advanced metering infrastructure (AMI) (e.g., smart thermostats, smart appliances, and optimization features) are predicted to also offer a range of household energy savings, including other benefits including comfort, conveniences, and security (Darby, 2018a; Tirado Herrero et al., 2018). Additionally, as outlined by Kaufmann et al. (2013), and further emphasized by the SGCC (2016a), customers see and the benefit of the smart grid, which can potentially lead to the successful uptake of this technology. Therefore, this highlights a range of demand management opportunities from residential smart metering infrastructure and technologies in various geographical locations.

Advanced metering infrastructure is being implemented worldwide, including in North America, Europe, Australia, and Asia (Depuru et al., 2011; Ehrhardt-Martinez et al., 2010; Faruqui et al., 2010b; Pullinger et al., 2014; Sovacool et al., 2017; Yang et al., 2017). Studies addressing the ability of this technology to impact electricity behaviours in a range of continents have taken place. Faruqui, Sergici, and Sharif (2010) analyzed twelve residential smart grid programs throughout North America, Australia and Japan identifying a range of 7-13% of energy savings in these programs. Martinez and Donnelly (2010), provided a meta-analysis of fifty-seven residential energy feedback programs throughout the United States, Canada, Japan and Australia, showing an average savings of 4-12%. An average savings of 3% was experienced in 18,000 homes across the United Kingdom (Hargreaves, 2018). Reductions in consumption related to the smart grid are predicted to be 5-15% (Verbong et al., 2013). However, particular elements need to be considered when investigating these ranges of savings. As identified by Delmas et al. (2013b), optimistic findings in energy feedback trials could be from less robust studies. The range of savings identified highlights the variability in how individuals respond to feedback for energy management (Darby, 2006; Sovacool et al., 2017).

Particular attention also needs to be paid to the claims of 30% energy savings from smart home devices used in conjunction in the smart grid (e.g., smart thermostats, smart lighting, smart appliances, etc.,) (Tirado Herrero et al., 2018). A limited number of studies have been completed in realistic environments (Darby, 2018a; Hargreaves, Wilson, & Hauxwell-Baldwin, 2018; Tirado Herrero et al., 2018). Additionally, these smart home technologies might promote energy-intensive lifestyles, such as convenience, comfort, or security, that may limit the potential savings (Darby, 2018a; Ford, Pritoni, Sanguinetti, & Karlin, 2017; Gram-Hanssen & Darby, 2018; Hargreaves et al., 2018; Tirado Herrero et al., 2018). Therefore, although there is a range of projected and measured savings, the opportunities for CDM presented by the smart grid and related smart home technologies, remain variable depending on socio-technical factors.

The smart grid can significantly impact future energy scenarios through enabling renewable energy opportunities, increase electric transportation, complement electricity pricing mechanisms such as TOU pricing (Blumsack & Fernandez, 2012). The literature has identified several key socio-technical possibilities from smart grid technologies. Firstly, the smart grid can provide increased resilience and reliability in the electric grid through improved communication systems and the ability to 'self-heal' during large system issues, which can reduce costs to utilities, consumers, and society. Additionally, security is improved through advanced monitoring, while energy independence is gained through localized energy generation and distribution (Stephens et al., 2015). Secondly, the smart grid can help consumers to reduce their electricity use and match price signals to reduce their costs. Thirdly, the smart grid offers significant benefits for the environment, including supporting the large-scale deployment of renewables, contributing to adaptation and mitigation, increasing the electrification of transportation, and reducing the carbon intensity of the electricity system. Lastly, the smart grid encourages citizen empowerment by facilitating active engagement in the generation and management of the electricity system at various scales (Stephens et al., 2015). With increased feedback, this increases the potential for consumer awareness and knowledge of billing and opportunities for micro-generation as well as for conservation (Burgess & Nye, 2008). As presented by Stephens et al., (2015, p. 25), "information is power: if consumers have more information, they have more control, and play an active role in aligning their priorities with management of their electricity systems." Advanced metering infrastructure provides specific benefits across stakeholder groups, including end-users, electricity retailers, network operators, and generators (Figure 7).

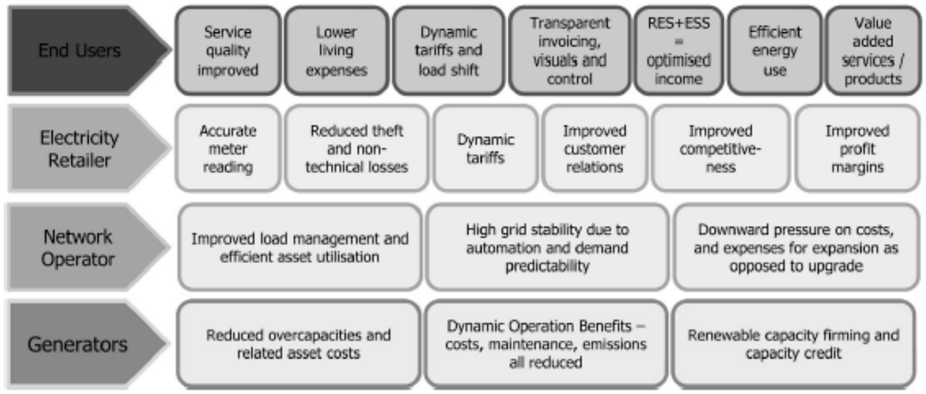

Figure 7 Benefits for critical stakeholders, Source: (Adna & Temmen, 2014)[11]

A significant possible outcome of this smart grid interconnectivity is the transformation of the roles of energy users through citizen engagement, where customers transform from passive 'energy consumers' to actively engaged 'energy citizens' or 'prosumers' who contribute to the electricity grid through production (Burgess & Nye, 2008; Goulden et al., 2014; Miler & Beauvais, 2012; Stephens et al., 2015). A variety of 'tools' to engage consumers with the interconnectivity of the smart grid system have been created, including web applications and in-home displays (IHDs) for real-time consumption feedback, system automation and optimization functions, and the integration of smart appliances. Additionally, householders can participate in renewable micro-generation and energy storage (Geelen et al., 2013; Stephens, Wilson, Peterson, & Meadowcroft, 2013). A variety of studies have assessed the ability of these technologies to reduce consumption in a range of continents (Ehrhardt-Martinez et al., 2010; Faruqui, Sergici, & Sharif, 2010a; Verbong et al., 2013). Therefore, highlighting the potential demand-side management (DSM) opportunities for smart grid technologies.

2.2.4 Smart grid challenges

The potential shortcomings of the smart grid should also be noted. First, the implementation of the smart grid can lead to increased vulnerabilities to cyber-attacks to disrupt the energy system or to steal confidential information. Therefore, bringing energy system concerns about the security of consumer data and vulnerabilities from malicious attacks. Second, weakened economic conditions can take place if market volatility occurs and through the decentralization of the energy grid, otherwise known as the 'utility death spiral' (Stephens et al., 2015). Third, the decentralization of the energy grid has the potential to integrate additional challenges to the electricity grid, including the

[11] In Figure 7 RES refers to renewable energy system and ESS refers to energy storage system.

volatility of daily energy demand and renewable energy generation; the uncertainty of renewable energy generation capabilities, and; the stability difficulties introduced to the distribution grid as a result of integrating renewables and electric vehicles. Fourth, a challenge for system-wide smart grid development is the requirement of significant upfront investment; thus, requiring innovative financing structures for broad-scale change, where utilities might not uphold the entire cost. Fifth, if consumers become isolated, and their privacy compromised, it can result in citizen disempowerment (Stephens et al., 2015). Sixth, the integration of renewables can introduce volatility of daily energy demand and renewable energy integration. Gangale et al., (2013) also acknowledge smart grid challenges, including the lack of consumer trust, and the uncertainties of different regional factors effecting policy implementation. Seventh, particular DSM challenges exist for smart grid implementation and achieving related goals. As identified by Ellabban et al. (2016) this includes consumer behaviour, security and privacy as well as the interoperability of the system. Lastly, vulnerability and poverty, as well as consumer resistance and ambivalence, can present additional challenges for smart metering rollouts (Sovacool et al., 2017). Therefore, although the smart grid presents economic, environmental, and societal opportunities, specific challenges exist for its effective implementation.

2.2.5 Beyond the smart grid: Consumer engagement for the development of 'smarter' consumers

As noted by Anda and Temmen (2014), and further emphasized by Ellabban et al. (2016), benefits from the smart grid can only be achieved through the cooperation and engagement of end-users. Methods of engaging customers can include value-added services, such as feedback devices, analytical tools, flexible billing cycles and dynamic rate plans, mobile applications, emails, short message service (SMS) and interactive invoicing, and public information (Anda & Temmen, 2014). Using multiple intervention types to address the behaviour can stimulate change (Stern, 2000). As mentioned by Delmas et al., (2010) while theory suggests that information programs may be effective, the empirical evidence indicates important differences in effectiveness based on the type of information provided. This is further influenced by consumer type and context (e.g., socio-economic level, education, income, age, etc.,) as discussed later in this literature review (Abrahamse & Steg, 2009; M. Brown, 1984, 1985; Costanzo, Archer, Aronson, & Pettigrew, 1986; Kowsari & Zerriffi, 2011; Lutzenhiser, 1993; Mills & Schleich, 2012). Understanding which interventions are the most effective, and to which type of consumers, is essential for the development of policies and programs surrounding energy conservation. To date, the keys to successfully engaging consumers with smart metering data are still relatively unknown, highlighting a crucial opportunity for identifying the effective means of delivery and presentation of smart metering data for successful consumer engagement (SGCC, 2016a). Therefore, further investigation into the impact of specific interventions on residential conservation behaviour in smart grid projects is necessary.

At the root of this opportunity to create demand-side intelligence and to empower users through real-time consumption data, a key question remains: *How can residential consumers be engaged and re-engaged in the smart grid for the shift towards a smart and sustainable energy culture?* Although these opportunities seem favourable, the potential of smart grid tools for shifting consumption demand ought to be examined in detail. The following sections evaluate the literature on the scales of energy governance, factors influencing household energy consumption, as well as the theoretical applications for further understanding and facilitating the creation of a 'smart' energy culture, within a residential context.

2.3 Scales of energy governance and consumption

2.3.1 Energy geography

The concepts of space, place, and scale, which are examined in energy geography, substantially influence the energy landscape. Energy geography provides insights on the scale and spatial attributes related to the human-environment relationship of energy consumption. As stated by Zimmerer (2011, p 706), "Geography is central to understanding and addressing the current energy dilemmas." Energy geography has focused on resource management, studying the inter-relationship between 'man' and the environment in regards to energy (Chapman, 1989) and the modes of production, distribution, use, and interactions of 'energy landscapes' (Calvert, 2015).

Over the past several decades, energy geography has transformed from a purely resource focus to a multidisciplinary field with socio-political research outcomes (Chapman, 1989, 2009)(Figure 8). Early studies involved a resource and economic geography perspective with a managerial and positivist lens (Calvert, 2015). During this shift, the role of geography in energy policy was emphasized as significant, since fixing future problems "…depends considerably on our ability to identify and understand the workings of energy in our societies and economies" (Willbanks, 1985, p. 506). This pivotal development involved the acknowledgement of the social element in energy studies and the importance of energy conservation.

1900-1950: Descriptions of spatial distribution of energy

1950- 1960: Focus on multi-component structure of energy systems

- 1950 - Pratt and Good - Volume on Petroleum
- 1950 - George- *Geographie de l'Energie*

1960-1970: Broader study of energetics

- 1963 - Odell- *An Economic Geography of Oil*
- 1964 - Manners - *The Geography of Energy*

1970-1980: Development of energy geography

- 1970s - American Association of Geographers (AAG) supported several monographs for energy geography
- 1972 - Carter et al. - Biophysical environment and flows of energy in environmental systems
- 1976 - Chapman - physical geography development
- 1976 - Cook - *Man, Energy, Society*
- 1977 - Odell- *Energy, Needs and Resources*
- 1979 - Inauguration of Energy and Environment specialty group in AAG
- Limited study on human geography
- Nuclear power research

1980-1990: Transition to socio-technical studies and human geography

- 1985 - Calzonetti & Solomon - *Geographic Approaches to Energy*
- 1982 - Wilbanks - "Location and Energy Policy"
- 1989 - Chapman - *Geography and energy: commercial energy systems and national policies*
- Discipline developing abroad

1990 - 2000: Electricity issues in supply, demand and generation

- 1995 - Walker - "Energy, land use and renewables: A changing agenda"
- 1996 - Kuby - *Investment strategies for China's coal and electricity delivery system*
- 1999 - Smil - *Energy in the Biosphere*

2000 - Present: Growing prevalence of energy geography

- 2004 - Solomon & Pasqualetti - "History of energy in geographic thought" in: *Encyclopedia of Energy*
- Multidisciplinary research
- Studies of carbon lock-in
- Geographies of energy transisions
- Energy geography and ties to climate change
- Energy poverty and energy security
- Smil's work on energy issues, transitions & outlooks (various)
- 2011 - Zimmerer "New Geographies of Energy"
- 2015 - Calvert - "From Energy Geography to Energy Geographies"

Calls for future studies

- Increase understanding of energy-society relationship
- Geo-political and geo-economic studies of global energy networks
- Geographical perspectives of socio-technical transitions
- Advanced spatial decision support for energy planning and technology implementation

Figure 8 Timeline of energy geography research (1900-Present), sources: (Calvert, 2015; Calvert & Simandan, 2010; M.J. Pasqualetti, 2011; Martin J. Pasqualetti & Brown, 2014; Solomon et al., 2003)

With the increased incorporation of socio-economic studies, energy geographers are well positioned to provide scientific and policy contributions to solving energy dilemmas. This emergence of ‘new geographies’ involves the assessment of energy landscapes while combining multiple perspectives and skills focusing on environmental change and resource use and integrating multidisciplinary contributions (Riordan, 1970; Zimmerer, 2011). Theories, concepts, positions, and techniques from numerous knowledge areas have been integrated into energy geography, providing meaningful and thoughtful research into the complex problems of energy. Consequently, “Geographical approaches are best conceived as an academic borderland,” and ‘energy geographies’ is a more appropriate label for this field of study (Figure 9)(Calvert, 2015, p. 4).

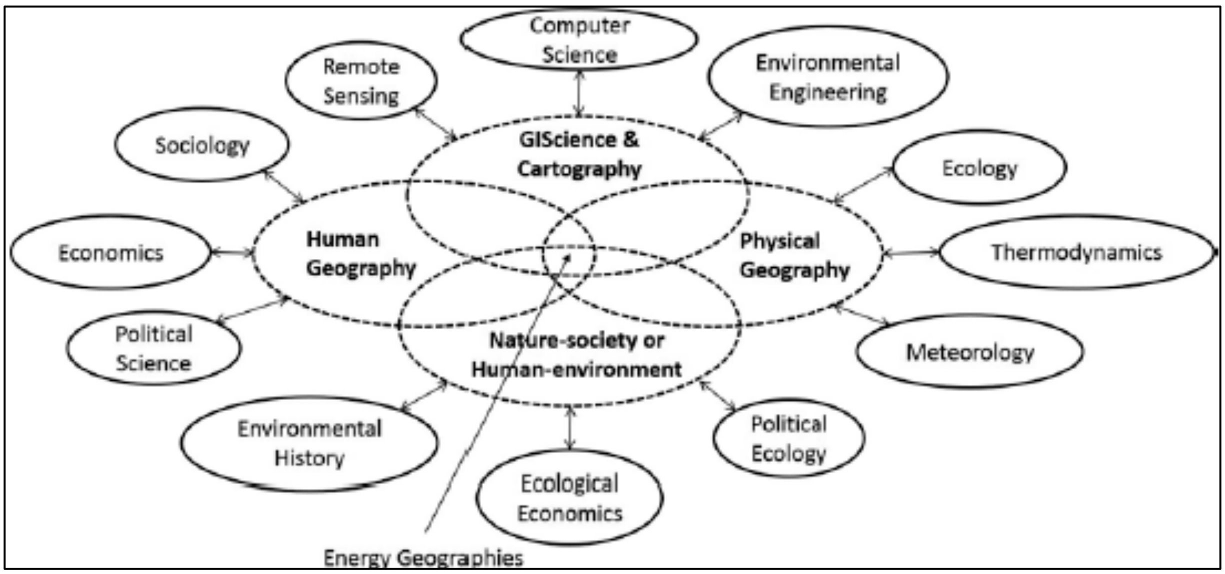

Figure 9 Fields covered in energy geography, source: (Calvert, 2015)

The study of energy efficiency and conservation in geographical studies has contributed to the understanding and potential of various policies and programs for conservation, in particular, residential conservation and incentives (Solomon et al., 2003). Energy geographers have also identified the importance of examining beyond technology and focusing on energy consumers, and different types of energy consumers, presenting opportunities for additional progress in this area (Solomon et al., 2003). Incorporating elements of behavioural geography is important to understand the sense of ‘place’ and its relation to household decision-making surrounding energy consumption in more detail. Since energy geography is, as identified by Calvert (2015), at ‘an academic borderland,’ it is also crucial to further integrate this holistic, integrated view to develop the study of ‘conservation landscapes.’ The study of consumption landscapes provides essential examples of technological drive in energy use, including energy grids and networks (Zimmerer, 2011); however, the transition to conservation studies has remained limited. What is needed is a focus on 'demand management' and 'energy innovation landscapes.' As demand management and clean energy transitions develop, investigating opportunities for these applications in energy geography research can contribute valuable knowledge for energy policy development.

2.3.2 Governing energy transitions

Similar to the production, transmission, and consumption of energy, energy governance is inherently linked to socio-spatial entities at various scales. Governance has been defined in different ways by multiple entities (Table 2). In this dissertation, governance involves the formal and informal rules that control societal aspects within jurisdictional boundaries and involve participation from multiple actors (e.g., the state, public and private sector, and community-level actors).

Table 2 Definitions of governance, source: (Sano, 2007)

Institution	***Definition***
The World Bank, 1994	The manner in which power is exercised in the management of a country's economic and social resources for development
The Commission on Global Governance	Governance is the sum of the many ways individuals and institutions, public and private, manage their common affairs. It is a continuing process through which conflicting or diverse interests may be accommodated and co-operative action may be taken
International Institute of Administrative Sciences, 1996	Governance refers to the process whereby elements in society wield power and authority, and influence and enact policies and decisions concerning public life, and economic and social development. Governance is a broader notion than government. Governance involves interaction between these formal institutions and those of civil society
The UNDP, 1997	The exercise of economic, political, and administrative authority to manage a country's affairs at all levels
The European Union, 2001	Governance means rules, process and behaviour that affect the way in which powers are exercised, particularly as regards to openness, participation, accountability, effectiveness, and coherence
Departmental for International Development (DFID), UK, 2001	We use governance to mean how the institutions, rules, and systems of the state – the executive, legislature, judiciary, and military – operate at central and local levels and how the state relates to individual citizens, civil society, and the private sector

Traditional and idealized forms of governance involve strong government involvement, such as market-based and regulatory approaches (Armitage, De Loë, & Plummer, 2012). 'New governance,' involves collaborative approaches between government and nongovernmental actors (Lockwood, Davidson, Curtis, Stratford, & Griffith, 2010). These hybrid structures aim to provide adaptive and flexible solutions at scales suitable to address complex issues while gaining knowledge from a diversity of actors. Additionally, these hybrid approaches help to further develop the roles, legitimacy and accountability of new actors (Armitage et al., 2012). These new connections fused between public and private sectors as well as civil society actors include mechanisms for public-social partnerships, public-private partnerships, private-social partnerships, and, ultimately, public-private-social partnerships (Delmas & Young, 2009). This new governance approach allows for dynamic and fast approaches for managing resources and governing complex issues.

2.3.2.1 Energy governance

Research on energy governance and policy provides insight into elements of energy control and access, mechanisms for management, and the influences of actors at various scales (e.g., global, national, regional). Energy governance involves the creation and application of rules to ensure that the 'collective actions' of production and consumption do not result in unfavourable outcomes and is motivated by goals of energy access, affordability, sustainability, and security (Florini & Sovacool, 2011; Van De Graaf, 2013). Energy governance has transitioned from traditional forms of government and market instruments to the governance of sustainability and environmental impacts through hybrid mechanisms (Armitage et al., 2012; Helm, 2002; Lemos & Agrawal, 2009). Hybrid governance models include multilevel frameworks and synergies between actors in the civil society and the private and public sectors; however, government participation is still necessary to avoid substantial negative climate change impacts (Armitage et al., 2012; Delmas & Young, 2009; Lockwood et al., 2010). Certain actors, goals, and challenges associated with each scale of energy governance, and the interplay among scales, have been identified in the literature (Table 3).

Table 3 Elements of energy governance from global to household scales

Scale of Energy Governance and Policy	Actors	Goals and Objectives	Challenges
Global & Continental	Intergovernmental organizations (e.g., IEA), Summits (e.g., G8), International NGOs (e.g., REEEP), Multilateral Banks (e.g., Asian Development Bank), Hybrid entities, Transnational networks, International energy companies (Dubash & Florini, 2011; Florini & Sovacool, 2009; Van De Graaf, 2013)	Control and access of public goods (Florini & Sovacool, 2009); security of supply and demand; economic development; international security; environmental protection and sustainability; and domestic good governance (Van De Graaf, 2013; Van de Graaf & Colgan, 2016)	Disjointed landscape of inter-state energy governance; multiplicity of actors in energy lifecycle; lack of integration of national energy policies at the global scale (Dubash & Florini, 2011)
National – Provincial (Canada)	Federal Government Provincial Government Neighbouring Government NGOs Community actors Private firms Utility companies	Provincial renewable energy generation and sustainable energy management goals (Ferguson-Martin & Hill, 2011; Stokes, 2013); provincial decarbonization strategies (Doern, 2005; Rosenbloom & Meadowcroft, 2014); and overarching federal influences on provincial energy policy developments through climate goals (Doern, 2005; Doern & Gattinger, 2003; Winfield, 2008)	Diverse supply of energy; National dependence on the U.S. for energy development; Division of policy between national and provincial powers; and increasing unevenness of national sustainable energy policy development (Doern & Gattinger, 2003; Rosenbloom & Meadowcroft, 2014; Rowlands, 2008; Winfield, 2008)
Regional/Local	Local government Local NGOs Community actors Private firms Utility companies Local champions	Reduce climate change impacts through goals and strategies set in community energy plans (Denis & Parker, 2009; Tozer, 2012) Improve resiliency and energy security at the community-level (Hoicka & MacArthur, 2017)	Jurisdictional issues; financial resource constraints; capacity and experience issues; and stakeholder behavioural barriers (Denis & Parker, 2009; Tozer, 2012)
Household	Individual actors Utility companies Local NGOs Provincial Government and regulators	To effectively manage household energy and meet personal goals (e.g., economic, or environmental)	Resource constraints, barriers of knowledge and behaviour, competing household attitudes, physical technical, and system components

The energy governance and policy literature emphasizes there is no 'one-size-fits-all' approach for governing energy and implementing policies (Egmond, Jonkers, & Kok, 2006; Florini & Sovacool, 2009; Rowlands, 2008); however, inconsistencies at each scale can result in poorly developed energy transitions (Florini & Sovacool, 2009, 2011). The lack of energy policy integration at different scales can obstruct overarching goals for climate change (Parker et al., 2003; Rowlands, 2008; Winfield, 2008). The theme of disjointed governance and policy is evident in the global energy governance literature, as well as in Canadian energy policy development (Doern, 2005; Egmond et al., 2006; Florini & Sovacool, 2009; Rowlands, 2008; Winfield, 2008). Additional complexities arise with the development of innovative energy technologies, such as advanced metering infrastructure. Therefore, presenting opportunities to integrate technical and governance knowledge areas in the study of the energy consumption landscape.

2.4 Socio-technical transitions and sustainable energy transitions

The transition[12] to a sustainable energy system involves the adoption of innovative technologies at various levels of the energy consumption-production landscape. Energy transitions are inherently socio-technical because they involve users and institutions in addition to infrastructure. Therefore, these transitions involve the social acceptance of related technological developments at socio-political, market, and community levels (Wustenhagen, Wolsink, & Burer, 2007). Several interrelated factors can cause a transition from one source of energy to another: increased prices of existing source and decreasing cost of alternative source; extreme environmental pollution from existing energy source; negative social impacts; energy supply shortages or depletion; technological change; changes in local economic activities, or; developments of new local resources (Solomon & Krishna, 2011).

The literature of socio-technical transitions contributes valuable insights into the integration of advanced energy technologies within the energy landscape. The socio-technical transitions literature moves beyond traditional technological transitions by incorporating artifacts, knowledge, resources, capital, and the interaction of human actors at multiple levels to the conceptualization of innovations (Geels, 2002, 2004). The multi-level perspective (MLP) framework assesses socio-

[12] This dissertation applies the term transition as change revolving around the complex interactions among economic, technological, social, and political factors, and the stabilization and transformation of dominant socio-technical practices (Meadowcroft, 2010).

technical transitions through three levels: niche, regime, and landscape (Calvert & Simandan, 2010; F. W. Geels, 2002, 2005, 2010; Frank. W. Geels & Schot, 2007).

The emergence of socio-technical transitions occurs from a shift in the stability of the regime-level network. As a result of the introduction of radical innovations, and the stabilization of a dominant design within niche-level markets, breakthroughs in mainstream markets can cause pressure on stable regime developments, otherwise known as a 'niche-push.' Additional pressures from landscape-level factors, such as changes in legislation and persistent problems, catalyze long-term development. Social change and internal, or external, pressures can cause regime-level changes (Smith, Stirling, & Berkhout, 2005). Adjustments in the regime through incremental changes in industry, user practices, or infrastructure results in a 'heating up' of the transformation, and an eventual 'cooling down' once the regime-level changes have been established (F. W. Geels, 2005; Frank. W. Geels, 2004).

The MLP highlights and accommodates the complexity of sustainability transitions and has been applied to studies in sustainable energy transitions (F. W. Geels, 2011; Rosenbloom & Meadowcroft, 2014; Verbong & Geels, 2010); thus, providing valuable knowledge on the socio-technical dynamics of the energy consumption landscape. Calvert (2015) identifies a substantial opportunity for geographical approaches to socio-technical energy transitions in the development of energy geography. Energy transitions have been a central focus of energy geography studies, with transitions in the 21st century taking place more rapidly, focusing on energy efficiency, smart grid promotion and renewable energy strategies (Solomon & Krishna, 2011). Developments can incorporate spatial sensitivity of energy studies, recognize the multiplicity of actors and networks, and create a link to the broader spatial transitions literature (Calvert, 2015; Coenen, Benneworth, & Truffer, 2012).

State intervention and policy reform are often mandatory within sustainability transitions (Meadowcroft, 2009); however, there is a lack of understanding regarding the agency of different actor groups and the role of governance in socio-technical transitions (Markard, Raven, & Truffer, 2012). The complexity and uncertainly of sustainability transitions deliver difficulties for governing and planning for end-states across jurisdictions. Due to this complexity and uncertainty, additional theoretical framings for deeper understanding towards energy and going 'beyond' behaviour-based approaches have been called for within the energy literature.[13] In particular, Walker and Shove (2007) call for new conceptualizations of innovations to incorporate user practice across space and time to address both this complexity and uncertainty. Therefore, the literature on energy policy, energy governance, as well as social acceptance and behavioural theories, can supplement this knowledge area.

2.4.1 Opportunities to understand user adoption of socio-technical innovations

Within this hierarchical approach to innovations, it is imperative to understand the actors involved within each level and their behavioural characteristics. This is particularly important for energy transitions, as the social acceptance of energy innovations involves acceptance at socio-political, market, and community scales, influenced by factors at each level (Wustenhagen et al., 2007). Consequently, the MLP approach often has a technological bias towards focusing on the innovation itself, rather than considering underlying social factors. As identified by Walker and Shove (2007), individual-level decision-making and adoption of innovations are missing from the socio-technical transitions literature. As stated by De Haan and Rotmans, (2011, p. 92) transitions "could be a fundamental change in the structures, cultures and practices of a societal system, profoundly altering the way it functions." The process of a massive systematic shift in innovation requires, not just the adoption of new technologies and policies, but also the adoption of micro-level system changes embedded in social practice and daily habits and routines. These elements are particularly critical for understanding the adoption of residential energy conservation initiatives.

2.4.1.1 Diffusion of innovations

At the consumer-level of system innovation, the rate of adoption and diffusion is important for large-scale system change. The diffusion of innovation involves the gradual adoption of innovation within a social system through specific communication channels (Jaffe & Stavins, 1994; Rogers, 1995). Discontinuous innovations require adopters to alter their current behaviour, whereas continuous innovations require no change in adopter behaviour (Egmond, Jonkers, & Kok, 2005). Several variables impact the rate of innovation adoption, namely: the perceived attributes; the type of innovation decision; the type of communication; the nature of the social system, and; the extent of the promotion efforts (Rogers, 1995). In a residential setting, perceived compatibility is an important

[13] Although uncertainty is an important consideration for energy governance and macro-level policy approaches, for the purpose of this dissertation, the focus remains on the complexity of smart grid applications specifically at the residential scale.

predictor for the adoption of conservation interventions (Vollink, Meertens, & Midden, 2002). According to Vollink et al., (2002), perceived high-levels of advantage are primary elements for maintaining consumers' interest in energy conservation interventions. Additionally, adopters can be categorized by the time in which they adopt the innovation (Figure 10). At the individual level, the decision process for adopting an innovation involves knowledge, persuasion, decision, implementation, and confirmation. Although the diffusion of innovations provides insights on the widespread adoption of technologies, it does not include the individual behavioural components and the capabilities for adopting a new product, which is developed in more detail in the technology acceptance model (TAM).

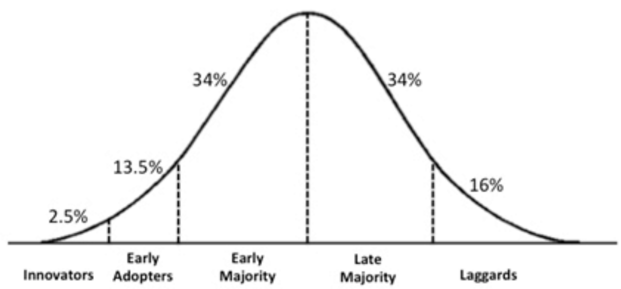

Figure 10 Diffusion of innovations curve and adopter categories, sources: (Moum & Thomsen, 2017; Rogers, n.d., 1995, 2004)

2.4.1.2 Technology acceptance model (TAM)

The TAM was originally proposed by Davis (1985) and was a development of the Fishbein and Ajzen's 1967 Theory of Reasoned Action (TRA) (F. D. Davis, 1985; Fishbein & Ajzen, 1975). TAM aims to provide an explanation behind user acceptance of information systems and computer technologies, while involving a broad range of consumer behaviour (Figure 11)(F. Davis, Bagozzi, & Warshaw, 1989).

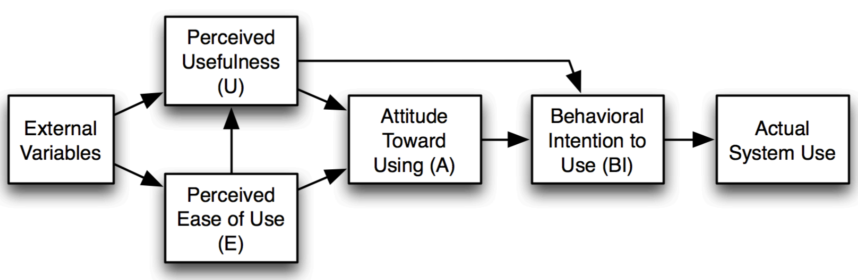

Figure 11 Technology acceptance model, source: (F. Davis et al., 1989)

In comparing both the TRA and TAM for the acceptance of computer technology within firms, a study by Davis et al., (1989) identified that individuals' behavioural intentions easily predicted their computer use; however, the TAM model further identified that perceived usefulness and perceived ease of use were the primary and secondary determinants for intention of use, respectively. Over the past few decades, the TAM has been applied to various types of system acceptance (Y. Lee, Kozar, & Larsen, 2003). However, the TAM is not without limitations, as past studies have focused on single measurement scales, self-reported usage, limited application of external variables as well as, limited longitudinal studies (Y. Lee et al., 2003). Thus, there are opportunities to develop this area of research.

Although a primary strength of this model is the validation of 'intentions of use' as a main determinant for technological acceptance, use intention is complex and can be influenced by a variety of factors. Ford et al., (2014) highlight the relevance for the TAM for adoption, uptake and use of residential smart grid and HEM technologies. Additionally, they highlight Venkatesh and Bala's (2008) development of TAM, to identify additional influencing factors for technological acceptance (Figure 12). In particular, this includes a more descriptive account of the factors influencing the perceived usefulness and the perceived ease of use. Ford et al. (2014) also address the complexity by defining crucial external elements for consideration in the development of HEM technologies for their successful adoption and use for sustainable behaviours, including: voluntariness, experience, subjective norm, image, relevance of technology, output quality, result demonstrability, self-efficacy, perceptions of external control, technology anxiety, technology playfulness, perceived enjoyment, and objective usability. Therefore, the TAM acknowledges the multitude of factors influencing technological acceptance, which is also relevant for studying HEM acceptance and use.

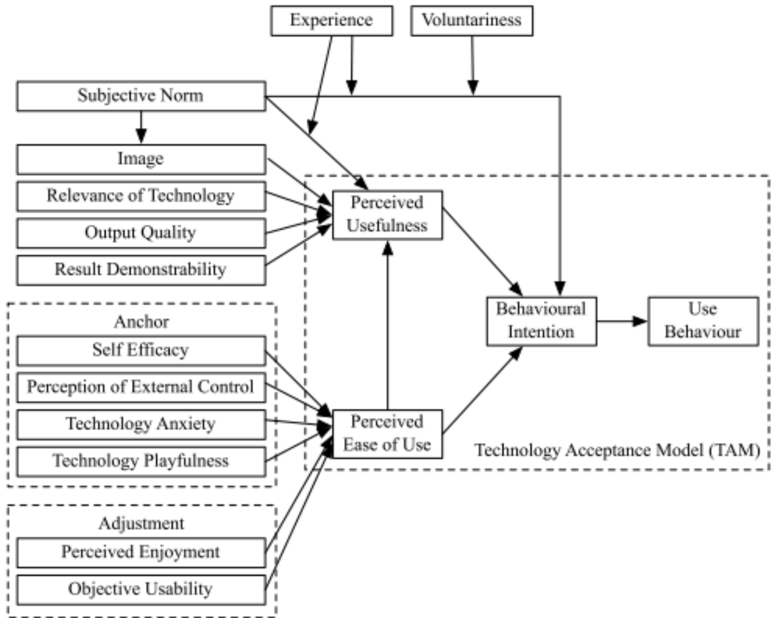

Figure 12 Technological acceptance model adapted by Venkatesh and Bala (2008), source: (Ford et al., 2014)

Although the TAM has some benefits, one particular weakness of this model is its failure to address the importance of goal-setting in achieving the desired behaviour, which is a critical element of individual behaviour (Bagozzi, 2007). Therefore, additional factors and approaches that address socio-technical elements need to be highlighted to develop a thorough understanding of the energy consumption landscape. The following sections of the literature review covers additional concepts and theoretical approaches related to the household energy actions and decision-making in the smart grid.

2.5 Factors and approaches influencing household energy consumption: Developing a holistic understanding of the energy consumption landscape

The energy consumption landscape is influenced by social, technical, and environmental elements over spatiotemporal scales. Consequently, involving a collection of activities, systems and actors across the energy lifecycle, including consumers, regulators, and producers of energy (Figure 13) (Bridge, Bouzarovski, Bradshaw, & Eyre, 2013; Stern, 2014). Due to the importance of the energy sector in economic development, as well as its implications in social and technological spheres, a multidisciplinary approach is crucial to develop a holistic understanding of the energy consumption landscape (Chapman, 2009; D. Scott et al., 2001; Shove, 2003b). Integrating the social sciences delivers a thorough understanding of the human dimension of energy consumption and opportunities for conservation (Stern, 2014).

Within the electricity grid, options for altering the flows of electricity system can focus on either demand-side response, which concentrates on changing the demand, or the levels of consumption, or supply-side responses, which focus on changing the electricity supply. As articulated within this chapter, the focus of the dissertation research is on demand-side responses in conjunction with the introduction of smart metering infrastructure. Demand-side response options come in many forms for shifting or reducing energy demand (e.g., pricing, efficiency and conservation programs, direct load control) (Darby, 2018a; Darby & McKenna, 2012; Haider, See, & Elmenreich, 2016; Sintov & Schultz, 2015). Due to the complexity of the energy landscape, the success of demand-side response programs can be influenced by a multitude of factors (Kowsari & Zerriffi, 2011; Šćepanović, Warnier, & Nurminen, 2017) as introduced in within this section of the literature review.

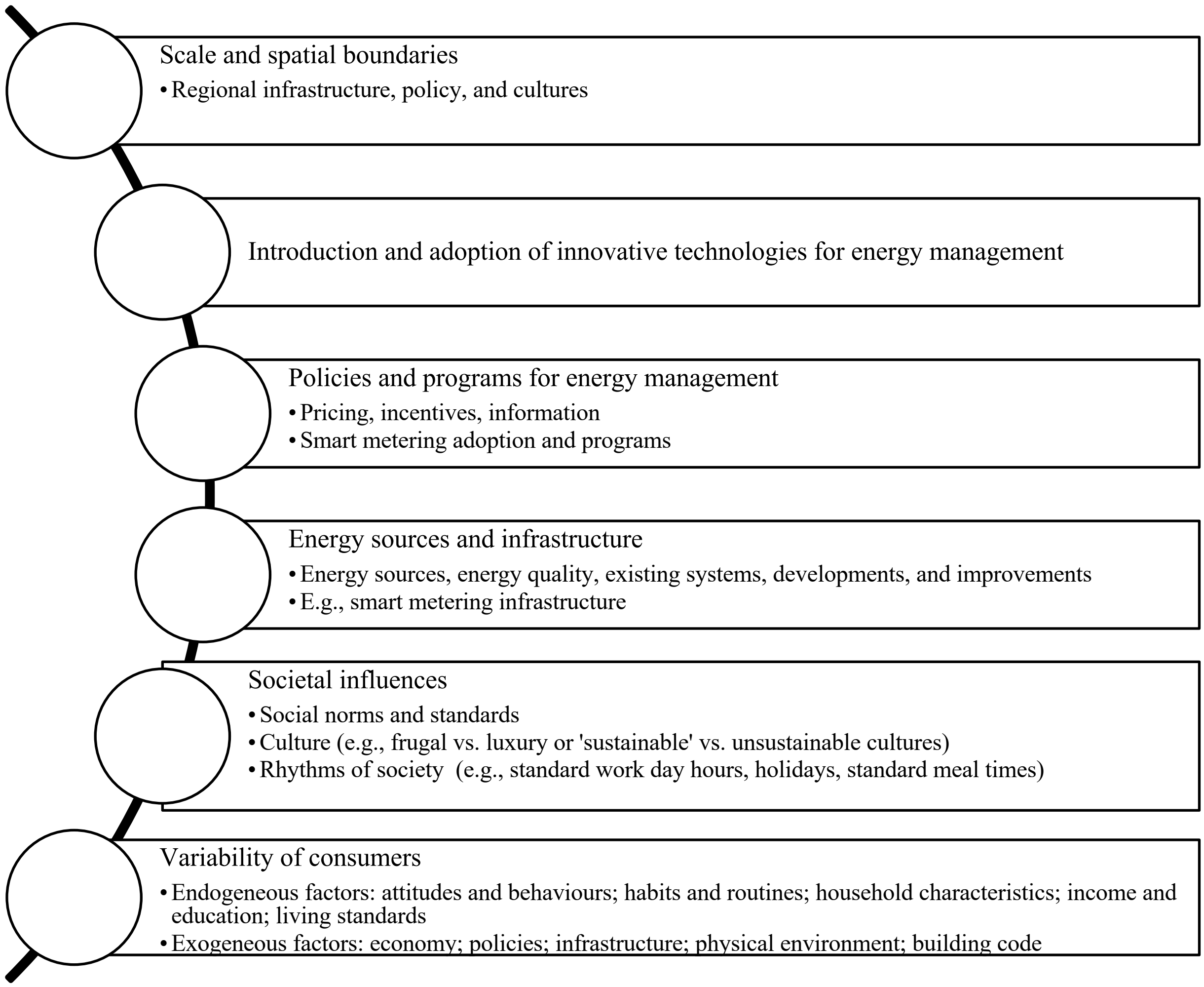

Figure 13 Influences and elements of the energy consumption landscape

At the residential scale, energy consumption is influenced by complex endogenous (e.g., economic, noneconomic, behavioural and cultural) and exogenous (e.g., physical environment, policies and regulations) factors in personal and contextual domains (Kowsari & Zerriffi, 2011). Several studies have attempted to conceptualize the multitude of factors influencing energy consumption through integrated frameworks. Kowsari and Zerriffi (2011) developed on Wilson and Dowlatabadi's (2007) integrated framework; however, it not include technical considerations; thus, it has been adapted in Figure 14 to visualize the complexity of factors impacting residential energy use, patterns and decisions.

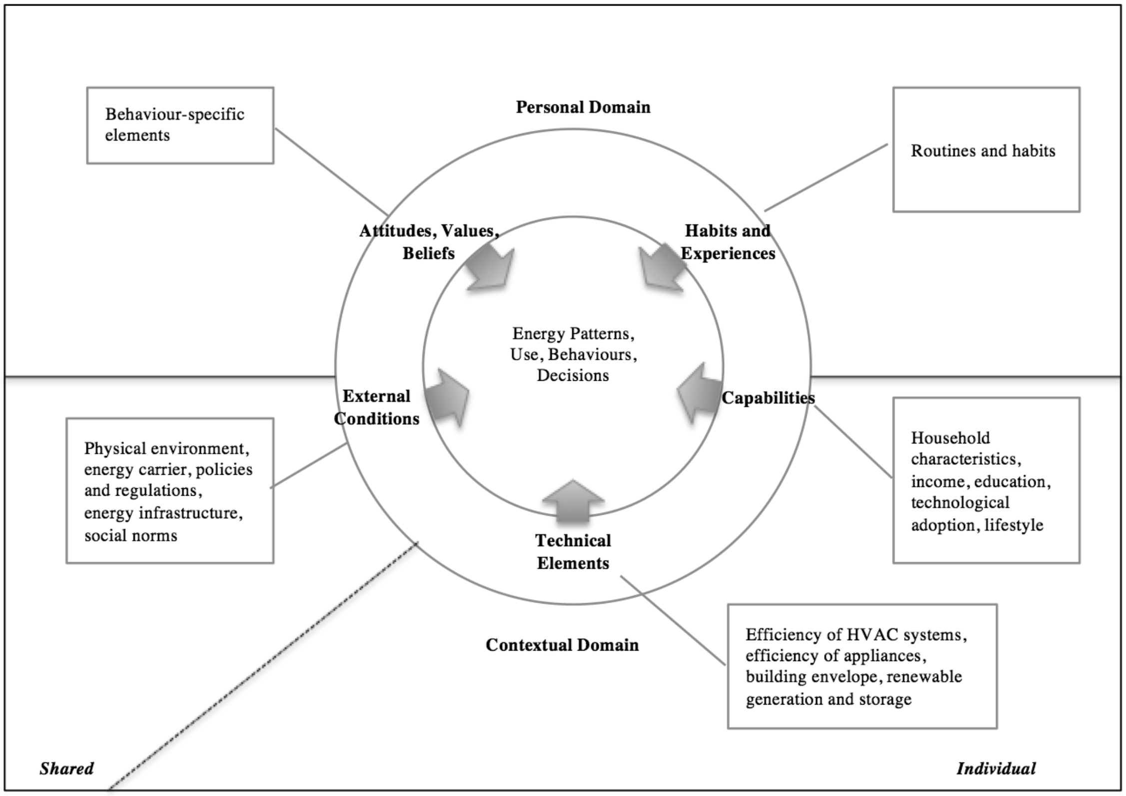

Figure 14 Endogenous and exogenous factors influencing household energy use, adapted from: (Kowsari & Zerriffi, 2011; Wilson & Dowlatabadi, 2007)

Specifically, in Canada, comfort is a significant contributing factor, where space heating constitutes the majority of residential energy use (61%) (Figure 15) (Natural Resources Canada, 2012).

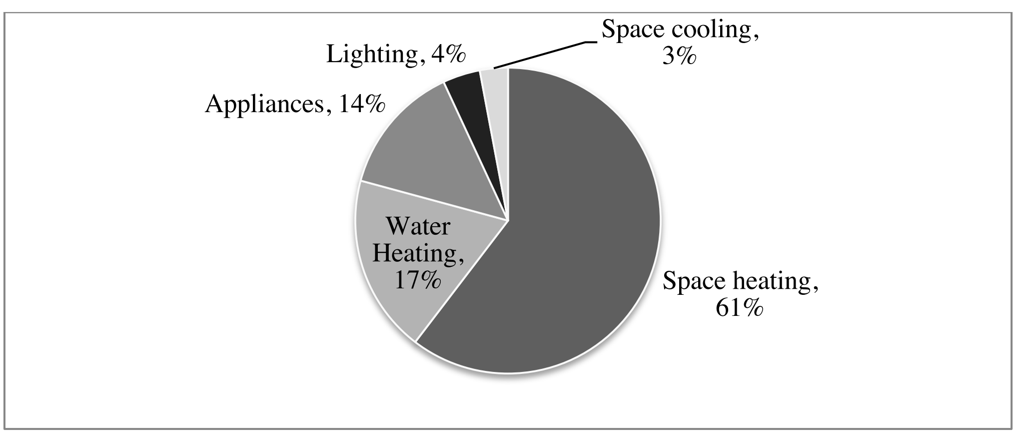

Figure 15 Distribution of residential energy use by end-use by percentage, 2016, source: (Natural Resources Canada, 2018b)

As presented, household dynamics contributing to consumption are complex. Socio-economic factors highly influence household energy consumption and conservation. Household energy use is positively correlated to household income (Abrahamse & Steg, 2009; Costanzo et al., 1986; Kowsari & Zerriffi, 2011) and household size (Abrahamse & Steg, 2009; M. Brown, 1984, 1985). Education levels (Mills & Schleich, 2012; Steg, 2008) and energy literacy (M. Brown, 1984; Lutzenhiser, 1993) as well as economic profile (M. Brown, 1984, 1985) positively correlate to the willingness to conserve and invest in energy upgrades. In regards to age demographics, households with younger members are more willing to invest in new and efficient technologies (Mills & Schleich, 2012); however, household dynamics and competing attitudes may influence the overall level of conservation (Abrahamse & Steg, 2009; M. Brown, 1984, 1985). Although these socio-economic factors contribute to household energy consumption, additional technical, social, and behavioural factors remain. These elements, as well as their approaches for conservation, are outlined in the following sections.

2.5.1 Technical factors and approaches to energy conservation

Physical building elements and technical efficiencies contribute to household energy consumption. According to Gardner and Stern (2009), approximately 30% of household energy savings can be achieved by increasing the efficiency of end-use technologies and systems. In 2009, Canadian households with energy efficiency improvements saved 470 PJ compared to those without improvements (Natural Resources Canada, 2012). The replacement, installation and maintenance of equipment are common technical approaches to energy conservation and included in a typology of policy approaches by Dietz et al. (Dietz et al., 2009) (Figure 16).

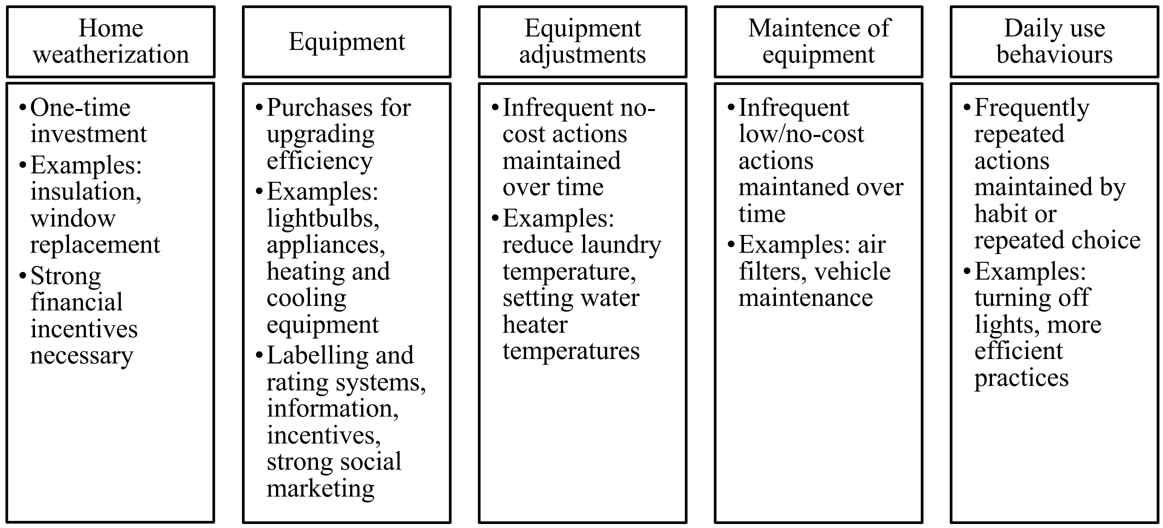

Figure 16 Typology of household energy reduction strategies, source: (Dietz et al., 2009)

Traditional technical approaches to energy conservation research concentrate on the engineering aspects of technology and building efficiencies (Parker et al., 2003). Modelling approaches are used to assess the potential of technological solutions; however, these technical studies rarely take into consideration the variability in consumer behaviour contributing to consumption patterns (Geelen et al., 2013; Scott et al., 2001). Instead, they assess building, technological and system efficiency, and present quantitative results (Dietz, Stern, & Weber, 2013; Geelen et al., 2013; D. Scott et al., 2001). Utilizing a traditional paradigm of science and economics in energy policy research may have created a "… blind spot in conventional techno-economic thinking that masks the human elements of energy technologies and use," (Florini & Sovacool, 2009, p. 1). Daily behaviours, equipment adjustments and maintenance offer the most abundant opportunities for energy reductions and are significantly influenced by behavioural and lifestyle changes, and motivated by policy tools and social marketing (Dietz et al., 2009; Mills & Schleich, 2012). Thus, technical approaches involve social integration and public support (Parker et al., 2003). Policy mechanisms to encourage technological adoption, include disclosure labels, tax exemptions, stronger regulations, lower interest rate loans, tax credits, and home energy rating systems (Parker et al., 2003; D. Scott et al., 2001). However, as argued by Shove (2018), energy efficiency is counterproductive due to its promotion of unsustainable expectations of 'service' related to energy as well as the abstraction of energy from the processes in which it is used. Consequently, a broader approach needs to be considered.

Habits, routines, and behavioural practices have a strong influence over the use of efficient technologies (Mills & Schleich, 2012). Additionally, Attari et al. (2010) identified that householders perceive curtailment actions (e.g., turning off lights, reducing the use of appliances) as more effective and attainable than energy efficiency improvements. Behaviours contribute to two-thirds of household energy use, compared to structural and technological components (Lutzenhiser et al., 2012). Therefore, technology on its own is not sufficient to change household consumption; it requires behavioural 'wedges' to change how consumers use technology and operate household systems to result in consumption shifts (Dietz et al., 2009). The theoretical lenses of behavioural and social practice theories can provide insights on factors contributing to the social components of consumption and approaches to reduce consumption.

2.5.2 Behavioural factors influencing energy consumption

Household energy consumption is multifaceted, and end-users significantly contribute to consumption variability. Differences between identical residential units can be up to 200%, with household behaviours contributing to this extreme variability (Chen et al., 2015; Dietz et al., 2009; Lutzenhiser, 1993; Mills & Schleich, 2012). Behavioural theories view several factors as critical influences, including attitudes, emotions, habits, agency, norms, and contextual factors (Figure 17) (Darnton, 2008; Jackson, 2005).

Attitudes	Emotions	Habits	Agency	Norms	Contexual factors
• Particular beliefs and principles related to a specific behaviour (Darnton, 2008)	• Meanings associated with technology and energy consumption behaviours (Shove, 2010)	• Routinized behaviours (Stern, 1999)	• An individual's consciousness of successfully fulfilling a behaviour to achieve a specific outcome. Often referred to as self-efficacy (Darnton, 2008)	• The 'social standard' for particular behaviours and activities (Darnton, 2008) • Can be either descriptive, what is done, or injunctive, what society thinks 'ought' to be done (Darnton, 2008; Jackson, 2005)	• Influence attitudes and perceived behavioural control. Interpreted in the 'C' in ABC theory (Darnton, 2008)

Figure 17 Factors influencing outcomes in behavioural theories

Factors influencing household energy behaviours are investigated and conceptualized in behaviour theories, which focus on endogenous and personal dimensions impacting energy consumption. The most prevalent approaches used in energy studies are the: Theory of Planned Behaviour (TPB), Norm Activation Model (NAM), Value-Belief-Norm Theory (VBN), and Attitude Behaviour Context (ABC) Model (Table 4). Norms, studied through the VBN and the NAM, have been strongly linked to energy behaviour (Abrahamse & Steg, 2009; Gadenne, Sharma, Kerr, & Smith, 2011; Schultz, 2000; Thogersen & Olander, 2006). In particular, the NAM has provided more insight than TPB to predict a range of energy behaviours (Abrahamse & Steg, 2009; Van Der Werff & Steg, 2015). However, it should be noted that contextual and technical elements contributing to energy consumption are not clearly addressed in these models. Exogenous components either influence attitudinal and perceived behavioural control elements, or are grouped into 'contextual' factors (e.g., ABC model) (Darnton, 2008).

Table 4 Summary of behaviour theories and factors related to energy consumption, sources: (Abrahamse & Steg, 2009; Bamberg & Moser, 2007; Darnton, 2008; Jackson, 2005; Mirosa, Gnoth, Lawson, & Stephenson, 2010; Stern, 1999; Thogersen & Olander, 2006; Van Der Werff & Steg, 2015; Zelezny & Schultz, 2000)

Theory	Type	Factors	Existing studies	Consideration of exogenous factors
Theory of Planned Behaviour	Rational Choice	Attitudes, Subjective norms, intentions, perceived behavioural control	• Attitudes and behavioural intention strongly correlated to behaviour (Bamberg & Moser, 2007; Hines, Hungerford, & Tomera, 1987) • NAM is more effective than TPB in predicting household energy use (Steg & Vlek, 2009)	Norms are the only external variable considered. External factors influence perceived behavioural control. Does not consider socio-economic or technical characteristics.
Norm Activation Model	Pro-social	Awareness of consequences and responsibility, personal norms	• NAM improves the explanation of energy consumption compared to TPB (Abrahamse & Steg, 2009) • Perceived behavioural control relates to energy conservation (Abrahamse & Steg, 2009) • Predicts range of energy use behaviours (Van Der Werff & Steg, 2015)	Consequences and norms are the only external variables considered. Does not consider socio-economic or technical characteristics.
Value-Belief-Norm Theory	Pro-social	Values, beliefs, norms	• Norms and VBN predict environmental behaviour. Positive association between beliefs and behaviour (Gadenne et al., 2011) • Values strongly related to behaviours and based on three-factor structure (Thogersen & Olander, 2006; Zelezny & Schultz, 2000) • Behaviours influenced by a variety of factors; personal values not a good predictor of behaviours (Mirosa et al., 2010)	Norms are the only external variables considered. Does not consider socio-economic or technical characteristics.
Attitude Behaviour Context Model	Pro-social	Attitudes, behaviours, context	• Strength of contextual forces highly influences intervention effect (Stern, 1999)	Grouped in contextual factors. No explicit list of factors.

Behaviour theories provide insights on consumption patterns at the individual level to understand the social element of energy consumption. Traditional models of individual behaviour are based on economic and rational choice theory and present behaviour as a linear decision-making process (e.g., Theory of Planned Behaviour). The development of socio-psychological theories extended past economic models to analyze origins of behaviour preferences, and can be applied to pro-environmental behaviour (PEB) (e.g., Value-Belief-Norm Theory, Norm Activation Model) (Darnton, 2008; Heimlich & Ardoin, 2008). Subsequently, theories of behaviour change were derived from the social sciences, including the Diffusion of Innovations, and other learning-based and systems thinking models. Notably, Prochaska, DiClemente and Norcross (1992) acknowledged several steps of behaviour change, including: pre-contemplation, contemplation, preparation, action and maintenance (Figure 18).

Behaviourist theories

- Dewey (1896) - *The Reflex Arc Concept in Psychology*
- Pavlov (1904) - Classical Conditioning
- Thorndike (1905) - Instrumental Learning
- Watson (1913) - *Psychology as the Behaviourist Views It*
- Skinner (1948) - Operant Conditioning

Theories of behaviour

- Fishbein & Azjen (1970) - Theory of Reasoned Action (TRA)
- Bandura (1977) - Social Cognitive Theory
- Schwartz (1977) - Norm Activation Model (NAM)
- Azjen (1986) - Theory of Planned Behaviour (TPB)
- Stern et al. (1999) - Value-Belief-Norm Theory (VBN)
- Fishbein & Yzer (2003) - Integrated Model of Behavioural Prediction

Models of behaviour and societal change

- Rogers (1962) - Diffusion of Innovation
- Social Practice Theory - (Giddens, 1979; Schatzki, 1996; Shove et al., 2013)
- Prochaska (1979) - Transtheoretical or Stages-of-Change Model
- Janz & Becker (1984), Rosenstock (1974) - Health Belief Model
- Fishbein et al,. (2001) - Determinants of behaviour change

Environmentally responsible behaviour and pro-environmental behaviour (PEB)

- Hines, Hungerford & Tomera (1987) - Complex Model of Factors Leading to PEB
- Hungerfold & Volk (1990) - *Changing Learner Behaviour Through Environmental Education*
- Stern et al. (1995) - Attitudes, Beliefs, Contexts Model
- Kaiser (1999) - Environmental attitude can be a powerful predictor of ecological behaviour
- *Journal of Social Issues* Volume 56, Issue 3 (2000) - Special Issue on environmentalism and proenvironmental behaviour

Applied models of behaviour change for intervention design

- Kotler & Zaltman (1971) - Social Marketing
- Kotler & Lee (2008) - Ten Steps for Social Marketing
- Gardner & Stern (1996) - Principles for Intervening to Change Environmentally Destructive Behaviour
- McKenzie-Mohr (1999) - Community-Based Social Marketing

Figure 18 An overview of developments in behaviour theories and models, sources: (Darnton, 2008; Fishbein & Ajzen, 1975; Fishbein & Yzer, 2003; Heimlich & Ardoin, 2008; Jackson, 2005; N. R. Lee & Kotler, 2008; Shove, Pantzar, & Watson, 2012)

2.5.3 Limitations of the behavioural approach

Solely relying on behavioural approaches can oversimplify the conceptualization of factors contributing to energy consumption. As highlighted previously, external elements (e.g., policy, technology, energy prices) are vaguely addressed. In most theories, external, socio-economic and technical factors are considered an ‘influence’ on attitudes or perceived behavioural control (Darnton, 2008; Jackson, 2005). A conclusive list of contextual factors is not offered, thus resulting in the inability to identify the role and effect of contextual factors in changing practices (Shove, 2010). Consequently, these models provide different explanations of the problem, rather than generating a holistic understanding to generate solutions (Strengers, 2012). As identified by Šćepanović et al. (2017) contextual, or external factors, can have a vital role in the effectiveness of residential energy interventions. These can include physical, socio-demographic, cultural, political, and institutional factors (Šćepanović et al., 2017). Thus, behavioural models do not provide a comprehensive conceptualization of the socio-technical factors contributing to household energy consumption.

Additionally, solely relying on behavioural elements to shift energy consumption has its limitations. Studies have shown a weak relationship between attitudes and behaviours (McKenzie-Mohr, 2000). Consumers are also influenced by ‘stone-aged psychological biases,’ including self-interest, short-sightedness, status, social imitation, and ignorance of problems (Van Vugt, Griskevicius, & Schultz, 2014). Not identifying these and other barriers to adoption can result in unsuccessful programs (Darnton, 2008; McKenzie-Mohr, 2000). Shove (2003b) argues for moving beyond the individualized behavioural approaches to address the products, standardized technologies, rationales, and practices that have been integrated into routinized societal habits. The development of policies surrounding behavioural models has resulted in a value-action gap, overlooked habitual impacts, and missed opportunities for societal shifts (Shove, 2010; Shove & Walker, 2014). A variety of studies have highlighted the lack and importance of integrating social and technical approaches for conservation approaches (D. Scott et al., 2001; Shove, 2003b, 2004). Thus, opportunities exist to extend beyond behavioural theories and intervention approaches to conceptualize the complexity of socio-technical factors influencing household energy consumption.

2.6 ‘Beyond ABC’: A practice-theoretical lens to household energy consumption

A contrast to behaviour-based models is Social Practice Theory (SPT). This is an emerging theoretical lens in energy geography studies. Schatzki defines practice as, “A temporally and spatially dispersed nexus of doings and sayings," (1996, p. 89). Practices develop as a conjunction of elements, which exist as performances by individuals, who act as the 'carriers' of practice (Shove et al., 2012). As Walker (2014, p. 50) explains, society, organizations and individual actors' actions are viewed as social practices, and these practices become "… interwoven bundles of practices configured by the 'hanging together' of institutional arrangements, shared structural meanings and norms, knowledge and skills, and varied material technologies and infrastructures." Therefore, social practice theory investigates societal change as transitions of compounded practices over time.

Shove et al. (2012) provide one of the most recent theoretical descriptions of social practice, and its importance to studying pro-environmental behaviours. At the root of their theoretical description of social practice theory are three elements: materials, competencies, and meanings (Shove et al., 2012) (Figure 19). A practice actively links these three components, which can shape each other, change over time, can link to other practices, and can shift from one practice to another.

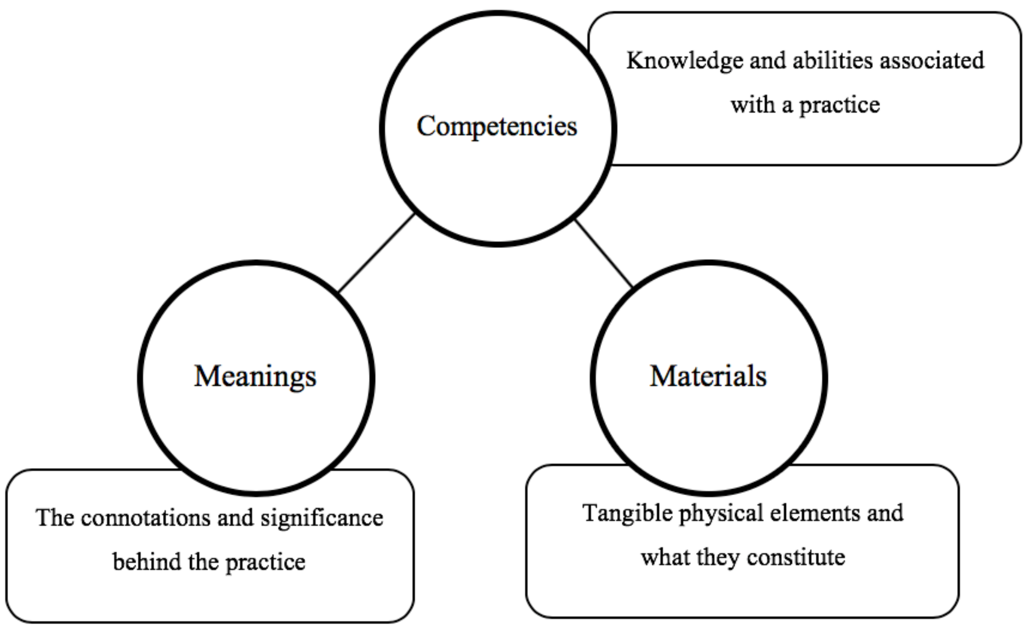

Figure 19 Conceptual framework of SPT, source: (Shove et al., 2012)

There are several differentiating factors between individual behaviour theories, discussed earlier, and social practice theory. Primarily, in social practice theory, the agent and their individual behaviours are not the sole focus of the theory, where behaviours are considered the 'tip of the iceberg' for social practice theory (Strengers & Maller, 2015b). Shove et al. (2012) also identify four key elements that differentiate behaviour and practice (e.g., basis of action, type of change, policy approach and lessons). Strengers (2012) further distinguishes between assumptions made between these two theories. In her paper, Strengers (2012) also adds a 'D' to the ABC model to include 'decisions' made by individuals. Table 5 outlines the differentiating factors between the behaviour and practice-theoretical approaches.

Table 5 Comparing elements of social practice theory and behaviour theory, sources: (Shove, 2010; Shove et al., 2012; Stern, 2000; Strengers, 2012; Strengers, Moloney, Maller, & Horne, 2015)

Element	SPT	Behaviour theory
Central unit of analysis	Individual behaviours are not the sole focus; they are the 'tip of the iceberg.' Dynamics of practice are central focus	Individuals and their actions are the sole focus
Base of action	Shared approach through society	Individual level
Change	Emergent, dynamic, and happens over time. Often uncontrollable	Causal, orderly, predictable, and controllable
Policy approach	Set within the arrangements of practice it is attempting to change	"… Carrots, sticks and sermons…" to reduce the barriers and increase change (Shove et al., 2012, p. 144)
Agency	Practices, people, and materials have agency	People have agency
Role of technology	Technology and supply systems form practices	Technology is separate from supply systems and people

Overall, social practice theory brings together social, technical, and environmental elements to conceptualize societal change. This theory establishes new technological artifacts as well as new markets, practices, infrastructures, and cultural meanings without reliance on policy-makers for a transition. Additionally, social practice theory provides a holistic approach to conceptualizing the re-shaping of social arrangements through radical innovations (Shove, 2010).

2.6.1 The SPT approach to energy and conservation

SPT views the main factors contributing to household energy consumption as a combination of the materials, meanings and competencies surrounding energy use (Shove et al., 2012; Walker, 2014). Therefore, this theoretical lens moves past a resource-centric and behavioural view and focuses on the social dynamics of energy consumption in light of materials, values and policies (Shove & Walker, 2014; Strengers, 2012, 2013). Walker (2014) explains that energy consumption patterns are influenced by dynamics, rhythms and societal synchronizations of energy practices (Figure 20). Changing the dynamics of energy demand involves synchronized changes, and can be the result of large-scale policies to shape consumption patterns (Shove & Walker, 2014; Walker, 2014).

The impact of these policies needs to influence a network of factors: the 'skills' needed to manage consumption, the 'stuff' or technologies to assist householders with management as well as the 'images' or norms associated with consumption and demand management (Higginson, McKenna, Hargreaves, Chilvers, & Thomson, 2015). Thus, socio-temporal patterns of energy consumption are considered in this theoretical lens.

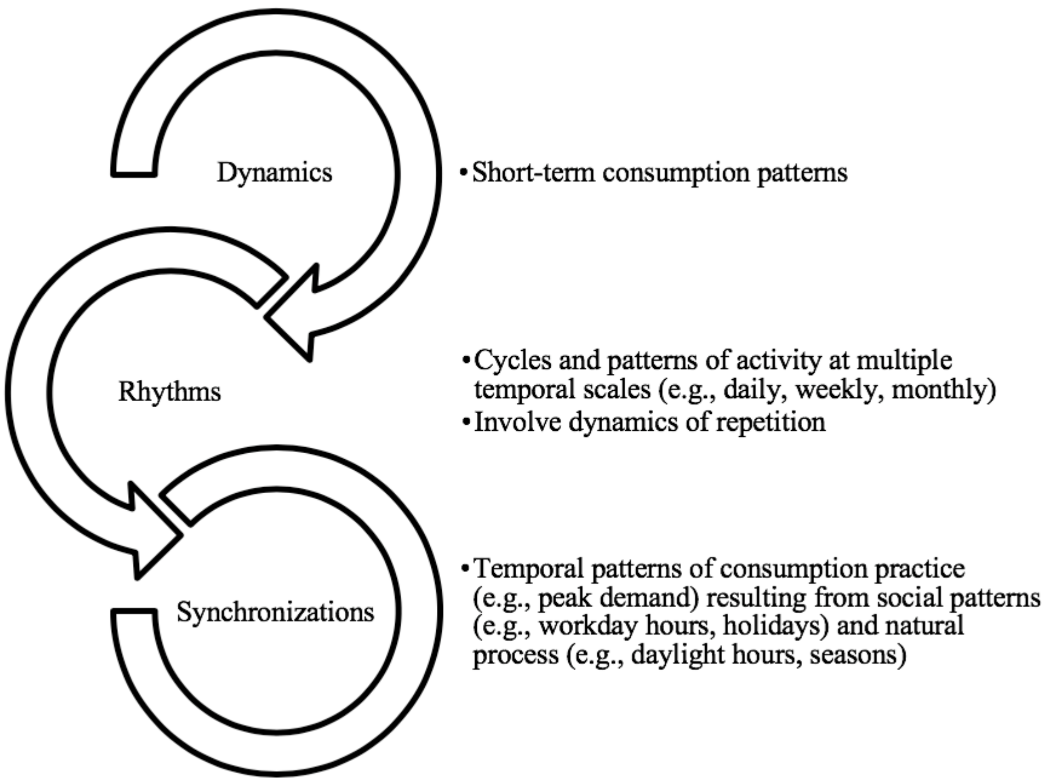

Figure 20 Socio-temporal factors of energy consumption patterns, elements adapted from: (Walker, 2014)

The SPT approach to energy conservation emphasizes the reorientation practice to sustainable patterns, rather than focusing on barriers and drivers of demand (Shove & Walker, 2014; Strengers, 2012, 2013). Three key elements are involved in the SPT approach to change energy consumption: reframing the peak demand problem from resource management to practices; changing 'wants and needs' to alter perceptions of non-negotiable behaviours of end-users, resulting in a shift in lifestyle; and redefining the role of end-users from passive consumers to co-managers of practice. These changes involve shifting conservation programs from addressing 'peaky' behaviours to lifestyle changes (Strengers, 2012).

2.6.2 Energy practices and the smart grid

In reviewing the practice-theoretical approach to energy consumption, it is evident that this approach can bring insights within the smart grid. AMI and associated smart technologies can result in a reorganization of energy practices at micro- and macro-scales. Specifically, smart grid transitions present opportunities for the synchronization of consumption rhythms, through: shifting peak consumption through energy storage; changing demand patterns and optimizing end-uses through automation; peak shifting through adhering to time-of-use pricing; consuming intermittent renewable energy sources, and; using feedback information to make more informed choices of energy use (Strengers, 2013; Walker, 2014).

Bulkeley, Powells, and Bell (2015) view the smart grid as a critical means for 'greening' the electrical network through systems of electric provision and the ability to govern social practice. In this case, end-users become self-governing entities, faced with new choices for consumption as a result of new pricing schemes, additional information, and the ability to co-manage their consumption. Conceptualizing the components of 'smart' energy practices can be visualized in the following figure, where the necessary transitions in energy consumption management (Strengers, 2012, 2013; Walker, 2014), as well as the materials (Stephens et al., 2015; Strengers, 2013) and other societal shifts for social practice change (Shove, 2003b; Shove & Walker, 2014) are applied to Shove et al.'s (2012) framework of social practice theory. The elements in Figure 21 do not constitute a single practice (e.g., cooking, cleaning, transportation); however, it outlines the 'smart' components influencing the idealized application of smart grid capabilities into various practices.

Meanings	Materials	Competencies
•Changing 'wants and needs' related to comfort, cleanlieness and convience, including: •Shifting to higher thermal flexibility •Non-negotiable actions become more adaptable •Use of appliances	•Introducing advanced metering infrastructure & household-level elements, including: •Smart meter/smart panel •Programmable thermostat •IHD/Feedback devices •Smart grid tools •Smart appliances •Additional smart home technologies	•Knowledge and skills needed for shifting and conserving energy using smart technologies •Knowlege of automation and optimization functions •Knowledge of conservation goals and methods to achieve them •Using skills and knowledge to become a co-manager of energy use •Aware of consumption levels and patterns

Figure 21 Smart grid components applied to Social Practice Theory, elements adapted from: (Shove et al., 2012)

2.6.3 Opportunities and limitations of the SPT lens for energy conservation

SPT utilizes ethnographic and qualitative methods to analyze how energy permeates into daily actions. Consequently, it can provide unique insights on socio-technical aspects of household energy consumption (Shove, 2004; Shove & Walker, 2014; Strengers, 2012, 2013; Wallenborn & Wilhite, 2014). Increased opportunities to study the ‘peaks and troughs’ of demand from access to real-time smart meter consumption data can develop further understanding of energy practices and opportunities to shift demand dynamics (Walker, 2014). Limited studies have used the SPT lens to investigate long-term temporal practices of household consumption, emphasizing novel opportunities for research development.

However, this area of literature lacks a clear set of strategies for practitioners to implement and design conservation programs and interventions. Additionally, the energy management strategies suggested by Strengers (2012) remain vague and may not provide enough clarity for effective implementation and widespread change in standards of ‘cleanliness, comfort and convenience’ called for by Shove (2003b, 2010). Therefore, this lack of clarity results in difficulties for application by policymakers and practitioners. Additional literature highlights SPT intervention approaches lack clarity on intervention strategies (Spotswood et al., 2017; Strengers & Maller, 2015a; Strengers et al., 2015). Although SPT emphasizes moving beyond behavioural approaches and incorporates socio-technical elements, it lacks insight on how to shift the meanings and competencies associated with energy practices. Existing intervention design strategies in CBSM and design thinking, discussed later, present opportunities to shift social practices associated with conventional materials, meanings, and competencies of energy consumption.

2.7 A comprehensive approach: The energy cultures framework

Energy is embedded in many aspects of our lifestyle, is influenced by a variety of personal, societal, technological, and environmental factors, and is consequently integrated into our 'culture.' As highlighted earlier, previous models have focused on either changing behaviours or practices and have limited capabilities to identify policy opportunities. One particular approach integrates socio-technical factors contributing to household energy consumption alongside engagement strategies: the energy cultures framework (ECF) (Stephenson, 2018; Stephenson, Barton, et al., 2015; Stephenson et al., 2010). This scalable framework, derived from social cultural theory, presents an actor-centred heuristic for the integration of factors influencing energy behaviours to understand opportunities for sustainable energy transitions (Stephenson, 2018; Stephenson, Barton, et al., 2015).

The overall energy culture is a result of three interrelated core elements, influenced by contextual factors (Barton et al., 2013; Darnton, 2008; Stephenson et al., 2010) (Figure 22). Firstly, material culture involves the technical elements and built environment (e.g., appliances, advanced metering infrastructure, insulation, building envelope elements) that are involved with energy use. Adopted from anthropology, the term material culture emphasizes artefacts' functional and symbolic properties, driven by underlying meanings, that influence and are influenced by behaviours (Stephenson, Barton, et al., 2015). Therefore, material culture can include elements that use energy (e.g., appliances), influence the level of consumption (e.g., efficiency of built environment), generate energy (e.g., solar panels), as well as inform or change energy consumption (e.g., feedback, smart meters, and energy hubs) (Stephenson, 2018; Stephenson, Barton, et al., 2015).

Secondly, energy practices and skills refer to the routinized consumption behaviours of societal actors as well as infrequent actions resulting in energy consumption, which are standard within society (e.g., time-of-use consumption patterns and dynamics of daily consumption). Energy practices are also strongly influenced by the existing material culture (Barton et al., 2013; Stephenson, Barton, et al., 2015; Stephenson et al., 2010). Ford et al. (2017) expanded the 'practices' element to incorporate skills and competencies required to fulfill these practices, which is applied in this literature review and dissertation. Therefore, energy practices in the ECF involves consumption actions as well as the adoption of material objects along with the related skills and competencies, for fulfilling actions.

Thirdly, norms and aspirations involve the meanings, attitudes, and knowledge surrounding energy consumption. Previously articulated as ‘cognitive norms’ in the original framework (Stephenson et al., 2010), the term ‘cognitive’ was removed in later iterations of the ECF to reduce unintentional ties to a specific field of psychology (Stephenson, Barton, et al., 2015). This dissertation applies Ford et al.’s (2017) extension to norms and aspirations to clearly capture the ‘expectations’ for transitions. Expected norms of consumption are those that are already visible within a community. On the other hand, aspirational norms are those not yet present in the context, and may facilitate transitions in material culture and energy practices to shift the energy culture towards the desired state (Stephenson, Barton, et al., 2015). As identified in Figure 22, the overall energy culture is influenced by the linked and interrelated forces of material culture, practices and skills, and norms and aspirations, as depicted by the arrows (Stephenson, 2018). Therefore, this scalable heuristic that depicts the energy culture, is an outcome of the interrelated elements of material culture, norms and aspirations as well as practices and skills surrounding energy consumption.

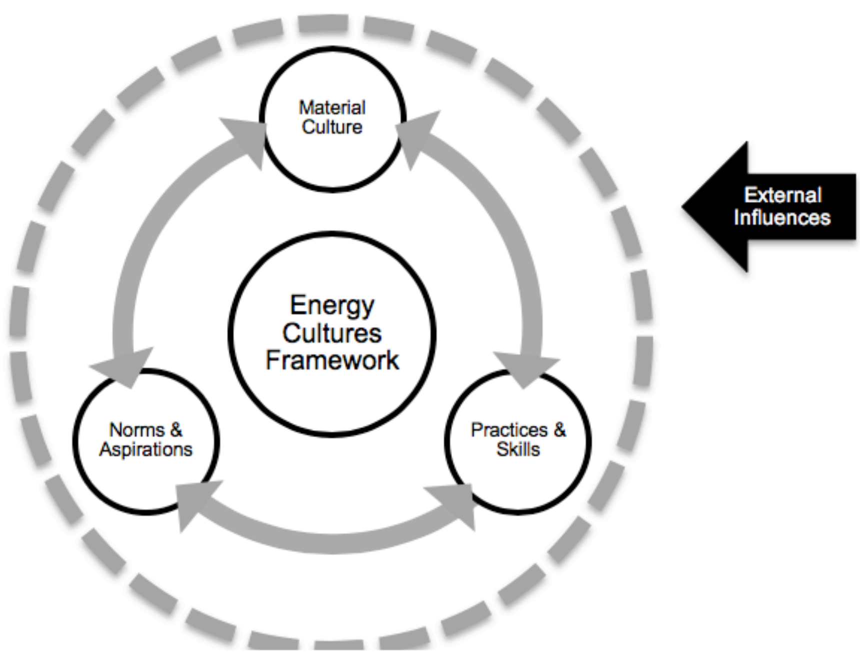

Figure 22 Energy cultures framework, adapted from: (M. G. Scott et al., 2016; Stephenson, 2018; Stephenson, Barton, et al., 2015; Stephenson et al., 2010)

This framework considers the influences of external forces. As identified in Figure 22, the dashed line indicates the permeable boundary between the energy culture and the external influences that are largely beyond the control of the actor (Stephenson, 2018). These external forces, or wider systemic influences influencing behaviours, exert influence on the energy culture (Stephenson et al., 2010). Consequently, this framework incorporates contextual factors associated with these three elements (material culture, norms and aspirations, and practices and skills), including policies and their associated interventions, for an in-depth understanding of the multitude of factors influencing energy consumption. Therefore, this framework includes the systemic influences that may preserve behavioural patterns, create opposition to change, or enable the uptake of new behaviours, which are largely beyond the control of the subject (Stephenson, Barton, et al., 2015). Various external influences impact the norms, material culture, and energy practices associated with a particular energy culture, highlighted by Ocampo (2015) and can include policies, technologies as well as societal forces influencing behaviours (Figure 23).

Material culture	Norms and aspirations	Practices and skills

• Energy efficiency and desigh
• House elements:
  • Size and age
  • Location and sun exposure
• Number of appliances (characteristics)
• House tenure
	• Policies, regulations
	• Retailers plans/costs
	• Attitudes and comfort preferences
	• Neighbours' behaviours
		• Demographic variables
		• Different room settings
		• Appliance settings
		• Energy management practices
		• Energy behaviours and habits
		• Retailers' plans

Figure 23 External influences of the energy cultures framework factors, sources: (Ocampo, 2015; Stephenson et al., 2010; Stephenson, Hopkins, & Doering, 2015)

The role of structure and agency has remained an important debate for consideration in studying the role of individuals and their actions in collective change. In particular, these concepts focus on the capacity of individuals to make their own decisions and to act independently. Classical and contemporary social science theories have taken these items into consideration, and these developments influenced the creation of the ECF (Stephenson, 2018). As previously mentioned, the ECF is an actor-centered framework to understand the heterogeneity of factors related to energy behaviours (Stephenson et al., 2010; Stephenson, Hopkins, et al., 2015; Wilson & Dowlatabadi, 2007).

As identified by Stephenson (2018) the creation and ongoing development of the ECF was influenced by several social theories. Lutzenhiser's (1992) cultural model of household consumption presented inspiration for the term 'culture' and development of this heuristic. Since Lutzenhiser's model this was not developed further, Stephenson et al. (2010), further applied this concept through the influence of several social theories (Stephenson, 2018). First, the emphasis of the role of habitus in shaping practices from Bordeau (1977), which is governed by external conditions, where the main focus of the ECF is to understand the interplay between heterogenous factors to shift from existing habitus by the adoption of more sustainable materials, aspirations, and practices (Stephenson, 2018; Stephenson, Barton, et al., 2015). Second, the interrelationship and roles of technologies, behaviour, and standards from sociotechnical transitions (Smith, Stirling, Smith, & Stirling, 2007; Stephenson, 2018; Stephenson, Barton, et al., 2015). Third, the role of causality and consequences from systems thinking (Midgley, 2003; Stephenson et al., 2010; Von Bertalanffy, 1968). Fourth, interactions between agency and social structures from Structuration . In particular, the ability for social practices and material artefacts to influence and be influenced by each other (Giddens, 1984; Stephenson, 2018). Last, the focus of the ECF on the broader range of cultural attributes indicated in social theory, which influence and are influenced by actors (Hays, 1994; Stephenson, 2018; Stephenson, Barton, et al., 2015). Therefore, the ECF views the role of agency and structure to be actor-centered, with the interrelationship between actors, systemic factors, and the interplay between artifacts, practices, and norms.

Since both the ECF and social practice theory are derived from cultural theories, similarities and contrasts are evident between the two approaches. A clear distinction is the role of the actor. Within the energy cultures framework, the actor has agency over their practices, whereas within practice theory, the practice is the primary focus. Consequently, within practice theory, the focus is on routines (Praktik), rather than the broader context and all-human action (Praxis) (Stephenson, 2018). As a result, actions are embedded in the overall study of the energy culture – practices, materials and norms – whereas the unit of analysis is the 'practice' within practice theory – materials, meanings and competencies (Shove et al., 2012; Stephenson, 2018; Stephenson, Barton, et al., 2015). Material culture is similar to practice theory's materials and includes buildings, infrastructure, appliances and other technologies (Ford, Walton, et al., 2017). However, within practice theory, materials either inhibit or promote certain practices, whereas, in the ECF, agents have control over materials, which influence demand (Ford, Walton, et al., 2017). Norms and aspirations are similar to practice theory's 'images' (Ford, Walton, et al., 2017). This element involves both the personal standards and their future goals, often influenced by the meanings held towards particular behaviours or services. Therefore, critical distinctive factors of ECF from practice theory are the agency of the actor, the separation of materials and actions, the consideration of societal norms, and the broader consideration of human actions.

Utilizing a multidisciplinary approach to study energy consumption facilitates a thorough understanding of factors influencing energy consumption as well as policy and program approaches (Wilson & Dowlatabadi, 2007). An integrated framework, such as the ECF brings value by being applicable at different scales, relevant to different contexts, and provides insights into the heterogeneity of factors influencing energy consumption (Stephenson, Hopkins, et al., 2015; Wilson & Dowlatabadi, 2007). The ECF, and its scalability offers an integration of socio-technical transitions, social engagement, behaviour change and policy approaches (Barton et al., 2013; M. G. Scott et al., 2016; Stephenson et al., 2010). This framework has been utilized in a variety of contexts, including the U.S. Navy energy demand (Dew, Aten, & Ferrer, 2017); energy in higher education (Ishak, Hamid, Iman, & Sapri, 2012); photovoltaic adoption (Ford, Walton, et al., 2017); energy demand in the elderly (Bardazzi & Pazienza, 2017); transportation and mobility (Hopkins & Stephenson, 2014, 2016; Stephenson, Hopkins, et al., 2015); timber technologies (Bell, Carrington, Lawson, & Stephenson, 2014); residential energy demand (M. G. Scott et al., 2016); energy poverty in New Zealand (McKague, Lawson, Scott, & Wooliscroft, 2016); residential smart grid context (Lazowski et al., 2018). The ECF, however, has only had limited and recent application to the Canadian context and the smart grid[14]; therefore, opportunities are evident for the extension and further application of this framework to the smart grid.

Stephenson (2018) presents an opportunity to utilize the ECF beyond energy, and into other sustainability behaviours. As an actor-centred approach, utilizing a scalable and comprehensive focus, this framework brings promise for integrating the understanding of intervention effects from energy behaviour studies, energy dynamics and synchronicities from SPT, and influences of technical transitions together with the strategies of design, and community based social marketing to shape conservation culture. As Stephenson (2018, p. 245) emphasizes, the outcomes of the energy cultures studies have recognized, "[…] how cultural formations, at any scale of actor, have outcomes with

[14] This research is delivered in Chapter 4.

social, economic, and/or environmental sustainability implications." As a result, this framework can have wide applicability for broader studies of 'sustainability cultures.'

2.8 Achieving both a smart and sustainable energy culture: Applying the energy cultures framework to the smart grid

This framework relates to social practice theory and socio-technical innovations theory to explain overall patterns of energy use within spatial and temporal boundaries (Darnton, 2008); however, this has only recently been applied to studying smart and sustainable energy cultures in existing literature, as a result of this dissertation (Lazowski et al., 2018). As identified by Darby (2018a), within residential studies of smart technologies, essential considerations need to be made on the role the users, the involvement of technology and control, and the boundaries of the home in relation to its larger impact(s). The ECF combines elements of material practice and norms and can include external forces, such as socio-technical innovations and relevant policies for smart grid implementation. Consequently, this framework allows for a detailed understanding of demand management behaviours and impacts of smart grid technologies and contextual factors. This framework provides an excellent opportunity for future studies to incorporate behavioural and societal theories in the transition of energy conservation and smart grid technologies in particular regional contexts.

Opportunities exist to develop this framework further and to specifically apply it to studying smart grid technologies and the development of a smart and sustainable energy culture. As previously mentioned, solely relying on technology for advancing to a 'smart utopia' of energy consumption is problematic; instead, a focus on social and technical elements needs to take place. Developing a smart and sustainable energy culture involves shifting aspirations among household consumers surrounding energy use to improve flexibility (e.g., thermal comfort, convenience, lifestyle), increase efficiency, and empowered decision-making surrounding energy use. Therefore, this requires a three-fold transition to reorient material culture, to reframe consumption norms and to shift energy practices. Energy cultures are inherently heterogeneous, and it is important to utilize this framework to separate different 'cultures' of consumption within research (Lawson & Williams, 2012; Stephenson et al., 2010).

Conceptualizing a smart and sustainable energy culture involves materials, norms as well as energy practices and skills. The first element is upgrading material culture through the adoption of building envelope improvements (e.g., energy retrofits and insulation), the installation of smart meters/panels for the collection of data as well as the use of optimization and automation functions, including programmable thermostats, control technologies, smart appliances, and technologies as well as in-home displays. The second element involves adhering to practices and developing skills that align with these 'smart' technologies to reduce consumption, peak-shift demand, and to adhere to energy conservation goals. The third element involves a shift in norms and aspirations through increased knowledge and motivation as well as related aspirations. External programs and policies can promote in these shifts through smart grid interventions, such as in-home displays, gamification techniques, incentives, and education forums. Applying this framework to specific regional contexts and applicable policies and programs can develop insights on how these interventions alter the respective energy culture. Thus, a great opportunity remains to extend this framework to investigate residential smart and sustainable energy cultures, as conceptualized below (Figure 24).

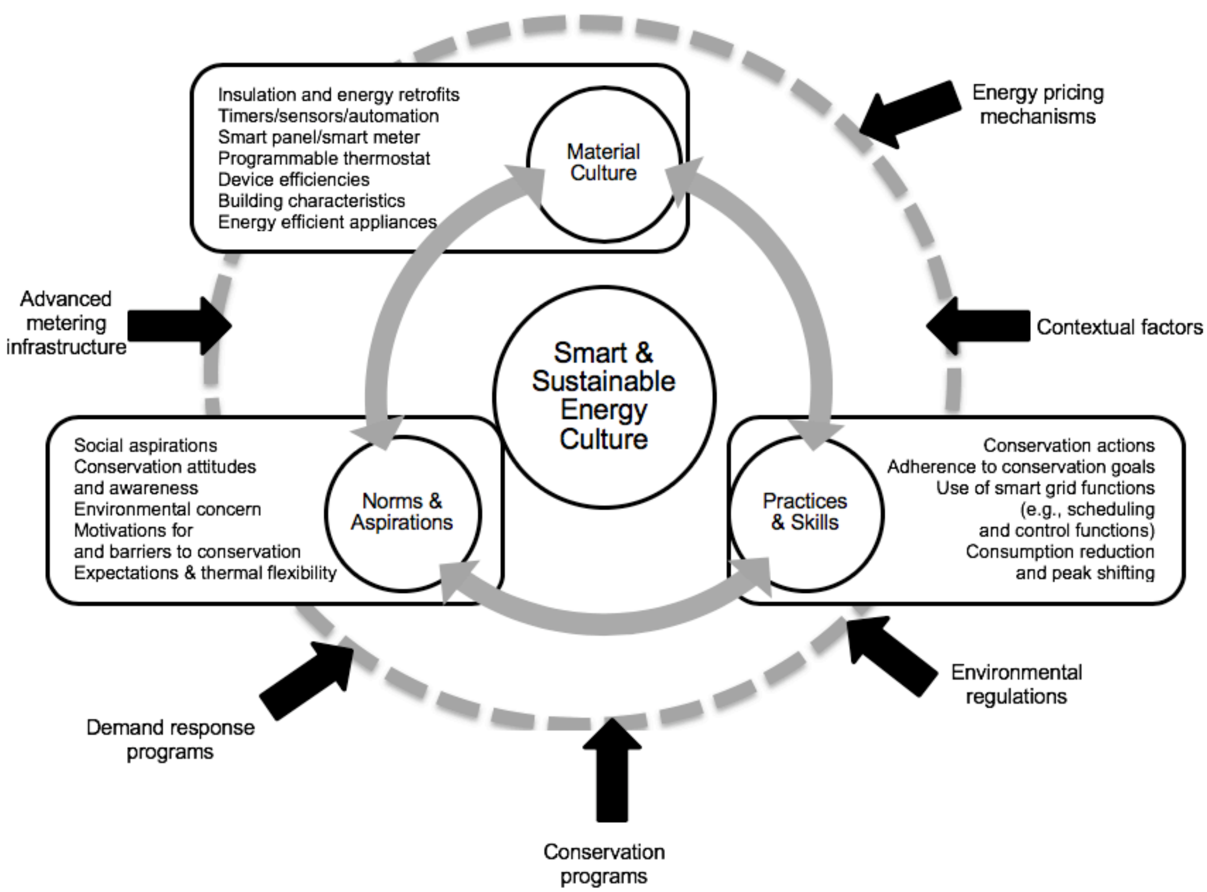

Figure 24 Smart residential energy cultures framework, source: (Lazowski et al., 2018)

Although the ECF allows for a thorough understanding of the heterogeneous factors surrounding the update of smart technologies for more sustainable energy management practices, certain tensions should be highlighted. Most prominently, is the contradiction between smart technologies and energy savings, where the computational power and connectedness of smart technologies require energy to function effectively. Additionally, is the potential for these smart technologies (e.g., smart thermostats, smart home appliances) to promote and maintain standards of comfort and convenience that, consequently, consume more energy. These concerns have been raised by Strengers and Nicholls (2017), who identified the potential for smart home technologies to transform energy practices towards increased energy consumption. Consequently, these tensions between sustainability and the potential for smart technologies are present, and identified in the literature calling into question the claims of the technologically-driven ‘smart utopia’ to deliver sustainable outcomes (Darby, 2018a; Strengers, 2013; Tirado Herrero et al., 2018). Therefore, the ECF can be further utilized to gain detailed understandings of the interrelationships between these smart technologies and their potential for promoting sustainable energy management through the shifting of energy practices, the reframing of norms and aspirations, as well as the adoption of material culture, as further articulated in Section 2.10.

2.9 Applications and opportunities for further development

Stephenson et al. (2010) identify the opportunities for utilizing the ECF to separate an overall population and understand different clusters of energy cultures. This framework was utilized by Lawson and Williams (2012) to cluster New Zealand households on their energy consumption, socio-economic data, as well as data collected from a household energy survey, to identify insights for effective policy development. Households were separated into four categories utilizing a two-phase clustering analysis: energy economic, energy extravagant, energy efficient and energy easy (Lawson & Williams, 2012). This study is not specific to the influence of the smart grid, nor were consumption load profiles utilized for consumption analysis, identifying opportunities for research development.

The collection of granular consumption data through AMI and smart meters facilitates an in-depth understanding of consumption practices. Energy consumption is embedded in daily routines, or ‘practices’ (Shove & Walker, 2014; Walker, 2014). Understanding the dynamics, and societal rhythms of consumption at multiple temporal scales (e.g., daily, weekly, monthly, annually) is crucial for understanding the energy culture of particular populations (Walker, 2014). Societal rhythms of consumption can create synchronizations of consumption for heating, lighting, cooking and other energy-intensive routines. These temporal patterns of consumption practices deliver opportunities to study patterns beyond the 'tip of the iceberg' related to household energy consumption. Additional knowledge of these synchronizations, often resulting in peak demand loads, can identify opportunities to manage consumption and shift demand dynamics. Utilizing smart metering data and load shape profiling methods provides significant occasions to understand the energy culture of specific populations and sub-groups in more detail. In particular, this can facilitate the investigation of consumption shape, consumption magnitude, climate sensitivity, flexibility of consumption, and the relative influences of norms, material culture and energy practices.

2.10 Encouraging a smart and sustainable energy culture: Governing energy consumption through effective engagement and consumer-centred design

Solely relying on smart grid technologies to facilitate residential sustainable energy transitions is problematic and can lead to forgone opportunities for CDM. Darby et al. (2018) identify that influencing household energy consumption involves 'box' of demand response where technologies, activities, and service expectations coexist and coevolve and, thus, influence the update of more 'sustainable' demand response within the home, as seen in Figure 25.

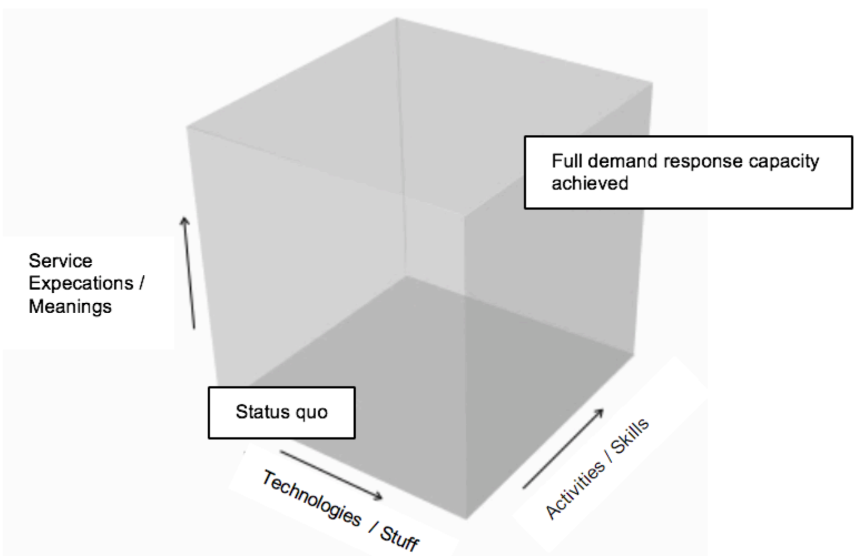

Figure 25 Demand response box, source: (Darby et al., 2018)

Rather than visualizing a 'smart utopia' of technological solutions to achieve societal energy sustainability, the limits of these technologies need to be recognized and the user constructions, as well as idealized societal outcomes, need to be reimagined (Strengers, 2013). The shift within Darby et al.'s (2018) 'demand response box' requires a multi-level shift within materials, skills and expectations. Instead, the focus should be on the development of a smart and sustainable energy culture by shifting energy practices, reframing cognitive norms, and reorienting material culture surrounding energy use (Figure 26). Transitioning from a top-town utility approach to consumer-centred approaches in the design of policies, programs and technologies can facilitate these changes.

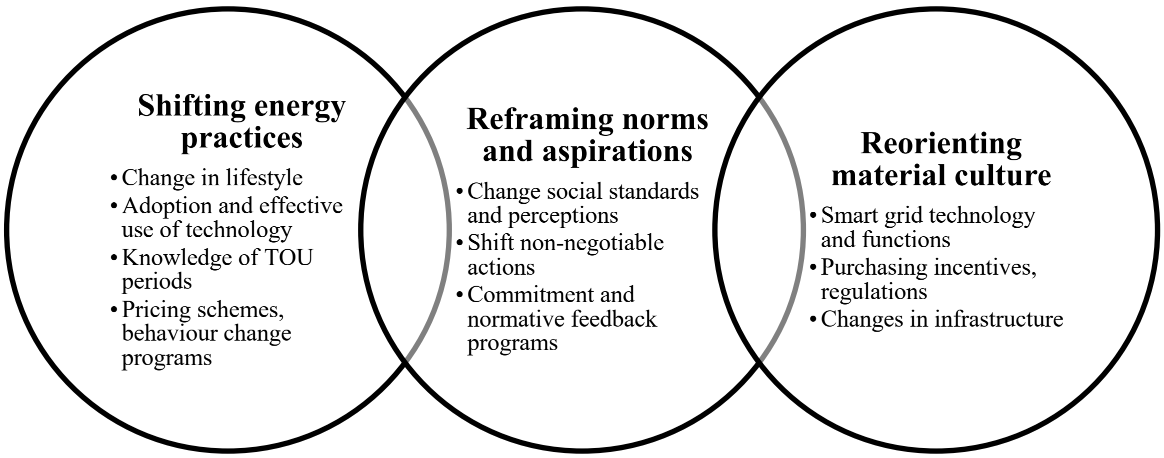

Figure 26 Transitioning to a smart and sustainable energy culture

As previously identified, the ECF presents a suitable approach to study socio-technical influences on overall patterns of energy use (Darnton, 2008); however, it has not yet been applied to the smart grid context. Using a multidisciplinary approach to shift materials, meanings and competencies surrounding energy practice can incorporate elements of technical knowledge areas, design thinking, behavioural knowledge areas as well as community-based social marketing to the adoption of 'smart' energy conservation practices. As a result, the ECF provides an excellent opportunity for future research to study the reorientation of material culture, the shifts of energy practices and the reframing of norms and aspirations as a result of smart grid tools and relevant policies.

Although the smart grid, and its associated tools, show opportunities for household energy management and transitions to sustainability, the literature has identified a serious caution regarding this 'proclamation': focusing on the technology and not engaging the consumer (Accenture, 2013; Anda & Temmen, 2014; Faruqui et al., 2010a; Gangale et al., 2013; Gaye & Wallenborn, 2014; Geelen et al., 2013). As previously identified, technology on its own is not sufficient to change electricity consumption; thus, additional elements need to be considered. The Smart Grid Consumer Collaborative (SGCC) (2016) identified that consumers are interested in smart appliances; however, interest in onsite power storage and smart homes was limited, highlighting that the smart grid still needs to mature for widespread adoption of other smart grid tools. Therefore, behaviour change and engagement are also crucial for utilizing residential smart grid tools for sustainable energy transitions (Accenture, 2013; Anda & Temmen, 2014; Faruqui et al., 2010a; Gangale et al., 2013; Gaye & Wallenborn, 2014; Geelen et al., 2013; Verbong et al., 2013). A crucial challenge to smart grid adoption is technological acceptance (Gangale et al., 2013; Park, Kim, & Kim, 2014). Effective consumer engagement, technological design and consumer targeting are essential to improve household acceptance of the smart grid and its associated tools.

2.11 Developing the 'smart' user: Types of intervention mechanisms and their effectiveness

Energy behaviour and decision-making at the household level substantially influence the successful adoption and use of smart grid technologies; therefore, it is crucial to consider consumer preference and engagement with these technologies with the introduction of the smart grid. For successful smart grid adoption, it requires the engagement of householders to become 'smart users' of these technologies and 'smart consumers' of energy. Energy behaviours and opportunities for conservation can be difficult to identify since energy is an abstract and invisible force (Burgess & Nye, 2008). Habits and routines embedded into daily lives strongly contribute to consumption levels, which make it challenging to promote conservation without increasing consumer awareness (Hargreaves, Nye, & Burgess, 2013). Additionally, culture and attitudes substantially influence these elements. The parallel delivery of behaviour change programs alongside the installation of advanced metering infrastructure is vital for effective smart grid implementation and to gain benefit from the system (Anda & Temmen, 2014). Therefore, smart grid policy must also include provisions for engagement mechanisms; however, which interventions are the most effective becomes the critical issue.

Various types of engagement mechanisms, or interventions, exist for stimulating conservation behaviour. In the smart grid context, benefits can be achieved through cooperating end-users through multiple intervention types such as feedback devices and analytical tools, mobile and web applications, normalization of feedback between peers and dynamic pricing mechanisms (Anda & Temmen, 2014). Encouraging conservation behaviour can be achieved through multiple types of engagement mechanisms. Primarily two forms of interventions exist, those that influence the participants before the behaviour (antecedent interventions) and those that occur after the action (consequence interventions) (Abrahamse, Steg, Vlek, & Rothengatter, 2005; Dwyer, Leeming, Cobern, Porter, & Jackson, 1993). The following sections outline these interventions. In behaviour change programs, antecedent interventions are generally more effective than consequence conditions (Dwyer et al., 1993); however, several studies have indicated the importance of the combination of antecedent mechanisms, such as commitments, with feedback and reward consequence interventions (Darby, 2006; McKenzie-Mohr & Schultz, 2014).

2.11.1 Summary of behavioural intervention effectiveness and opportunities for future research

The behavioural lens has remained dominant in the study of energy behaviours and interventions for change. Wilhite and Ling (1995) conceptualized a relatively straightforward linear process for energy behaviour change, where increased feedback led to changes in behaviour; however, recent literature has established that information alone is not sufficient to shape energy behaviours (Abrahamse, Steg, Vlek, & Rothengatter, 2007; Hargreaves et al., 2013; McCalley & Midden, 2002), which remains consistent with feedback intervention theory (FIT) (Karlin, Zinger, & Ford, 2015). Consequently, a variety of intervention types have been studied in the literature. Overall, energy behaviour interventions are most effective when provided in combination. As indicated by Abrahamse et al. (2007), a combination of tailored information, goal-setting and feedback are effective in reducing direct energy use. Existing research has studied the impact of behavioural approaches on household electricity conservation, developing a thorough knowledge of behavioural interventions to shift energy consumption, in particular: information, feedback, goal-setting, and consequences; however, there are limitations and opportunities to develop this area of research (Table 6).

Table 6 Summary of intervention effectiveness knowledge gained from existing studies

Energy Intervention Type	Classification	Knowledge Gained from Existing Studies
Information	Workshops	Have limited behavioural effects (Abrahamse et al., 2007)
	Mass Media	Can be successful when used in combination (Abrahamse et al., 2007)
	Home Audits	Mixed-results (Abrahamse et al., 2005, 2007)
	Energy Modelling	Increases knowledge but might not yield significant savings (Abrahamse et al., 2005, 2007)
Feedback	Enhanced Billing	Savings of 5.5% compared to normal billing (Ehrhardt-Martinez et al., 2010).
	Normative Feedback	Up to 20% reduction when combined with private feedback (Delmas & Lessem, 2014). Benefits contested in literature; potential for 'rebound effect' (K. Buchanan, Russo, & Anderson, 2015; Karjalainen, 2011) Can appeal to competitive nature (Delmas & Lessem, 2014; Midden, Meter, Weenig, & Zieverink, 1983; Peschiera, Taylor, & Siegel, 2010; Wood & Newborough, 2007) Effective in contests with rewards (Abrahamse et al., 2005)
	Frequency	More frequent feedback is more effective; can provide behaviour-specific feedback (Abrahamse et al., 2007; Darby, 2006; Karlin et al., 2015)
	Direct vs. Indirect	Direct feedback is more effective –can provide real-time and disaggregated consumption feedback (Darby, 2006) Range of 5-15% savings with direct feedback (Darby, 2006; Ehrhardt-Martinez et al., 2010). Range of 0-10% savings with indirect feedback (Darby, 2006).
	Granularity	Types of comparisons: fuel consumption, appliance use, historical consumption, room comparisons, energy use predictions (Wood & Newborough, 2007) Appliance-level feedback might not result in energy savings (Aydinalp Koksal, Rowlands, & Parker, 2015)
Goal Setting and Commitments	Public vs. Private	Public goals establish norms and are more successful (Abrahamse et al., 2005; McKenzie-Mohr and Schultz, 2014).
	Self-Set vs. Assigned	Self-set goals are more effective; can control commitment (Dwyer et al., 1993; McCalley and Midden, 2002).
	Difficulty Level	Too high: impossible to obtain; too low: reduces motivation (Karjalainen, 2011).
	Oral vs. Written	Written goals are more durable and effective (Abrahamse et al., 2005; McKenzie-Mohr and Schultz, 2014).
Positive or Negative Consequences	Rebates Discounts Low-interest loans	Pre-action financial incentives can encourage increased participation by reducing financial costs (Stern, Berry, & Hirst, 1985) Low-interest loans are effective for encouraging home retrofits (Berry, 1984) Availability, information provided, and convenience are important for financial incentive acceptance (Berry, 1984; Stern et al., 1985)
	Energy Pricing	Peak-load critical pricing with enabling technology can result in peak-load reductions of 30%, whereas TOU results in 5% (Newsham & Bowker, 2010).
	Performance-based Incentives	Largest potential for residential energy reductions from retrofits (Hoicka, Parker, & Andrey, 2014) Incentives may not encourage durable behaviour or PEB 'spill-over' (Darby, 2006; McKenzie-Mohr & Schultz, 2014).

For effective program implementation and participant behaviour change, it is vital to understand the participants' perspective of energy conservation programs (Crosbie & Baker, 2010). Although existing studies provide insights on interventions, the majority of studies have focused on intervention effectiveness presenting quantitative outcomes, either through surveys (Chen, Delmas, & Kaiser, 2014; Delmas & Lessem, 2014; Ek & Söderholm, 2010; Gangale et al., 2013; Wood & Newborough, 2003) or pre-post quantitative analysis methods (Asensio & Delmas, 2015; Aydinalp Koksal et al., 2015; Chen et al., 2015; Harring, 2015; Jacobsen & Kotchen, 2011; Jain, Taylor, & Peschiera, 2012; McCalley & Midden, 2002; Ueno, Sano, Saeki, & Tsuji, 2006). Since energy consumption is rooted in daily behaviours and activities (Chen et al., 2015; Dietz et al., 2009; Mills & Schleich, 2012), it is vital to understand how consumers interact with these interventions to shift their actions, which can be achieved through qualitative methods. Limited qualitative studies focusing on intervention implementation, effectiveness, and impact(s) on household decision-making and daily activities have taken place (Burchell, Rettie, & Roberts, 2016; Crosbie & Baker, 2010; Hargreaves, Nye, & Burgess, 2010; Hargreaves et al., 2013; Karjalainen, 2011; Nilsson et al., 2014). Additionally, since regional characteristics contribute to consumption behaviours (M. Brown, 1984), qualitative methods can enable additional insights to design effective intervention strategies based on location-specific factors. Utilizing a mixed-method approach can provide a comprehensive overview of the behavioural impacts and intervention effectiveness.

User preference has a significant influence on intervention effectiveness (T. Brown & Wyatt, 2010; Karjalainen, 2011); however, the majority of studies focus on behavioural impacts (e.g., attitudes and awareness), rather than the intervention usability, design, or user preference (Abrahamse et al., 2007; Delmas, Fischlein, & Asensio, 2013c). Studies focusing on quantitative consumption effectiveness often analyze short-term effects (less than one to one year) (Abrahamse et al., 2007; Chen et al., 2014; Crosbie & Baker, 2010; Delmas et al., 2013c; McCalley & Midden, 2002). Consequently, insights on long-term behavioural changes and intervention influence are limited in these existing studies. Temporal studies are essential for understanding long-term trends and potential influences of interventions (K. Buchanan et al., 2015; Hargreaves et al., 2010). These elements pose opportunities for future research to focus on user-centred feedback through qualitative or mixed-methods studies and to investigate long-term influences of CDM interventions.

2.12 Shifting practices and re-framing norms through intervention design strategies

A primary objective of intervention design is to identify techniques that change individual behaviours without requiring repetitive intervention (De Young, 1993). Steg and Vlek (2009) identify that informational strategies (e.g., information, social support, and public participation) and structural strategies (e.g., products and services, financial strategies, and regulatory measures) can be applied. Froehlich et al. (2010) identify five key elements to motivate environmental behaviour through interventions: information, goal setting, comparison, commitment, and feedback. These are highly applicable for shifting dynamics of energy consumption.

Gardner and Stern (1996) provided a list of eight principles for interventions in the promotion of pro-environmental behaviour, creating a foundation for intervention studies in the literature (Table 7). Four critical issues for encouraging pro-environmental behaviour were highlighted by Steg and Vlek (2009) including identifying which behaviours should be changed, which factors determine the behaviour, which interventions could be best applied, and the effects of interventions (Table 7).

Table 7 Comparison of principles for behavioural intervention design, sources: (Darnton, 2008, pp. 23–24; Gardner & Stern, 1996)

Principles for encouraging environmental behaviour (Gardner & Stern, 1996)	Principles for changing environmental behaviour (Darnton, 2008)
1. Utilize multiple intervention types to address limiting factors of behaviours 2. Understand the situation from the actor's perspective 3. Apply understanding of human choice processes when limiting factors are psychological 4. Address conditions beyond the individual that constrain pro-environmental choice 5. Set realistic expectations about outcomes 6. Continually monitor responses and adjust programs accordingly 7. Stay within the bounds of the actors' tolerance for intervention 8. Use participatory methods of decision making	1. Identify target behaviour and audience group 2. Identify relevant behavioural models at societal and individual levels 3. Select key influencing factors to design intervention strategy objectives for intervention strategy 4. Identify effective techniques to influence behaviours that have worked in the past 5. Engage the target audience for the intervention 6. Develop a prototype intervention 7. Pilot the intervention and monitor continuously 8. Evaluate the impacts and processes 9. Gain feedback and learn from the evaluations

Subsequently, Darnton (2008, pp. 23–24) provided a set of nine principles for developing interventions based on behavioural models, based on a thorough literature review of behavioural models and intervention design. These principles differ from Gardner and Stern's (1996) principles by including prototyping and piloting the intervention. Although these nine principles develop Gardner and Stern's (1996) principles, areas of improvement remain.

Several studies have empirically tested which intervention types are appropriate to achieve pro-environmental behaviour. A meta-analysis of pro-environmental behaviour change studies conducted by Osbaldiston and Schott (2012) concluded that pro-environmental behaviours can be changed, that certain treatments are more effective than others, and that treatment effectiveness is not uniform between interventions and target audiences.

Schultz (2014) presented a framework to identify *when* specific interventions are suitable for implementation (Figure 27). Those interventions that are the most effective (i.e., those with high benefit with low barriers) include education, feedback, prompts and cognitive dissonance.

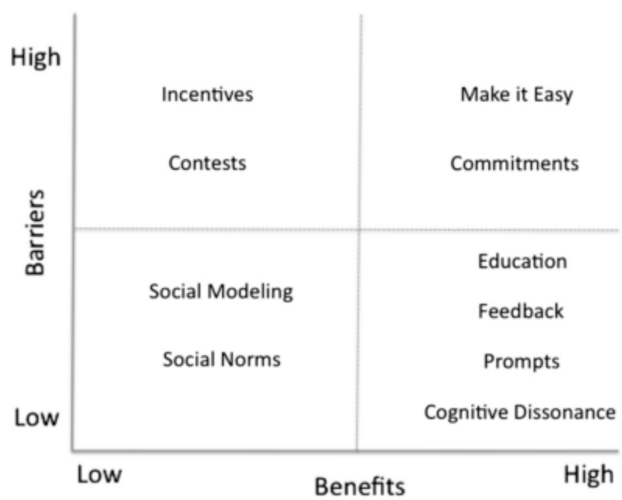

Figure 27 When interventions are suitable for implementation, source: (Schultz, 2014)

Previous work has provided essential elements for the continual development of interventions; however, they are missing integral elements for effective implementation, which are highlighted in the concepts of social marketing and community-based social marketing.

2.12.1 Social marketing

As an applied model of behaviour change, social marketing strategies integrate stakeholder engagement to shape consumer behaviours. Social marketing was introduced by Kotler and Zaltman (1971) and uses marketing principles to transform public behaviour towards social goals (N. R. Lee & Kotler, 2008; Lefebvre, 1996). Whereas traditional marketing involves the promotion of goods and services, social marketing focuses on values to achieve social improvement and desired behaviours (N. R. Lee et al., 2008). Social marketing has similarities to traditional marketing, including customer targeting and market research, establishing objectives, and application of the marketing mix (product, price, place, and promotion). Most notably, Kotler and Lee (2008) established ten steps for social marketing, which incorporate monitoring and evaluation for continual improvement, setting the foundation for social marketing strategies (Figure 28).

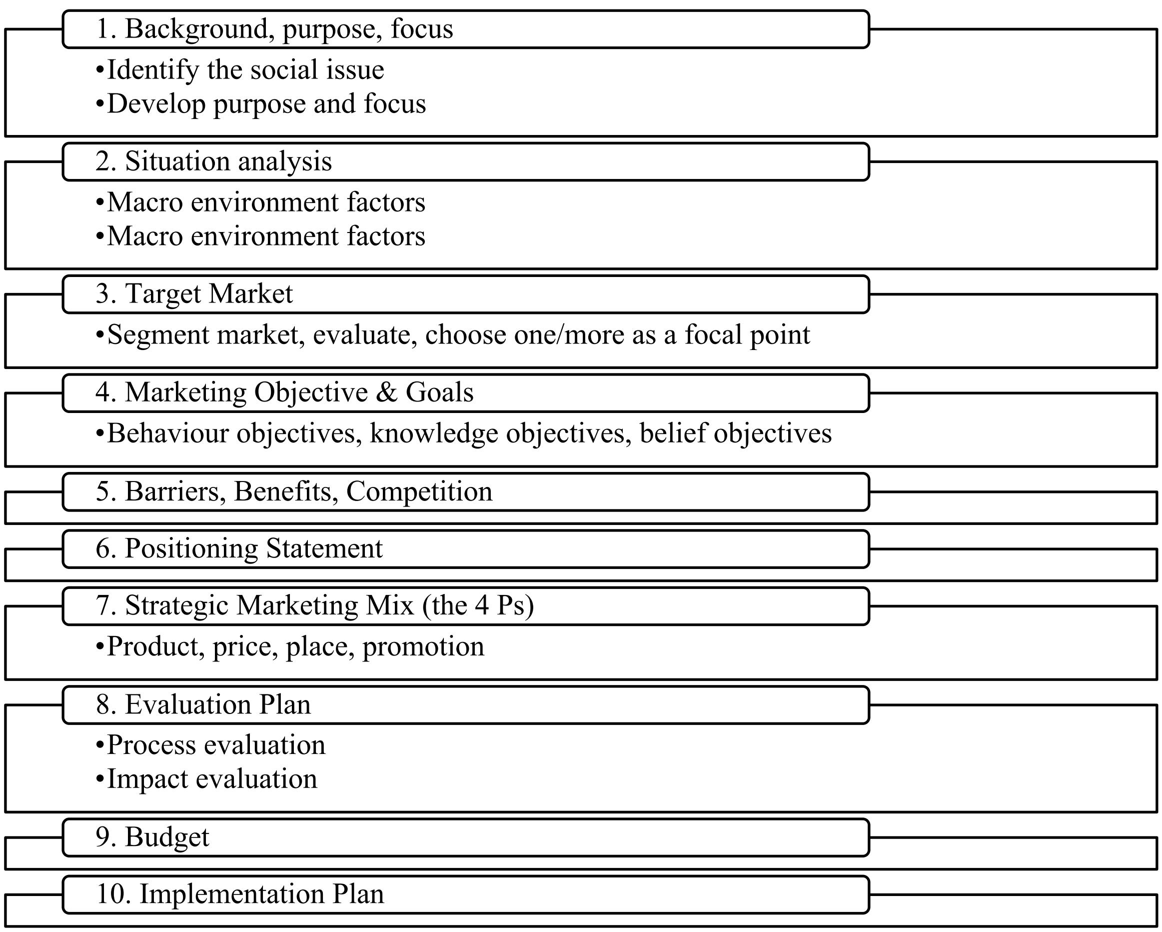

Figure 28 The 10 Steps of Social Marketing, source: (N. R. Lee & Kotler, 2008)

2.12.2 Community-based social marketing (CBSM)

At the community-level, CBSM is a strategy focused on 'fostering sustainable behaviour' and moves beyond traditional attitude-behaviour and economic self-interest models (McKenzie-Mohr, 2011). CBSM outlines five critical elements for successful behaviour change programs (Figure 29). Identifying barriers and benefits for participation is a crucial step, and builds upon Gardner and Stern (1996), highlighting the importance of interacting with target audiences before program implementation. By identifying barriers, it results in the classification of divisible (those behaviours which can be divided further) and non-divisible behaviours[15] (singular behaviours at the root of an action). Ensuring that the targeted behaviours are divisible makes the program development more effective (McKenzie-Mohr, 2011). These strategies have resulted in successful program implementation for various PEBs, including: anti-idling campaigns (McKenzie-Mohr, 2001); residential energy conservation (Kassirer, Korteland, & Pedersen, 2014); university campus energy conservation programs (Chan, Dolderman, Savan, & Wakefield, 2012); and residential water conservation programs (Stinchcombe, Wildman, & Wiltshire, 2005). As a result, CBSM specifies appropriate strategies to integrate stakeholder engagement into the understanding of the energy consumption landscape, and for smart grid project design to shift energy cultures.

[15] Divisible behaviors refer to those that are can be divided further into multiple behaviors (e.g., water conservation), whereas non-divisible behaviors are singular behaviors at the root of an action (e.g., conserving shower water) (McKenzie-Mohr, 2011).

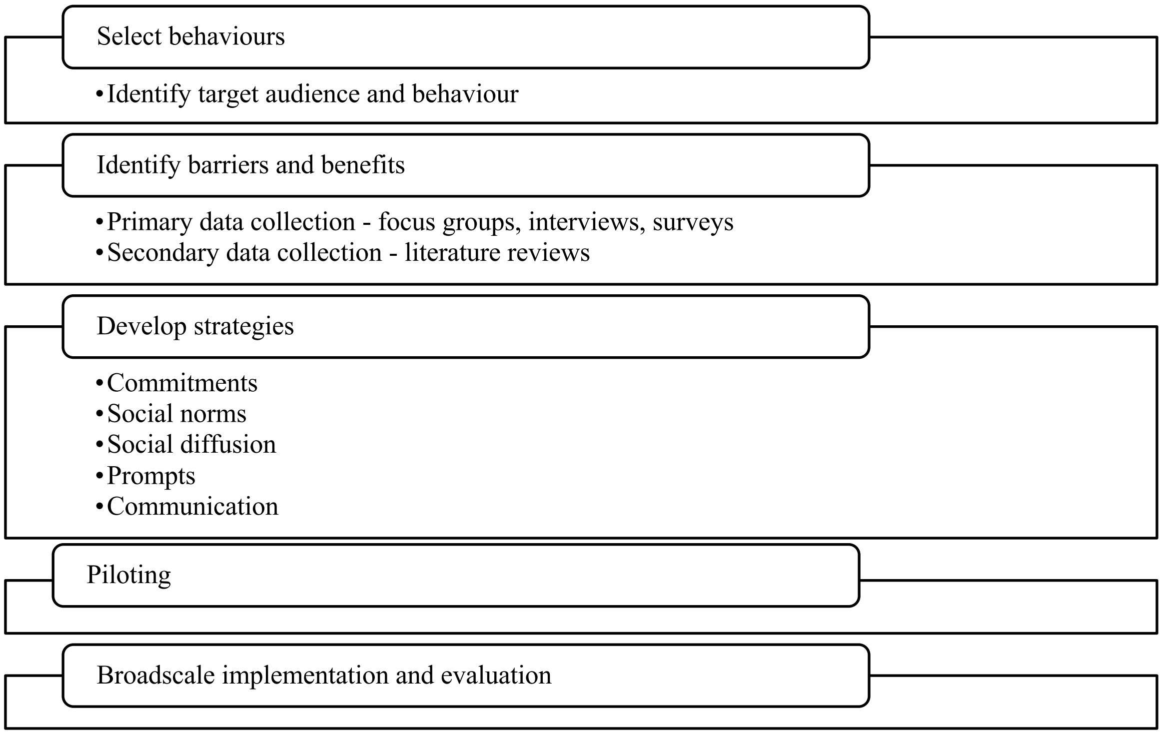

Figure 29 Five stages of CBSM, adapted from: (McKenzie-Mohr, 2011; Mckenzie-Mohr, 2000)

2.12.3 Consumer targeting and identification

Understanding targets and types of consumers is integral for effective design of and engagement with smart grid tools. A central element of CBSM involves identifying and understanding the target market (Goulden et al., 2014). Different types of interventions and technologies will appeal to different types of smart grid users (Goulden et al., 2014; Naus, Spaargaren, Van Vliet, & Van der Horst, 2014; Silvast, Williams, Hyysalo, Rommetveit, & Raab, 2018). For the most part, consumers and their energy practices are ‘anonymous’ to utility providers (Summerton, 2004). Implementing successful smart grid projects requires user-centred strategies (Accenture, 2013; Römer et al., 2012; Verbong & Geels, 2007), which can be achieved through the effective establishment of target markets.

Unfortunately, a majority of smart grid tools have been created for a particular user-archetype: the ‘new’ or ‘ideal’ smart grid consumer (Gaye & Wallenborn, 2014). This consumer is identified as 25 to 35 years old, college-educated, highly energy literate, technically-savvy, and energy diverse with an average income of US$70,000-100,000 (Gaye & Wallenborn, 2014; Strengers, 2013). However, this profile only represents 11-13% of the US population (Strengers, 2013).

Additionally, the smart grid is composed of diverse actors with different goals, attitudes, and preferences (Gaye & Wallenborn, 2014; Naus et al., 2014). To utilize smart grid tools in the transition to a sustainable energy future a more comprehensive consumer group needs to be included and identified; therefore, targeting strategies can be applied, to ensure programs and technologies appeal to the appropriate target markets.

Consumer classifications have been created in the existing literature for PEB and technological innovation, most notably Roger's (1995) categories for the diffusion of innovations, as well as Ogilvy and Mather's (1992) and Roper's (2000) consumer categories for environmental consumers (Rex & Baumann, 2007). Energy consumers have also been classified, utilizing characteristics related to the willingness to purchase renewable energy (Rowlands, Scott, & Parker, 2003) and the resistance to energy policies (Summerton, 2004). Additional studies on energy behaviours and factors contributing to consumption have resulted in a variety of characteristics for user typologies. Characteristics utilized in existing consumer typologies have been implemented throughout within the literature (Accenture, 2014; Frades, 2016; Gaye & Wallenborn, 2015; Lutzenhiser, 1993; Rex & Baumann, 2007; Rowlands et al., 2003; SGCC, 2016b), and include:

- Socio-economic categories: age, household income, education level;
- Cost of energy and willingness to spend;
- Environmental values: liberalism, altruism, ecological concern; activist, realist, complacent, alienated;
- Smart grid technology acceptance: interest in energy products and technologies;
- Technological education;
- Level of energy consumption;
- Patterns of energy consumption (e.g., load shape profiles);
- Level of energy management;
- Energy literacy;
- Lifestyle type;
- Level of comfort and flexibility;
- Diffusion of innovation categories; and
- Type of environmental consumer.

The energy cultures framework has also been applied by Lawson and Wilson (2012) to separate New Zealand households into four cohorts utilizing both socio-economic and household energy data from a survey: energy economic, energy extravagant, energy efficient and energy easy. Although this applies socio-economic data and utilizes the energy cultures framework for detailed understanding of energy use, this particular study was not directly related to the smart grid. Consequently, thus it is crucial to investigate typologies of smart grid consumers.

Three recently developed smart grid consumer typologies stand out in the literature. Firstly, Curtius et al. (2012) identified three categories based on perceived benefits and concerns of the smart grid: supporters, who expect benefits; ambiguous, who express equal benefits and concerns; and skeptics, whose concerns outweigh benefits. Secondly, the SGCC (2016) developed a comprehensive characterization of five segments of the empowered consumer characterized by environmental, economic, and technological goals (Table 8).

Table 8 Characteristics of the empowered consumer, source: (SGCC, 2016b)

SEGMENTS	PERSPECTIVES	KEY DEMOGRAPHICS	AWARENESS AND INTEREST
Green Champions	*"Smart energy technologies fit our environmentally aware, high-tech lifestyle."*	Youngest, more likely to be college educated	Highest levels of awareness and interest in almost all concepts
Savings Seekers	*"How can smart energy programs help us save money?"*	Younger, more likely to be college educated	Modest awareness level and high interest, especially peak time savings and time-varying rate
Status Quo	*"We're okay; you can leave us alone."*	More likely middle age low income renters living in non-single family dwellings, less likely to be college educated	Lowest levels of awareness and interest in all concepts
Technology Cautious	*"We want to use energy wisely, but we don't see how technologies can help."*	More likely homeowners who are older in age, less likely to be college educated	High levels of awareness and low interest in all concepts except smart appliances
Movers & Shakers	*"Impress us with smart energy technology and maybe we will start to like the utility more."*	More likely middle age high income single-family homeowners, and college educated	High levels of awareness but moderately low interest in all concepts except smart appliances

Similarly, Gaye and Wallenborn (2014, 2015) developed a typology of four smart grid consumers based on six dimensions: environmental motivations, economic motivations, technical aptitude, intervention appropriation, electricity consumption management, and thermal flexibility (Figure 30). These existing typologies provide insights for smart grid technology and policy development, and present opportunities to integrate with holistic frameworks. Although segmentation can bring insights for understanding consumer needs beyond the general population, certain considerations should also be identified. The challenge of 'simplifying' the needs and complexities of consumers through segmentation is an important consideration, as is the appropriateness for segments to address diverse consumer characteristics. Therefore, to ensure targets are effectively applied, the selection of segmentation techniques and classification, alongside the use of appropriate data are important to consider. Opportunities exist to develop these main smart grid typologies and address main market segments of smart grid programs for effective intervention design.

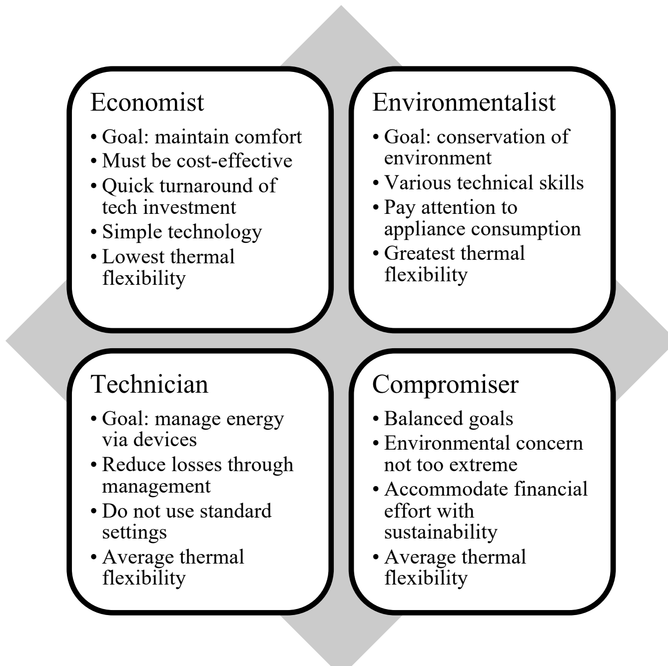

Figure 30 Typology of smart grid users, source: (Gaye & Wallenborn, 2014, 2015)

2.12.4 Re-orienting material culture through design thinking

The importance of complementarity between technology and desired behavioural outcomes has been highlighted in the literature; thus, the use of intentional design is a crucial factor to create a synergy between smart grid technology and behaviour (Geelen et al., 2013). The successful design of the smart grid moves beyond technology and involves the consumer (Goulden et al., 2014). To improve technological acceptance, it is important for consumers to perceive the value and usefulness of the product, through interaction design and increasing intuitiveness of smart grid tools (Kaufmann et al., 2013; Park et al., 2014). Putting the user at the centre of the design process, and focusing on the desired societal change is fundamental to successful smart grid deployment (Accenture, 2013). The design thinking process can deliver insights for the effective creation of smart grid tools.

The implementation of new programs, products, or services to change energy consumption patterns requires effective planning, preparation, and design. Radical innovations are often the result of the utilization and implementation of design strategies (Jones, 2013). The definition of design is sophisticated and holds a broad range of meanings including, "…an aspiration to create, […] a passion to help humankind, […] a strategy to effect change, [… and] the desire to impact the world," (Berger & Mau, 2009, p. 29). Design was generated to solve wicked problems[16] by utilizing knowledge from a multitude of knowledge areas to create radical innovations (R. Buchanan, 1992; Jones, 2013).

Specific design strategies to shape individual behaviour towards sustainable actions have been developed (Tromp, Hekkert, & Verbeek, 2011). In an energy context, designers can use scripting and behavioural steering, forced functionality and eco-feedback to shape energy consumption (Wever, van Kuijk, & Boks, 2008). Certain design strategies used to shape individual behaviours have been provided by Tromp et al. (2011), including:

- Create a perceivable barrier for undesirable behaviour;
- Make unacceptable behaviour overt;
- Make the desired behaviour a necessary activity to achieve the product function;
- Provide the user with arguments for the desired behaviour;
- Suggest actions;
- Trigger difficult motivations for the same behaviour;
- Elicit emotions to trigger action tendencies;
- Activate physiological processes to reduce behaviour;
- Trigger human tendencies for automatic behavioural responses;
- Create optimal conditions for specific behaviour; and,
- Make the desired behaviour the only possible behaviour to perform.

Energy behaviours are not only influenced by user knowledge and competencies, they are also influenced by meanings, appearance, and functionality of end-use technologies. Overall, design thinking implements a user-centred process for effective creation of technologies and products to address wicked problems, such as shaping energy demand towards more sustainable energy practices, which can be further, integrated into social marketing and CBSM strategies.

[16] The term wicked problems refers to issues with many interdependent factors, presenting as impossible to define and to solve. Rittel and Webber (1973) presented the definition of wicked problems alongside the ten characteristics of wicked problems, which are related to policy and planning processes.

2.12.5 Design thinking: an iterative process

The design thinking process includes observing and identifying consumer needs, generating ideas, prototyping and testing products (T. Brown, 2008). Good smart grid design goes beyond the technology and understands how the technology interacts with behaviours and routines (Goulden et al., 2014). Utilizing this process can create essential knowledge and the development of useful products, by establishing *how* the consumer can seamlessly integrate these tools into their lifestyle. Consequently, designers play a critical role between engineers, policymakers and utility providers to generate meaningful interaction and change within the smart grid (Geelen et al., 2013).

Design thinking is a cyclical process that flows from inspiration to ideation to implementation (T. Brown, 2008) through stages of understanding, exploring and materializing (Gibbons, 2016). Through utilizing design thinking, new forms of value are created by integrating empathy, integrative thinking, collaboration and experimentalism into the process of product and consumer design (Berger & Mau, 2009). At the root of design thinking is quick innovation, aimed at learning through failure and user feedback (Berger & Mau, 2009).

2.13 Opportunities for multidisciplinary smart grid research

Throughout this literature review, several themes and opportunities for research have been highlighted, along with their justification, presenting limitations in the existing literature. The following sections summarize these opportunities for future research.

2.13.1 Facilitating social science approaches in smart grid and energy research

The integration of social science can advance energy efficiency research. Social science can provide critical contributions, specifically: to solve complex energy issues requiring more aggressive policies; to address the limitations of economic theory to predict technological acceptance; to address the skepticism of 'technological' fixes for energy problems, and; to focus on the role of behaviour and social dynamics in energy use and opportunities for change (Lutzenhiser, 2014). However, existing energy research in notable energy journals lacks depth in social dimensions. In particular, Sovacool et al. (2015) identify three critical trends from current energy research: minimal studies on social elements; 'disciplinary chauvinism' towards social science methodologies and perspectives; and a lack of diversity of energy researchers. Currently, social science researchers are underrepresented and constitute less than 19.6% of authors for existing energy publications in *Energy Policy, The Energy Journal* and the *Electricity Journal* from 1999-2013; whereas 67% were affiliated with economics, sciences, and energy fields (Sovacool, 2014; Sovacool et al., 2015). Consequently, existing research perspectives are ‘homogenous’ and technical in nature (Sovacool, 2014). Since energy has an influential role in connecting and modifying ecosystems and social systems, the understanding of human-environment relationships and their associated behaviours is an important topic to pursue in social science research (Harper, 2012). In the context of smart grid research, integrating knowledge areas of technical, social engagement, and design studies can provide novel insights on consumption patterns and opportunities to effectively introduce smart grid technologies for sustainable energy transitions (Figure 31).

Incorporating user-centred knowledge for the effective design of interventions can be extended through the utilization of qualitative and mixed-method research (Crosbie & Baker, 2010). Where consumption data analysis can highlight quantitative consumption changes, qualitative data analysis, through interviews and focus groups, can provide knowledge on intervention feedback and energy practices (Hargreaves et al., 2010; Strengers, 2011b). A majority of studies focusing on energy conservation policy solely utilize quantitative methods (Sovacool, 2014). Minimal studies on smart grid research have focused on qualitative insights, identifying opportunities for future research, further highlighting the importance of integrating social and technical research.

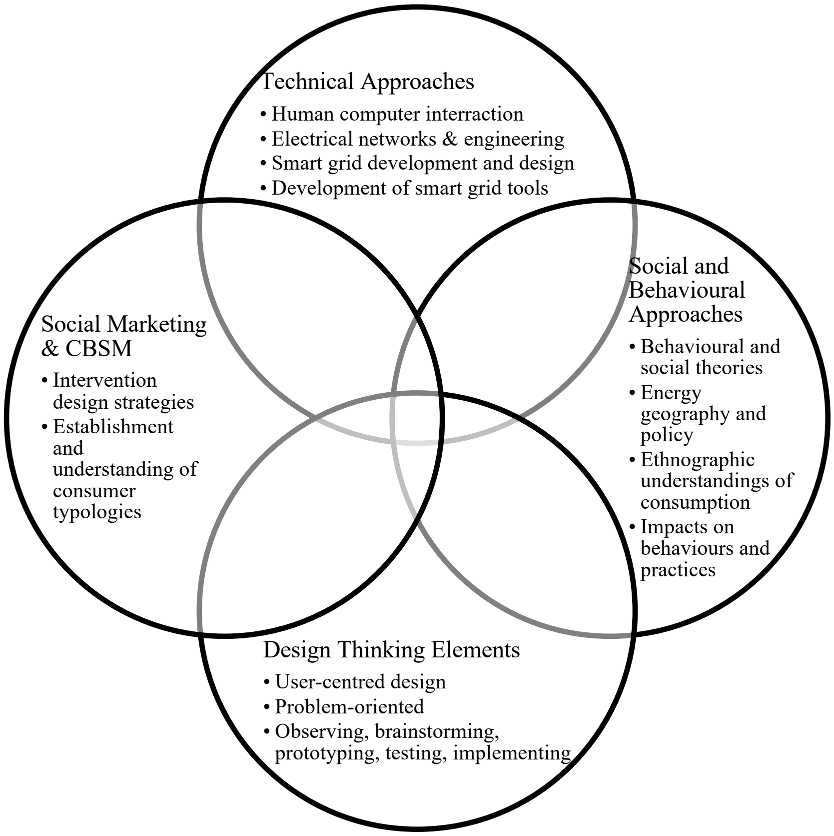

Figure 31 Combination of knowledge areas for studying smart and sustainable energy cultures

2.13.2 Understanding smart grid consumer segments

As previously identified, the classification of smart grid users is essential for the introduction of smart grid technologies, since different user types will respond differently to smart grid technologies (van Dam, Bakker, & van Hal, 2010) and different users have different motivations for using these technologies (Silvast et al., 2018). Moving beyond the 'ideal energy consumer' archetype can aid in the development of effective smart grid tools and user engagement (Gaye & Wallenborn, 2014; Naus et al., 2014; Strengers, 2013). Current smart grid user typologies have attempted to classify consumer segments and bring opportunities to integrate additional socio-technical and demographic data for understanding types of smart grid consumers. In particular, Gaye and Wallenborn's (2015) typology provides a promising foundation for development. The utilization of qualitative interview data and socio-economic factors can generate meaningful developments to smart grid user typologies. The application of load shape profiles and consumption patterns brings additional insights for consumer market segmentation and analysis, with limited applications in the

Ontario smart grid (Frades, 2016; Kwac et al., 2014; Oracle, 2015). Utilizing and advancing these typologies and segmentation techniques to analyze how certain consumers' engage and re-engage in the smart grid also bring value for smart grid policy development.

2.13.3 Utilizing long-term analysis to study occupant behaviour and engagement in the residential smart grid

As identified earlier, several limitations have been identified in assessing the existing literature assessing the impact(s) of interventions on household energy consumption, providing methodological opportunities for future studies. Utilizing long-term temporal analysis methods can identify whether interventions encourage sustained behaviours (Burchell et al., 2016; Hargreaves et al., 2013; Stromback, Dromacque, & Yassin, 2011; van Dam et al., 2010). Limited energy intervention studies analyze long-term impacts, where most studies analyze impacts within six months to one year. Multi-year studies, incorporating engagement and re-engagement can provide insights on household temporal rhythms of energy consumption (Hargreaves et al., 2013); thus long-term studies are essential for future smart grid and energy intervention development.

2.13.4 Applying the energy cultures framework to residential smart grid research

Lastly, these opportunities for future research to integrate multiple social and technical knowledge areas and methods can be incorporated into the ECF in a smart grid context. As previously identified, energy consumption is influenced by a variety of endogenous and exogenous factors, requiring a holistic model for knowledge generation, and understanding of residential energy consumption patterns. Due to its recent development and holistic characteristics, the ECF offers ample opportunities for future multidisciplinary and mixed-method research on factors influencing smart home energy management and the establishment of a sustainable residential energy culture. In particular, this framework can be developed by its application to residential smart grid research.

2.13.5 Investigating integrated approaches to intervention design

As highlighted in the earlier sections, multiple perspectives and approaches are available for intervention design related to sustainability shifts. In particular, the main approaches include social marketing, community based social marketing, social practice theory and design thinking. Each approach highlighted in this literature review presents strong avenues for intervention design, yet they remain within their disciplinary silos. Creating solutions for climate change challenges requires multidisciplinary methods in research and intervention design (Creutzig et al., 2018; Sovacool &

Hess, 2017; Steg et al., 2015; Vlek & Steg, 2007). This multidisciplinary perspective is similarly the case for smart grid interventions and research (Ghiani et al., 2018). Therefore, a substantial opportunity exists to highlight and define prospects for establishing a unique and integrated approach to intervention design that harnesses the strengths of existing disciplinary approaches to comprehensively address the full range of factors influencing the adoption of sustainable practices, such as the complexities identified in the energy literature.

2.14 Conclusion

Opportunities to increase capabilities of energy CDM through smart grid technologies, particularly at the residential scale, have been promoted throughout the literature; however, technology on its own will not transform society into the idealized 'smart utopia.' This transformation requires integration of effective policy development and user-centred design to reorient material culture, reframe norms and aspirations, and shift energy practices towards a smart conservation culture. Additionally, to fully eliminate the 'triad of anonymity' between utilities, consumers, and energy practices in the current electricity system, utilities need to be fully informed of their consumer groups through the construction of user typologies to effectively utilize smart grid interventions (Summerton, 2004). The utilization of mixed-methods research can develop knowledge of household energy decision-making for effective construction of user identities as well as feedback on intervention effectiveness. Furthermore, the investigation of spatiotemporal rhythms of residential consumption can be developed through long-term analysis of intervention impacts. Meaningful insights on the energy consumption landscape, and opportunities for CDM can be gained through the utilization of a holistic integration of social and technical research. In particular, knowledge areas of energy geography, energy policy and governance, socio-technical transitions and diffusions, behaviour theories, as well as consumer engagement and design aid in understanding the relationships between scale, sustainability, and governance of the energy consumption landscape. This literature review, and related research opportunities set the foundation for the dissertation research encompassed in the following chapters.

3. Chapter 3 – Methodology

The following sections provide an outline of the methodology used in this dissertation research. As previously articulated, this dissertation includes four manuscripts. These four manuscripts involve two Ontario residential smart grid case studies, as well as a conceptual review. Due to the early and advanced progress of smart metering infrastructure in Ontario, residential smart grid projects became prominent at different scales; thereby, an opportunity was presented to assess long-term engagement and re-engagement within a small-scale residential smart grid case study (Chapters 4 and 5) alongside a large-scale implementation of residential IHDs (Chapter 6) in Ontario. Additionally, the methods applied in each respective manuscript, as identified in this chapter, applied both qualitative and quantitative approaches for understanding consumer engagement and the impact of smart grid technologies on residential energy cultures. Therefore, this research extends beyond a postpositivist approach to identify energy management changes that took place in conjunction with residential smart grid technologies, and to understand underlying and contributing factors to these changes. Within this chapter, Section 3.1 outlines the methods for the EHMS case study (Chapters 4 & 5), Section 3.2 delivers methods for the IHD case study (Chapter 6), and Section 3.3 specifies the methods for the engagement model paper (Chapter 7).

3.1 EHMS case study methodology

The first case study included in this dissertation is the multi-year Energy Hub Management System Project (EHMS). Specifically, two separate manuscripts deliver the research for this case study as part of this dissertation (Chapters 4 and 5). Throughout the project, both whole-house and appliance-level data were collected. Additionally, two phases of participant interviews and initial surveys were conducted. As discussed in detail within the following sections, several behavioural mechanisms were also introduced throughout the study. Within Chapters 4 and 5, a combination of qualitative interview data and quantitative consumption data were used to assess changes in residential energy culture throughout the project. Overall, this research aims to gain further understanding on the long-term engagement and re-engagement in the residential smart grid and to develop a holistic understanding of household decision-making, energy management practices and related influencing factors. By utilizing a combination of both qualitative and quantitative data, Chapters 4 and 5 deliver a thorough analysis of participants' residential energy cultures for a comprehensive understanding of household energy management, the role of smart grid engagement mechanisms, and underlying factors influencing household energy management and energy culture change(s). The following sections outline the details of the EHMS project followed by the specific research objectives and methodologies utilized for Chapters 4 and 5 respectively, followed by an overview of the related and overarching details for the EHMS case study.

3.1.1 Chapter 4: Research objectives and methodology overview

The research objectives in Chapter 4 entitled '***Towards a smart and sustainable residential energy culture: assessing participant feedback from a long-term smart grid pilot project***' are twofold: (1) to identify whether the project influenced participants' energy culture; and, (2) to highlight what factors influenced the adoption of a smart energy management culture within the participating households. These two aims are met by a qualitative methodology to assess the changes in participants' energy cultures throughout the study. The study delivers the first aim by assessing the changes in attitudes and awareness towards energy management as well as changes in practices and material culture throughout the project. The study delivers the second aim by examining the major motivations and barriers influencing participants' energy management.

The research presented in Chapter 4 utilizes qualitative insights from the first round of interviews, as articulated within the following sections, to fulfill the research objectives. Specifically, to summarize the research methodologies applied, Chapter 4 utilizes the insights from Interview 1 and the Welcome Survey to understand and articulate changes in households' energy culture as a result of EHMS project participation, as articulated in Section 3.1.9.1. Following, Chapter 4 utilizes qualitative data from Interview 1 to provide feedback on the interventions utilized throughout the project. The methods applied in Chapter 4, assess the qualitative data from Interview 1 to identify barriers and motivations surrounding household energy management within the participating households. Lastly, the methods applied in Chapter 4 categorize households based on Gaye and Wallenborn's (2015) smart grid user typology by utilizing the insights on energy management motivations identified during Interview 1 and the Welcome Survey, as articulated in Section 3.1.9.3.

3.1.2 Chapter 5: Research objectives and methodology overview

The manuscript in Chapter 5 entitled ***'Re-engagement in a long-term smart grid study: Influences on household energy management practices'*** provides a mixed-methods approach to assess the changes in energy culture within participants in the EHMS study. Specifically, this chapter utilizes both qualitative and quantitative data to achieve the three research objectives: (1) to determine whether the introduction of the weekly electricity report feedback and mobile tablet feedback resulted in changes in energy management practices, in both conservation and peak shifting; (2) to identify the particular energy practices contributing to those shifts, and; (3) to highlight the contributing factors and participant insights on re-engagement and 'smart' energy management practices.

The research presented in Chapter 5 utilizes consumption data at whole-house and appliance-levels, as well as qualitative insights from both sets of interviews, to fulfill the research objectives. The research methodologies applied in Chapter 5 utilize whole-house and appliance-level consumption to assess changes in consumption during the re-engagement of households through both the weekly electricity report and the tablet introduction, as articulated in Section 3.1.7.3. Additionally, methods are applied to analyze insights from participant interviews to develop a thorough understanding of user experience with the re-engagement mechanisms, as articulated in Section 3.1.9. Chapter 5 methods assess participant engagement with the tablet by utilizing Google Analytics Data for mobile web portal engagement, as articulated in Section 3.1.8. Lastly, the research conducted for Chapter 5 compares changes in consumption and levels of On-Peak share for whole-house and laundry practices to perceived levels of energy management identified in Interview 2, as articulated in Section 3.1.9.4.

The following sections provide EHMS project details and summarize the data collection methodology utilized for this dissertation research. Additionally, the following sections provide an overview of the analysis utilized for the research articulated in Chapters 4 and 5. The respective research manuscripts deliver additional details on the specific research methodologies applied (Chapters 4 and 5).

3.1.3 EHMS Recruitment and participant selection

The EHMS project was an opt-in residential smart grid program that took place between 2010 and 2016 in Milton, Ontario. Participants for the EHMS project were recruited through email by the utility company, Milton Hydro. Households who had previously been interested in the project were sent an invitation. Twenty-eight households accepted the invitation. From the twenty-eight households, twenty-five households were selected based on: (1) their acceptance of control features, and (2) their household type, to provide variety in the program. As a result, twenty-five households in Milton, Ontario were involved in this opt-in program. Project participants were provided with technologies to monitor and control electricity consumption data at the circuit level. Participants received a smart panel or Brultech technology to collect circuit-level consumption information. This technology provided circuit-level feedback and monitoring as well as control, scheduling, and optimization features (Aydinalp Koksal et al., 2015).

3.1.4 Sample size and study length

Throughout the project, the participating households fluctuated. Several reasons account for this, including participants leaving the project, technological issues, or late entry into the program. Although 25 participants initially enrolled in the program, several households withdrew from the program and were not considered for this analysis. There were data collection issues in a few households. After four years of participation, approximately half of the households were still active and willing to be involved in interviews and re-engagement. Therefore, 15 of the original households were included for Interview 1, 12 of the original households were included for Interview 2, and 14 of the original households were re-engaged with both a tablet and an electricity report and available for quantitative analysis (Table 9). These households are further identified in Tables 10 and 11.

Table 9 Details and procedure for participant feedback

Element	Method	n	Timeframe	Analysis
Initial project recruitment	Email and participant opt-in	25 joined program	Project start	n/a
Initial survey	On-line web survey	12	Project start	Quantitative coding of responses
Interview 1	In-person semi-structured interviews (active participants); Phone interviews (inactive participant)	15	Autumn Year 3	Qualitative coding of transcribed interviews using NVivo Quantitative comparison between responses from the interview and initial survey
Interview 2	Phone interviews	12	Autumn Year 4	Qualitative coding of transcribed interviews using NVivo Quantitative comparison between responses from interview 1, interview 2, and the initial survey

3.1.5 Participant profiles

The participating households in the EHMS study had specific built environment and household profile characteristics (Table 10 and Table 11). These contextual factors are important to consider when investigating household energy cultures (M. G. Scott et al., 2016; Stephenson, Barton, et al., 2015; Stephenson et al., 2010). For the built environment, participating households be classified as 'new suburban build' where the majority of households were detached two-storey homes and built after 2000. The majority of households in the study were 1500–2999 ft^2. In terms of household socio-economic profiles, households had income levels between CAD 80,000 - 150,000 + before taxes and achieved post-secondary education levels (Bachelor's degree or higher). Household sizes were on average four people. These participant attributes align with the census population data for Milton, Ontario (Lazowski et al., 2018; Statistics Canada, 2017).

Table 10 Dwelling profiles of EHMS participants[17]

Hub	Dwelling Size (Square Feet)	Year Built	Style of Dwelling
1	2000-2499	1970-1979	Detached two or more storey
2	1500-1999	1970-1979	Detached two or more storey
4	2000-2499	2000-2006	Semi-detached two or more storey
5	1500-1999	1970-1979	Detached two or more storey
6*	2500-2999	2007-2010	Detached two or more storey
7	3000-3499	2000-2006	Detached two or more storey
9	1500-1999	2000-2006	Detached one storey
10	1500-1999	2000-2006	Detached two or more storey
12*	2000 - 2499	2000 - 2006	Detached two or more storey
16	1000-1499	2000-2006	Row housing (attached on both sides)
17	1500-1999	2000-2006	Semi-detached two or more storey
18**	3000-3499	2000-2006	Detached two or more storey
21	2500-2999	2000-2006	Detached two or more storey
22	2500-2999	2007-2010	Detached two or more storey
23	2500-2999	2007-2010	Detached two or more storey
24	2500-2999	2007-2010	Detached two or more storey

Note: * households only included in Chapter 4, ** household only included in Chapter 5. The remainder of households are in both Chapters 4 and 5.

[17] Profile of the household at the beginning of the project.

Table 11 Socio-economic profiles of EHMS participants[18]

Hub	Age (Years)					Total # of Occupants	Household Income (Before Taxes)	Highest Certificate/ Diploma/ Degree in Household
	0-5	6-13	14-17	18-64	65+			
1	0	0	0	2	0	2	$150,000 and over	Bachelor’s Degree
2	0	0	0	3	0	3	$150,000 and over	Bachelor's Degree
4	2	2	0	2	0	6	$80,000- $89,999	Bachelor's Degree
5	2	0	0	2	0	4	$125,000- $149,999	Bachelor's Degree
6*	1	0	0	2	0	0	$150,000 and over	Bachelor's Degree
7	1	0	0	2	0	3	$150,000 and over	University Certificate or Diploma below Bachelor Level
9	0	2	1	2	0	5	$90,000- $99,999	University Certificate or Diploma below Bachelor Level
10	0	1	1	3	0	5	$60,000- $69,999	Bachelor's Degree
12*	1	1	0	2	0	4	$150,000 and over	Degree in medicine, dentistry, veterinary medicine, or optometry
16	1	1	0	2	0	4	$90,000- $99, 999	Bachelor’s Degree
17	1	1	0	2	0	4	$90,000- $99, 999	Bachelor's Degree
18**	0	2	0	2	0	4	$100,000- $124, 999	Bachelor's Degree
21	2	0	0	2	0	4	$125,000- $149,000	University Certificate or Diploma below Bachelor Level
22	1	0	0	2	0	3	$90,000- $99,999	Bachelor's Degree
23	2	0	0	2	0	4	$150,000 and over	Master's Degree
24	1	2	0	5	0	8	$150,000 and over	Bachelor's Degree

Note: * households only included in Chapter 4, ** household only included in Chapter 5. The remainder of households are in both Chapters 4 and 5.

3.1.6 Electricity consumption data collection

Consumption data were collected for both whole-house and appliance-level consumption to assess the changes in consumption during the study period. The local utility collected whole-house level consumption data was collected via smart meter. Appliance-level data were also collected

[18] Profile for the household at the beginning of the project.

through either a smart panel (Figure 32) or an alternative design with an intermediate technology, depending on their household profile (Figure 33).

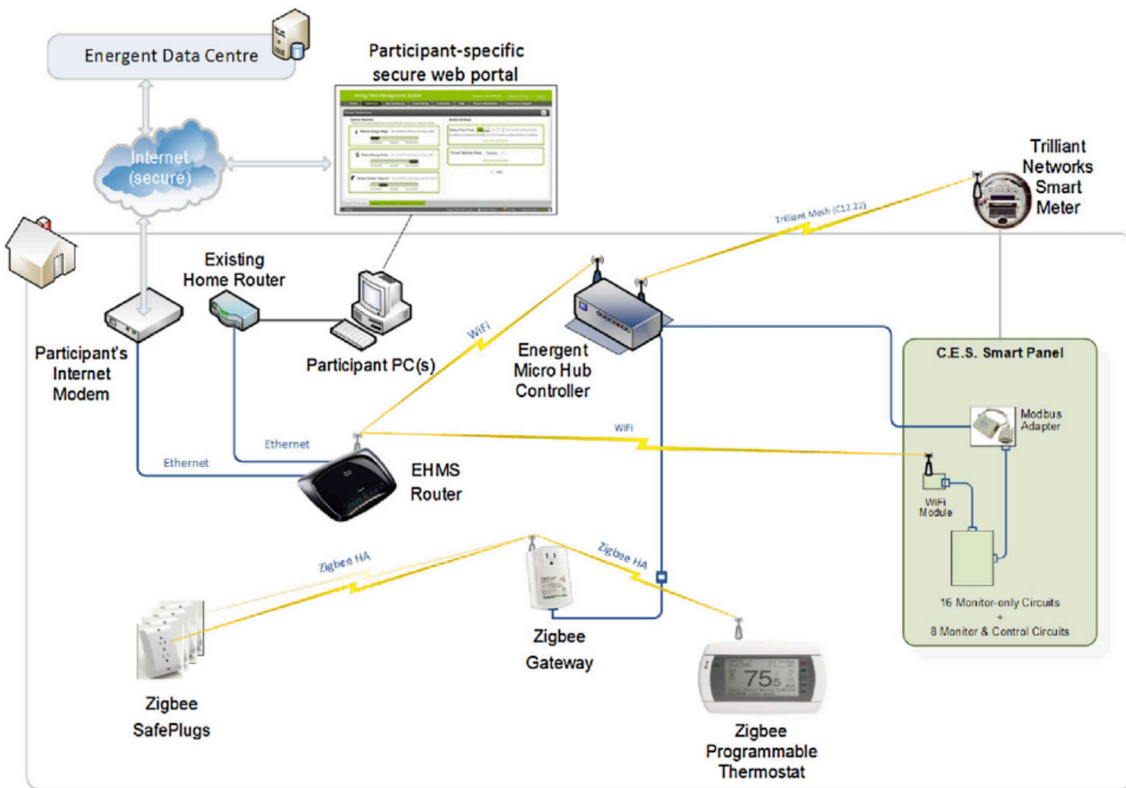

Figure 32 System design for households with existing electrical panel replaced with a smart panel, source: (Kantor, Rowlands, & Parker, 2017)

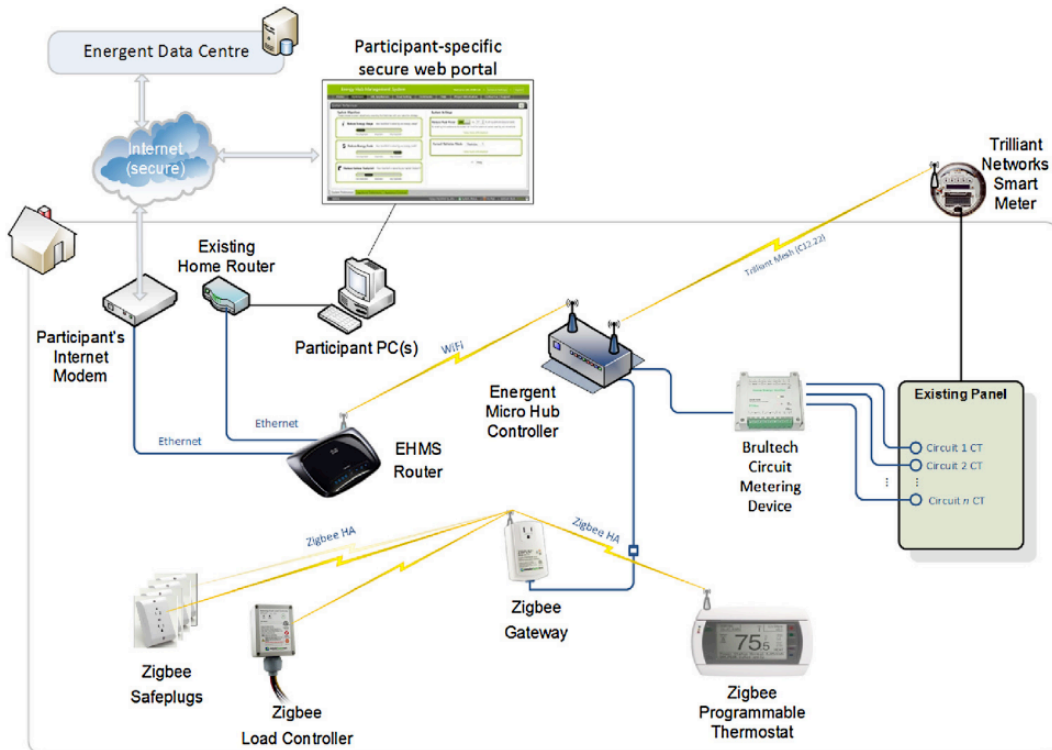

Figure 33 System design for the alternative design with the existing electrical panel and an intermediate metering device, source: (Kantor et al., 2017)

The project partner, Energent, collected appliance data at five-minute intervals. The consumption data were available beginning from the participants' project entry until their specific project exit date. For this dissertation research, the consumption data were aggregated at one-hour intervals for analysis over particular study periods. The data availability was subject to the installation of technology, the appliance profile of each household, and the participants' project start and closure dates. Particular appliance-level data were collected from the Energent Database to assess appliance-level consumption patterns. Specifically, the main discretionary loads include: the air conditioner, laundry (washer and drier), dishwasher, cooking (stove and oven) as well as entertainment devices (e.g., Television, gaming consoles, satellite box, etc.,). This appliance-level data collection facilitated the assessment of discretionary (appliance-level) loads, as well as energy practices of cooling comfort, laundry, dishwashing, cooking, and entertainment.

3.1.7 Project elements: Engagement mechanisms and participant involvement

Throughout the study, a series of project engagement mechanisms, initiated by the EHMS project, were provided to the participants with various purposes. Table 12 identifies the engagement mechanisms that focused on shifting consumer behaviour and the mechanisms discussed in Chapter 4 and Chapter 5. Specifically, Chapter 4 focuses on the goal setting, web portal, reminder emails, webinar, incentivized control, and weekly electricity report mechanisms. Chapter 5 focuses on the weekly electricity report and tablet engagement mechanisms.

Table 12 Description of the project-led behavioral engagement mechanisms

Item	Description	Classification	Frequency	Timeframe
Goal setting	Self-set goal for consumption reduction monitored on web portal.	Goal setting	Ongoing	December 2011-project end
Web portal	Web-based portal providing access to whole-house and appliance-level consumption feedback. Access to settings for scheduling, goal setting and control also included.	Feedback, monitoring, and control	Ongoing	November 2011 - April 2012
Reminder emails	Bi-monthly emails sent to remind participants to log in to the web portal.	Reminder	Bi-Monthly	January 2012-August 2013
Webinar	A webinar to introduce the control feature and other elements of the web portal.	Education	Once	March 2013
Incentivized control program	Households were invited to use the air conditioner 'control' function in return for C$100 for each week’s participation for two weeks during July and August 2013.	Control	Twice	July & August 2013
Weekly electricity report	A weekly email sent to participants indicating their total, On-Peak, and appliance-specific consumption. It compared their consumption to other households in the project as well as to the previous year. Conservation tips were provided.	Feedback	Weekly	June-December 2014
Tablet[19]	Mobile version of the web portal providing access to whole-house and appliance-level consumption feedback. Access to settings for scheduling, goal setting and control also included. Provided in the form of a tablet (free of charge to participants) as well as a mobile web application.	Feedback, monitoring, and control	Ongoing	Delivered September - November 2014. Access available until project end

[19] The tablet is not included in Chapter 4 analysis.

3.1.7.1 Weekly electricity reports

The report provided consumption feedback to active, and available participants on the Friday of each week during the re-engagement period. The weekly report (Figure 34) was designed by Huber (2016) utilizing seven main key elements as developed by a thorough literature review (Table 13). The respective research chapter (Chapter 5) articulates additional design details.

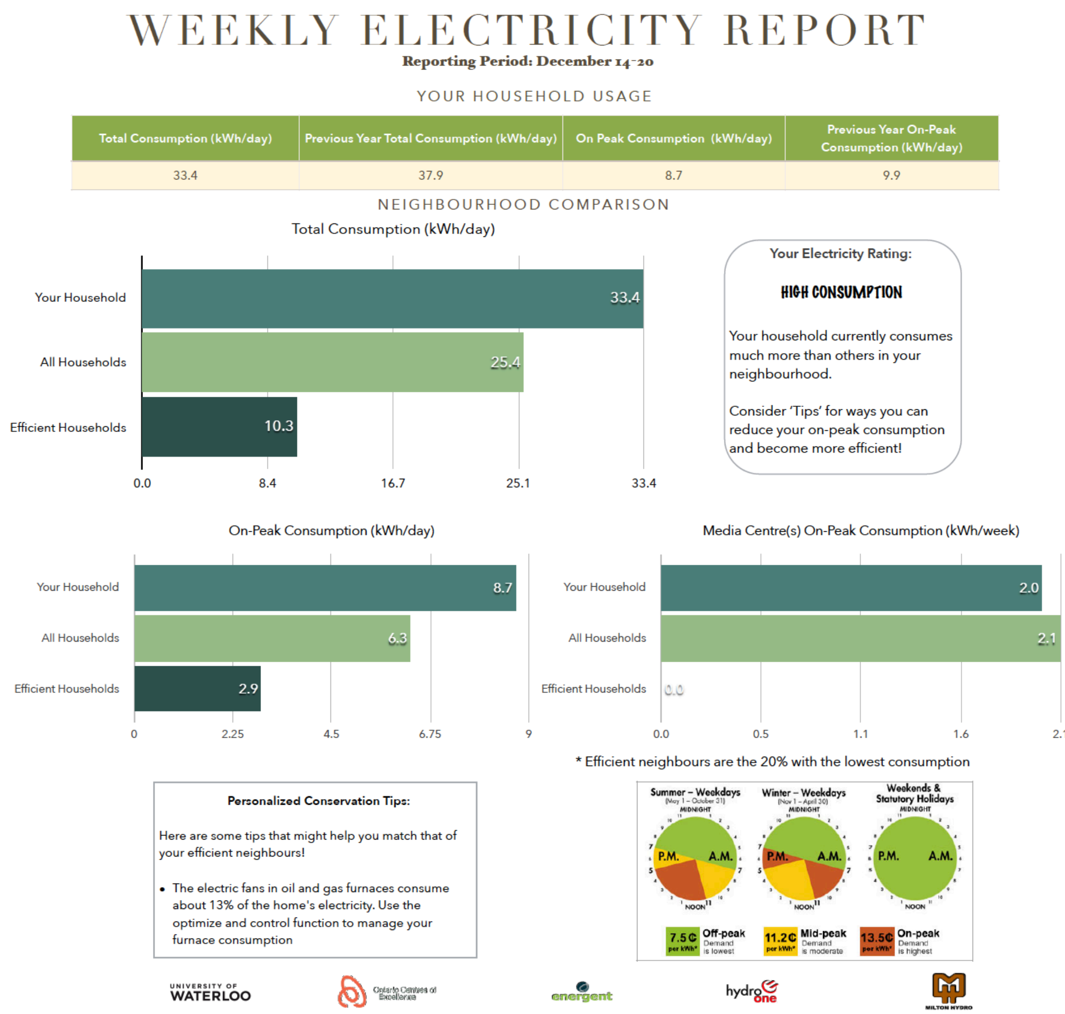

Figure 34 Weekly electricity report overview

Table 13 Overview of report elements in comparison to key design elements

Seven elements identified by Huber (2016)	EHMS electricity report element
1. Normative and/or historic comparison	Normative feedback provided: Compared to participant group average, as well as all households and efficient households Historic comparison provided: Compared previous year daily consumption for total and On-Peak consumption (kWh/day)
2. Consequent and direct	Provided direct consumption to consumers with the total amounts
3. Tailored and (appliance) specific	Provided personalized conservation tips Provided feedback for a particular circuit and appliance each week
4. Multiple measures of consumption	Provided daily consumption (kWh/day) for total and On-Peak consumption
5. Persistent and consistent	Provided at 4:00 PM each Friday
6. Reinforcement	Provided personalized conservation tips
7. Clarity and attractiveness	Font size, colours used, and variety of fonts utilized to emphasize particular points

The report was provided to participants each week; however, it was only provided to specific participants due to technical limitations. As a result of specific technical issues[20] related to the connectivity of the smart meter, data for some households were unable to be collected for weekly participant feedback. Seven households were provided with the newsletter during the summer weeks (June – August), and an additional seven households (fourteen in total) were provided with the report during the autumn months (September – December).

3.1.7.2 Tablet

The tablet was provided to 14 active participants beginning in the autumn of 2014 and delivered from September to November. The central tablet elements align with Karlin et al.'s (2013) typology classification of a sensor display and closed management network. These tablet elements include a dashboard home page, Time-of-Use (TOU) clock, appliance usage (both individual & multi-appliance), goal-setting, control settings, and optimization settings. The tablet provided a mobile

[20] These technical issues were a result of connectivity issues, where communication between the household and the datahub were disconnected for certain reasons (e.g., WIFI connectivity, smart plug issue, or smart panel issue). Therefore, causing disconnections between specific household and the project hub at certain timeframes.

version of the web portal, which allowed for equal access to the mobile web application to all active participants. The respective research chapter delivers additional tablet design details (Chapter 5).

3.1.7.3 Consumption data analysis: Re-engagement

Consumption at both whole-house and appliance-level were assessed for changes, in conservation and Peak shifting. This procedure assessed whether re-engagement with an electricity report and a tablet influenced household energy consumption. Fourteen households were involved with this analysis. To compare the overall consumption of the participants over the study period the average hourly consumption per month (kWh) was collected for each participant group total and TOU period consumption at whole-house and appliance levels. Monitoring and baseline data were collected, where the baseline data were collected for the same period of the monitoring year, for the year before re-engagement. Since households were provided with the report and the tablet during different timeframes, as a result of technological disruptions, a seasonal analysis was performed over two study periods. The first period studied the introduction of the newsletter for a 12-week period during the summer months (June – August) (n = 7). The second period studied the newsletter and the tablet introduction over a 10-week period during the autumn months (September – December) (n = 14). Consumption data for both the baseline and monitoring periods were aggregated to the weekly level, to reduce fluctuations at household levels. Average weekly consumption was assessed between the baseline and monitoring year periods (Table 14).

Average weekly consumption data per household were analyzed to determine whether the reductions after the re-engagement introduction were statistically significant. Paired tests were completed to evaluate the average consumption levels before and after the study period. This test determined whether the consumption levels in total and TOU consumption (aggregate & disaggregate levels) were equal and if the differences were statistically significant. This procedure tested the following hypothesis, where *L is* the particular energy load:

$$H_0\text{: Weekly Mean Consumption}_{\text{Monitoring}L} = \text{Weekly Mean Consumption}_{\text{Baseline}L}$$

Household weekly consumption data were assessed for normality and outliers. The Shapiro Wilks test of normality was utilized. Households that did not pass the Shapiro Wilks test of normality ($p<0.05$) were assessed using non-parametric methods, specifically the related samples Wilcoxon Signed-Rank Tests, to test the null hypothesis. In these cases, the Wilcoxon Signed-Rank Tests resulted in the same outcomes as well as the paired samples t-tests; therefore, the parametric paired samples t-tests were used for comparing the means in consumption. Paired samples t-tests were utilized for the households to test the hypothesis mentioned above.

Table 14 Summary of consumption analysis periods

Engagement	Base period	Monitoring period	Households
Electricity report introduction in summer	12 weeks summer year 2 (June – September 2013)	12 weeks summer year 3 (June – September 2014)	n = 7 (1, 3, 4, 6, 11, 13, 14)[21]
Electricity report and tablet introduction in autumn	10 weeks – autumn year 2 (September – December 2013)	10 weeks – autumn year 3 (September – December 2014)	n = 14 All households

3.1.8 Studying engagement: Google Analytics

Google Analytics data were used to assess the engagement of consumers with the mobile web application. This service provided information about consumer engagement with the mobile web application accessed by the tablet, as well as other devices. From the period of January 1, 2015, to study closure Google Analytics data analysis services directly measured: user interaction, in general and per page visit; length of user interaction, in general and per page visit; and access location and device used. The analytics data were collected through the online Google Analytics platform. These data were utilized to assess user engagement with the tablet and mobile web portal.

3.1.9 Qualitative data collection and analysis

To collect the interview data for the EHMS qualitative analysis, two rounds of interviews took place. The following sections outline the methods for data collection and analysis.

3.1.9.1 Interview 1: Procedure and analysis

In-person and phone interviews were conducted to collect participant feedback. These interviews measured the perception of the effectiveness of the study interventions and other elements of the study using both open-ended and standardized survey questions. The interviews assessed households' awareness, attitudes, and actions towards energy management as well as intervention effectiveness. The interviews mostly consisted of close-ended survey questions, including Likert scales (Appendix A).

[21] These household numbers provided are anonymized participant ID numbers.

Interviews took place from September 2014 to November 2014, inclusive. Interviews were approximately 1 hour and took place in person with active participants and over the phone with inactive participants. The University of Waterloo's Office of Research Ethics approved the interview questions and participant contact procedures. Interviews were recorded and transcribed with permission from the participants. Following transcription, participants approved the transcribed interviews for analysis. Interview questions were both structured and open-ended. Structured questions reflected the questions asked at the beginning of the program through welcome and consent surveys for comparison of responses at both stages of the study. Likert scales were used to assess the following elements:

- Levels of motivations and barriers related to household energy management (Scale of 1 – 7, strongly disagree to strongly agree);
- Participants' perception of their consumption in comparison to others in their neighborhood, before and after the study (scale of 1 – 5, very low to very high);
- Preference of communication types (scale of 1 – 5, not very preferable to very preferable);
- Intervention effectiveness (scale of 1 – 5, not effective to very effective);
- Level of energy management awareness, attitudes, and action statements (scale of 1 – 7, strongly disagree to strongly agree); and
- Level of energy management awareness, attitudes, and action statements before and after the study (scale of 1 – 5, low/none to high).

Qualitative data collected from transcribed interviews were analyzed using NVivo software. The interviews were coded based on the main elements related to changes in energy cultures in the home, including: contextual factors related to household energy management; changes in material culture; changes in norms (attitudes and awareness of energy management within the home), and; changes in energy practices (actions towards energy management within the home). Additionally, codes were used to identify the primary motivations and barriers related to energy management provided within the description of responses, as well as study engagement mechanism feedback.

The standardized responses collected through the Likert scales were assessed quantitatively using SPSS and Excel software. Likert scales were utilized to assess: the level of effectiveness of intervention mechanisms, level of energy culture elements (practices and norms), and levels of household energy management. Total responses were calculated for the Likert scales and survey responses. Questions that remained the same as those used within previous surveys (attitude, awareness, action statements; and motivation and barriers) were compared using a percentage change formula, where R_1 is the initial rating from the welcome survey, and R_2 is the rating provided in the interview:

$$\textit{Percentage change in statement rating} = \frac{R_2 - R_1}{R_1}$$

3.1.9.2 Interview 2: Procedure and analysis

A second phase of interviews was conducted with participants at the end of the study, and approximately one year following the tablet introduction. These follow-up interviews measured the study's influence on self-reported energy consumption levels and obtained feedback on the tablet, mobile web application and EHMS study (Appendix B). The second phase of interviews took place with participants over the phone with twelve participants who received a tablet and were willing to participate. The University of Waterloo's Office of Research Ethics approved the interviews and respective procedure. The interviews were approximately 1 hour. Interview questions were both structured questions (e.g., Likert scales, rating and select the response) and open-ended questions. Questions asked during the interviews were framed around gaining information on motivations and goals surrounding energy management, changes over the course of the program (in household profile, built environment and energy management), feedback on and experience with the tablet, financial motivations for shifting discretionary appliance usage to Off-Peak periods, and levels of actions, awareness and attitudes towards energy management. Likert scales were utilized to assess the following elements:

- Tablet effectiveness for household energy management (scale of 1-5, not very effective to very effective);
- Level of awareness, attitudes, and actions towards household energy management (scale of 1-5, low to high);
- Level of On-Peak energy price increase to switch discretionary load appliance usage to Off-Peak (2x Off-Peak or 15¢/kWh; 3x Off-Peak or 22.5¢/kWh; 4x Off-Peak or 30¢/kWh; 5x Off-Peak or 37.5¢/kWh; 6x Off-Peak or 45¢/kWh);[22] and

[22] At the time of the interviews, Off-Peak price was 7.5¢/kWh, and On-Peak price was 13.5¢/kWh.

- Level of willingness to use control features to manage appliance and heating/cooling consumption (scale of 1-5, not very willing to very willing).

Similar to the first interviews, the outcome of the second interviews involved both qualitative data (open-ended questions) and quantitative data (Likert scales). Qualitative data collected through the transcribed interviews were analyzed using NVivo software. One researcher transcribed the interviews and coded the transcriptions through NVivo to analyze main findings. The results of the analysis measured the influence of the study's smart grid technologies on participants' energy practices and delivered participants' feedback on the tablet.

3.1.9.3 Categorizing participants using a smart grid typology

Understanding types of consumers can be useful for deriving findings; therefore, households participating in the first interview were categorized by a smart grid consumer typology (Summerton, 2004). Although the energy cultures framework had previously been used to understand household segments by Lawson et al. (2012), their specific typology did not include smart grid considerations. Therefore, a typology to complement the smart grid technological aspect of this study, as well as the energy cultures framing, was identified. Gaye and Wallenborn's (2015) typology of smart grid users for home energy management, applied to these participants, delivered a detailed understanding of the 15 households in the first interview (Figure 35). This typology captures elements related to the energy cultures framework and also aligned with Ontario factors of energy consumption related to the smart grid, including thermal flexibility, electricity management, environmental motivations, and technological preferences.

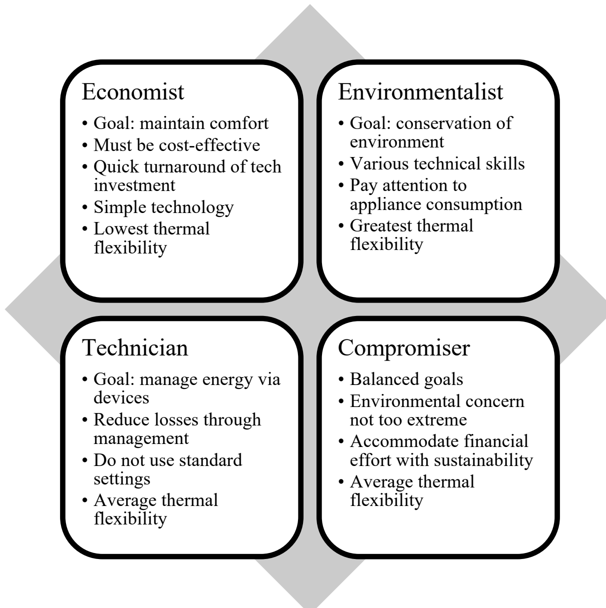

Figure 35 Typology of smart grid users, source: (Gaye & Wallenborn, 2014, 2015)

An assessment of participants' motivations and barriers to energy management was used to categorize the participating households (Chapter 4). This aligned with Gaye and Wallenborn's (2015) typology, which associates the energy management goals and barriers, as well as particular household preferences to typology segments. The four categories of Gaye and Wallenborn's (2015) typology were then applied (economist, environmentalist, technicians, compromiser). The three factors utilized were from Interview 1, specifically outlined in the following questions:

- The ranking of motivation statements for energy management (Question 1 of Interview 1)[23]
- The responses for an open-ended question regarding the main barriers for shifting energy consumption during the EHMS study (Question 21 of Interview 1)[24]
- The responses for an open-ended question regarding the primary motivations for shifting energy consumption during the EHMS study (Question 22 of Interview 1)[25]

As identified in Table 15, 8 participants were classified as 'economists' and 7 were categorized as 'compromisers.' For the 8 households categorized as economists, participants

[23] Question 1 from Interview 1: What are your current motivations for energy management decisions in your home? What are your current motivations for participating in the EHMS project? Please rate your motivations from 1 – 7. For a detailed list of the statements provided see Appendix A.
[24] Question 21 from Interview 1: Are there barriers that prevented you from shifting your energy consumption during the EHMS project?
[25] Question 22 from Interview 1: What motivated you to shift your energy consumption during the EHMS project?

expressed saving money as their main motivation for management. Additionally, maintaining lifestyle and comfort, having low thermal flexibility, and not willing to sacrifice household comfort and convenience to benefit the environment were factors influencing these participants' energy management. The 7 households categorized as 'compromisers' saw technology as an important aspect of increasing their awareness to reduce consumption, while also being motivated by economic and environmental concerns for energy management. Since no participants expressed environmental protection as their sole or primary motivation for energy management, there were no 'environmentalists.'

Table 15 Household typology categorization

Household	Typology
1	Economist
2	Economist
4	Economist
5	Compromiser
6	Economist
7	Compromiser
9	Economist
10	Compromiser
12	Economist
16	Compromiser
17	Compromiser
21	Compromiser
22	Compromiser
23	Economist
24	Compromiser

3.1.9.4 Comparing interviews and consumption data

This study also determined whether participants' perceived level of energy management correlated to consumption levels (Chapter 5). To perform this analysis consumption data following the re-engagement monitoring period were compared to study insights gathered from the second interview (n=12). Only the twelve interview participants were utilized this analysis. The Spearman's rank-order correlation assessed the relationship between household energy consumption and rankings given by interviewed households on energy management action and awareness. Average weekly consumption for the 10-week autumn period was used to compare whole-house and laundry-level consumption with participants' ratings. This procedure tested the following hypothesis:

H_0: $\rho = 0$, the correlation coefficient is equal to zero in the population; there is no association between the variables.

3.1.10 EHMS Case study: Limitations and boundaries

Although the EHMS case study presented in the dissertation (Chapters 4 and 5) allows for a thorough assessment of both qualitative and quantitative data, associated limitations and boundaries need to be acknowledged. Firstly, the limited sample size for the overall study (n=25) resulted in small samples for analysis, specifically for Interview 1 (n=15), for Interview 2 (n=12), and for the cleaned consumption data (n=14); thus, the results are unable to be applied to the general population. However, future research and program development can apply these case study results and insights at larger scales, especially considering the value small sample sizes provide for mapping future research (Hargreaves et al., 2013). Secondly, this is a convenience sample. Although the participants were volunteers, they consist of Milton Hydro customers that already expressed an interest in participating in a smart grid study. Therefore, these participants are not representative of a typical residential consumer. These participants might be more willing to participate in this study due to their interest in smart grid technology and home energy conservation. Thirdly, this sample only consists of participants from Milton, Ontario, presenting additional external validity constraints for applying the results to other regions. Lastly, technical issues[26] resulted in limited data availability for particular households, at whole-house and appliance-levels. These data constraints also influenced household participation in re-engagement feedback with the electricity report. This methodology chapter, as well as the respective research chapters (Chapters 4 and 5), fully articulate these data constraints and respective sample sizes.

[26] As identified previously, these technical issues were a result of connectivity issues, where communication between the household and the datahub was disconnected for certain reasons (e.g., firmware updates, WIFI connectivity, smart plug issue, or smart panel issue). Therefore, causing disconnections between specific household and the project hub at certain timeframes.

Multiple factors in technological studies can contribute to small sample sizes. Common causes in smart grid pilot research involve the substantial costs and the installation procedures for these technologies (Bager & Mundaca, 2017; Bradley, Coke, & Leach, 2016; Hansen & Hauge, 2017). Consequently, studies with similar sample sizes outside of Canada are apparent in peer-reviewed literature (Bager & Mundaca, 2017; Bradley et al., 2016; Hansen & Hauge, 2017). Despite this limitation, the use of both qualitative and quantitative participant data within this multi-year study provides a thorough understanding of household decision-making and feedback on long-term residential smart grid engagement mechanisms. As a result, the results within Chapters 4 and 5 provide valuable insights for residential smart grid research that can be extended with larger samples. Furthermore, studies with small sample sizes can make considerable contributions to the literature as outlined by Hargreaves (2013), by informing policy and decision-making by catalyzing new areas for discussion and illuminating new system dynamics and by offering lessons for subsequent investigations with larger, and thus more representative samples. Therefore, despite these limitations, the outcomes of the research presented in Chapters 4 and 5 provide valuable insights for developing smart grid research and can be tested in larger audiences.

3.2 Methodology for IHD case study

The second case study included in this dissertation is the in-home display (IHD) case study. Specifically, this case study involves one manuscript (Chapter 6), entitled '***Who's responding anyway? Assessing segment-specific responses to real-time energy displays'*** This section presents an overview of the second case study utilized in this dissertation and the related methodologies applied. This second case study incorporates an analysis of IHDs on residential energy consumption within participating homes in central Ontario (n=5274) compared to a control group (n=3020). Specifically, this case study applies a quantitative approach to study responses to the IHD feedback within the general population as well as participant segments.

3.2.1 Research objectives

The IHD case study and respective manuscript (Chapter 6) applied three research objectives: (1) to examine whether the IHD influenced the consumption of the general population of the participating households; (2) to assess whether different consumer cohorts responded differently to real-time feedback provided through the IHD, and; (3) to determine whether segmentation of households illustrates smart grid policy insights for consumer engagement. An analysis of household consumption data was completed to fulfill these objectives. The following sections provide a brief overview of the procedure for collecting, cleaning, and analyzing the data. The respective manuscript (Chapter 6) provides the full details for the analysis methodology (Chapter 6).

3.2.2 Recruitment, participant selection and data collection

The households incorporated in the participant cohort of this study had particular characteristics. Three characteristics determined the participant group: first, households had smart meters already installed; second, households had electric water heaters; and third, households had opted-in to the PeakSaver Plus program. In Ontario's PeakSaver Plus program during critical periods on summer days (May 1 to September 30), participating households were alerted to the surge in demand and their thermostat, electric water heater, or pool pump is adjusted for a maximum of four hours during the periods of 12:00 PM to 7:00 PM, Monday to Friday. As a result of opting-in to the PeakSaver Plus program, participants were provided with an IHD. This study utilized households that had fulfilled these requirements (n=5274), alongside a randomly selected control group of 3020 homes within the geographic area. The control group was randomly selected by the local distribution company and, therefore, did not necessarily have electric water heaters, and these households were not PeakSaver Plus program participants. Permission for consumption data analysis was obtained from the households analyzed by the local distribution company.

The IHDs were delivered to each participant by mail. Participants could install the IHDs by connection to a standard outlet. The IHD connected to each home's smart meter. The device provided whole-house electricity consumption data, for the past 24-hours and the past month. As seen in Figure 36, the IHD had a black-and-white display with individualized whole-house feedback for both consumption levels (kW) and cost of consumption ($/hour) in real-time. A cycling light arc also provided for real-time feedback. In the arc and level of consumption was indicated by the speed of the arc (fast movement for high-level consumption, slow movement for low-level consumption), and the colour represented the TOU period (green for Off-Peak, yellow for Mid-Peak and red for On-Peak).

Figure 36 IHD utilized in the study

Two years of hourly consumption were collected for the 5274 homes with the IHDs installed as well as the 3020 homes without IHDs (September 9, 2012 – September 9, 2014). These hourly data were collected from smart meter readings as collected by the relevant utility. This study utilized the delivery date is the ‘installation’ date for this study and assumed that each household activated their IHD and placed it within a centralized location in the home, beginning on the delivery date.

This study used climate data from Environment Canada’s Climate Weather Database weather station in closest proximity to the municipality (Environment Canada, 2015).[27] The heating degree days[28] (HDDs) and cooling degree days[29](CDDs) were studied using a base temperature of 18°C, which is the standard used by Environment Canada.

3.2.3 Analysis methodology

This study utilized a multiphase analysis, outlined in detail in the related manuscript (Chapter 6) and briefly summarized in the following sections and highlighted in Figure 37. In general, the analysis involved household characterization, household clustering, and impact analysis for the total population and consumer segments.

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[27] The site remains undisclosed for non-disclosure agreement purposes.
[28] HDDs are the number of Degrees Celsius the temperature goes below a certain threshold. In the case of this study, 18.0°C is the base temperature to align with typical Canadian building standards and Natural Resources Canada data. HDDs can be indicative of temperatures where heating mechanisms are utilized within buildings to increase temperature towards room temperature.
[29] CDDs are the number of Degrees Celsius the temperature goes above a certain threshold, which is 18.0°C in this study. CDDs can be indicative of temperatures where cooling mechanisms are utilized within buildings to reduce temperature towards room temperature.

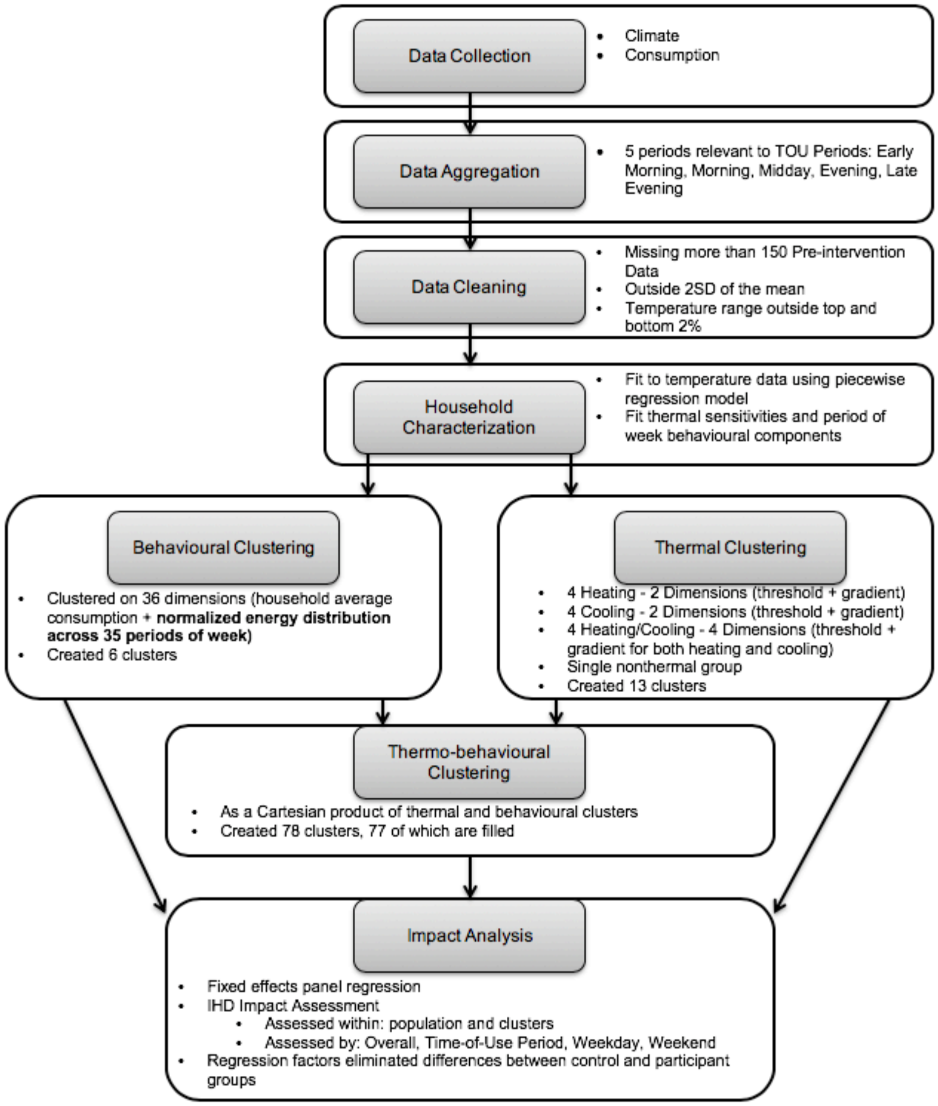

Figure 37 Methodology process for IHD case study

3.2.3.1 Aggregation of the data

The data utilized within this study (consumption, temperature, and heating and cooling degree hour data) were aggregated to reduce computational requirements. Hourly data were aggregated into five daily periods from hourly data, which aligned with the Independent Electricity System Operator (IESO) TOU periods. Similar to the IESO TOU periods, weekends were considered Off-Peak.

3.2.3.2 Data cleaning

The original households in the dataset included outliers and insufficient data; therefore, several stages were completed to remove outliers and households with insufficient data. Households with less than 150 pre-IHD readings (approximately one month) were removed. Outliers were then addressed, where households outside two standard deviations of the mean of the hourly consumption data were removed (0.26 kWh, 4.7 kWh). The original dataset included 6879 participant and 3359 control households, and following data cleaning the dataset included 5274 participant households and 3020 control households.

3.2.3.3 Household characterization

Household consumption data were fit to temperature data to characterize households based on their thermal consumption loads. Four piecewise regression models were utilized: notable heating load, notable cooling load, notable heating and cooling load, and notable non-thermal load. The full details for this characterization are provided in detail in the related manuscript (Chapter 6).

3.2.3.4 Household clustering

Households were clustered into consumer segments utilizing the model outputs from the household characterizations. Full details for this clustering process are provided in detail within the research manuscript (Chapter 6). K-means clustering methodology was utilized for segmenting households into particular archetypes for heating load, cooling load, or heating and cooling load. Thirteen thermal segments were created (12 thermal and 1 non-thermal). K-means clustering was also utilized for the behavioural patterns. Six behavioural segments were generated. Final thermo-behavioural clusters were generated as a Cartesian product of thermal and behavioural clusters. Seventy-eight thermo-behavioural clusters were generated as a result of this process.

3.2.3.5 Regression analysis

As identified in Figure 37 above, and completely described in Chapter 6, this stage involved both standardization and IHD impact assessment. Control group standardization was utilized to reduce notable consumption differences between the control and treatment groups that would influence the validity for equal comparison. Substantial differences in consumption related to both temperature and behavioural elements were identified, and standardization was applied to correct these differences. Specifically, correcting for seasonal variation and daily usage fluctuations. The correction measures were included in the regression stage, and the full details are provided in Chapter 6.

An impact regression was utilized to assess the influence of the introduction of the IHD on overall whole-house consumption and TOU consumption patterns at various scales: firstly, the effect on average total consumption; second, the effect on TOU consumption; and third, the effect on day type (weekend and weekday) consumption. This procedure was conducted for the general population and clusters at each stage of the analysis, as fully described in Chapter 6.

3.2.4 Limitations and Boundaries

Certain limitations for the IHD study should be highlighted. First, only hourly consumption data were available for this study. As a result, the socio-economic, technological, and population profiles of each household are unknown. Household electricity consumption changes are the only measures available for analysis in this study. Therefore, this case study can only observe specific characteristics of household energy culture. Furthermore, this study was unable to collect and assess participant data beyond consumption alongside IHD installation (e.g., socio-economic profile, technology profile, energy preferences, smart grid preferences); therefore, there is no confirmation of participant profiles, IHD use and related IHD feedback. This study assumes the IHD was located in a 'high-traffic' area of the home (e.g., kitchen or family room); however, the device location of the IHD was not confirmed nor guaranteed during the study period. Second, this study assumes that the 'installation' date was IHD delivery date. Third, with two years of consumption data, and IHD installations beginning four months into the dataset, a full year of baseline consumption was not available for comparison of pre- and post-installation consumption levels for some households. Thus, it was integral to utilize the control group for testing the treatment effect of the IHD installation. As a result of these limitations and related assumptions, certain information on external factors of household consumption is unavailable and should be taken into consideration when interpreting the results of this study. Despite these limitations, the size of the dataset alongside the availability of a large control group for comparison delivers strength to this study for assessing the changes in consumption in conjunction with the IHD introduction within the population and particular user segments.

3.3 Engagement model conceptual paper methodology

The final manuscript (Chapter 7) in this dissertation provides a conceptual review of societal intervention design for sustainability shifts and presents a novel engagement model for intervention design. Within Chapter 7, the paper entitled **‘*ENGAAGGE: Towards an integrated model for collective change*’** aims to review the literature related to engagement for societal change, identify the main opportunities as well as key strategies for developing an integrated model for intervention design. Four primary research objectives are applied within Chapter 7, specifically: (1) to evaluate the main disciplines studying consumer engagement and societal change related to sustainability shifts. In particular, this involves social marketing, community based social marketing, social practice theory, and design thinking; (2) to identify the strengths and limitations of each approach; (3) to highlight opportunities for developing an integrated model for intervention design, and; (4) to propose a new integrated model for sustainability intervention design, harnessing the strengths of the existing approaches found within the literature, and posing avenues for future research to apply and test the model.

As a result of a thorough review of social marketing (SM), community based social marketing (CBSM), social practice theory (SPT) and design thinking (DT) intervention approaches, this paper identified opportunities for combining approaches and developing a novel intervention design model. As a result, this paper proposed and outlined a new integrated model for intervention design. The following sections summarize the methodology applied for the research presented in Chapter 7.

3.3.1.1 Methods

The conceptual paper delivered in Chapter 7 applied several steps to develop the ENGAAGGE model (Table 16). First, this paper reviewed the key conceptual approaches related to societal change and consumer engagement in sustainability shifts specifically related to intervention design and development. Specifically, this conceptual review focused on approaches applied in the literature related to sustainability shifts, specifically: social marketing (SM), community based social marketing (CBSM), social practice theory (SPT), and design thinking (DT). Since this manuscript is conceptual, this procedure involved a scoping and review of the main developmental pieces related to each approach for intervention design as well as pieces reviewing and critiquing each intervention design approach. Second, this paper identified and reviewed the intervention elements for each approach. Chapter 7 summarizes each approach in detail, along with their key elements. This procedure involved collecting the main conceptual focus, policy approach, agency, the role of technology and main methodologies utilized for each approach. Furthermore, this paper presents the notable strengths and limitations of each approach as an outcome of reviewing the literature related to these approaches. Third, this paper identified the key elements for intervention design were identified as a result of the literature review. This procedure highlights the seven key elements for intervention design, including: empathizing; identifying the issue; identifying target audience; developing solutions; prototyping; implementing and evaluating; and revisiting the problem and idea(s). Fourth, Chapter 7 introduces and proposes a new integrated engagement model: the ENGAAGGE model.[30] This novel model presents eight stages for applying an empathy-centred approach for intervention design.

Table 16 The ENGAAGGE model for intervention design

E	N	G	A	A	G	G	E
Empathize and understand the problem throughout the process	**N**orm evaluation: existing and aspirational	**G**ather detailed background information	**A**rticulate the problem and the audience	**A**ctively ideate the potential solution(s)	**G**auge, test, and re-test through prototyping	(re)**G**roup, redefine and evaluate the norms, barriers, motivations, and prototypes	**E**valuate and implement refined intervention and continue monitoring for success

The ENGAAGGE model proposed in Chapter 7 utilizes the key elements and knowledge gathered from the evaluation of the existing approaches of SM, CBSM, SPT, and DT (Figure 38). Furthermore, this model harnesses the related approaches' strengths to address the limitations in each of the reviewed approaches.

[30] The ENGAAGGE model is named after the 8 steps identified in Table 16: **E**mpathize and understand the problem throughout the process; **N**orm evaluation; **G**ather detailed background information; **A**rticulate the problem and audience; **A**ctively ideate potential solution(s); **G**auge, test, and re-test through prototyping; (re)**G**roup, redefine and evaluate the norms, barriers, motivations, and prototypes; **E**valuate and implement refined intervention and continue monitoring for success.

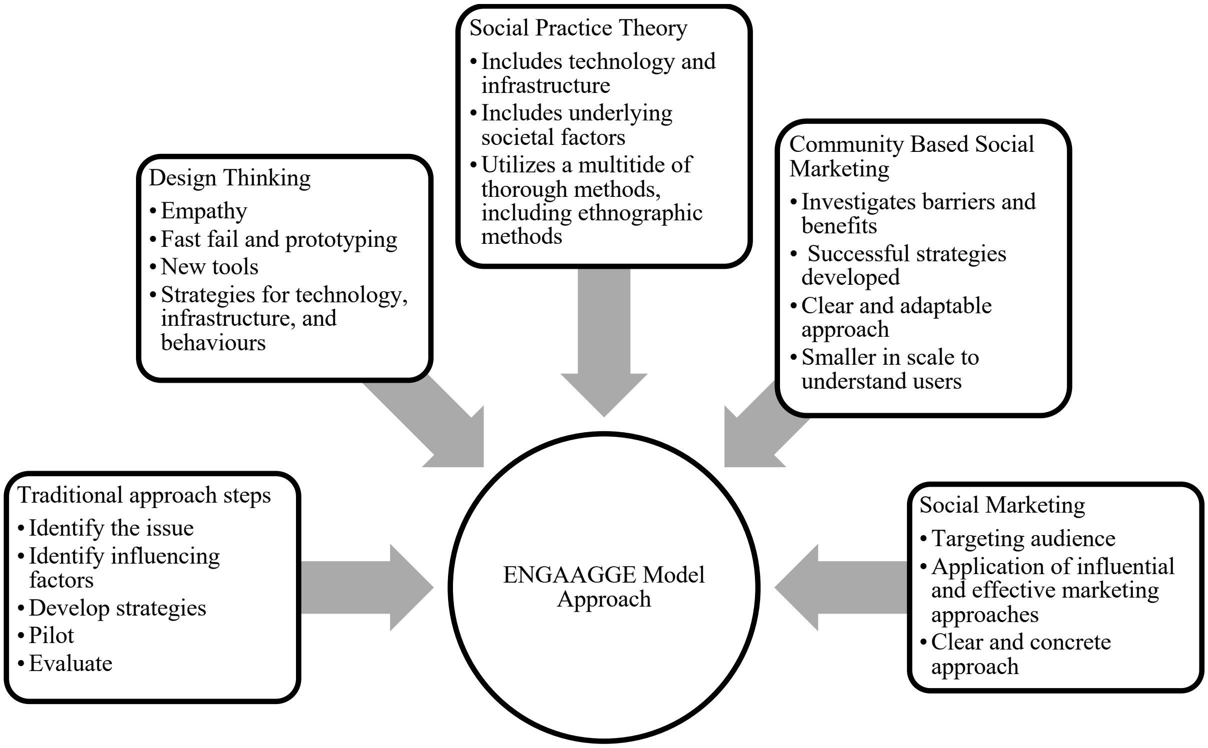

Figure 38 Strategies integrated from each approach

Utilizing effective strategies for solution development, testing, and implementation is critical. Identifying and comparing the main strategies implemented by each approach (SM, CBSM, SPT, and DT) is a crucial element of the conceptual review presented in Chapter 7. The development of the ENGAAGGE model highlighted and integrated specific techniques for model application. Chapter 7 discusses the integrated elements, as well as potential avenues for application in detail. Lastly, the paper compared the existing approaches reviewed to the proposed ENGAAGGE intervention model to highlight how the integrated approach brings novel features for intervention development. Although applying and testing the model was outside the scope of the research, Chapter 7 provides a brief overview of potential areas to apply this novel proposed model.

3.4 Conclusion

This chapter outlined the methodology applied in the four research manuscripts included in this dissertation (Chapters 4 to 7). The methodologies applied within these respective papers provide multiple contributions to the literature. First, the utilization of large sample sizes, as applied within Chapter 6; second, the application of mixed-methods research approaches, as utilized within Chapters

4 and 5; third, integrating qualitative findings within long-term smart grid research, as applied in Chapters 4 and 5; fourth, utilizing multi-year consumption data for assessing changes in consumption, as presented in Chapters 4-6; fifth, utilizing a multi-intervention study to assess smart grid consumer engagement as articulated in Chapters 4 and 5; and last, assessing the key literature related to societal change approaches, as presented in Chapter 7. Overall, the methodologies utilized within these respective papers apply social science approaches to studying smart grid consumer engagement and highlight opportunities for increased societal engagement. Consequently, the aforementioned methodologies bring together two smart grid case studies and one conceptual paper to further develop social science applications within energy and sustainability research. The manuscripts applying the research methods reviewed in this chapter, and their respective results, are outlined in the following chapters.

4. Chapter 4 – Towards a smart and sustainable residential energy culture: assessing participant feedback from a long-term smart grid pilot project

Background: Smart grid tools (e.g., individualized disaggregated data, goal-setting and behavioral suggestions/feedback) increase opportunities to reduce or shift residential electricity consumption, but can they shape residential energy culture? And what underlying factors influence this shift? Insights are identified from a qualitative analysis of a three-year residential smart grid project in a suburb of Toronto, Canada. Interviews evaluated whether participants experienced changes in their energy culture and identified underlying factors. In particular, the impacts of the project tools on participants' norms (attitudes and awareness towards energy management), material culture (technical changes) and energy practices (conservation/peak shifting actions) were assessed, and motivations and barriers towards energy management were identified. The effectiveness of engagement mechanisms (e.g., web portal, reminder emails, webinars, incentivized control program and weekly electricity reports) was also evaluated. By examining detailed qualitative feedback following a multi-year suburban smart grid project in Ontario this study aims to (1) assess the changes in energy culture over the duration of the 3-year project and to (2) assess the underlying factors influencing household energy consumption and smart home energy culture.

Results: Findings from the interview were compared to results of an initial project survey to identify longer-term influences on energy culture. Increases in self-reported awareness and practices were accounted for, with the web portal and individualized weekly feedback email reported most frequently as causes of change. While increased awareness was obtained, participants needed additional guidance to make substantial changes. Although participants were financially motivated, norms of lifestyle and convenience, as well as competing household values of energy management were the largest barriers to home energy management.

Conclusions: This study showcases challenges for engaging homeowners with home energy management technologies due to norms as well as competing household interests. Nuanced findings as an outcome of this study framed around energy cultures can influence future studies on smart grid engagement and consumer behaviour with larger samples sizes. In particular, future studies can further investigate: the motivations and barriers surrounding residential energy cultures; how to

engage different ‘cultures of consumption’ within households, and; elements to effectively educate consumers beyond disaggregated feedback.

Keywords: Conservation and demand management (CDM); Demand-side management (DSM); Energy cultures; Feedback; Household engagement; Smart grid; Time of use (TOU) pricing.

4.1 Background

4.1.1 Consumer engagement and the smart grid

Residential smart grid infrastructure incorporates two-way flows of electricity and information from the utility to the consumer and back; thus, changing the typical roles of utilities and consumers (Stephens et al., 2015; Winfield & Weiler, 2018). Smart grid technologies allow for both smart control and user-centred control and can facilitate the integration of household appliances for scheduling and management (Stephenson et al., 2017). This enables ‘demand-side intelligence,’ facilitating increased real-time electricity cost and consumption feedback to consumers to increase their awareness and energy management to achieve a more sustainable residential energy culture (Miler & Beauvais, 2012, p. 12) (Stephenson et al., 2010). As a result, the smart grid provides opportunities to reduce and shift residential electricity consumption, which can decrease the financial, environmental, and social costs of the electricity supply. The influence of smart grid infrastructure in enabling electricity conservation and demand management (CDM) is widely proclaimed in literature and policy (Darby, 2010; Römer et al., 2012).

Various jurisdictions have experienced the development of a smart residential energy culture through smart grid technology deployment. Savings of approximately 7-13% have been experienced in advanced residential smart grid projects in North America, Australia, and Japan (Faruqui et al., 2010b). A variety of smart grid tools – mechanisms to engage consumers with the smart grid system and smart meter data – can be deployed. These tools allow users to view data and optimize appliance use for household electricity management (e.g., mobile or web applications, goal setting, and appliance control mechanisms). Additionally, many customers see positive value from smart metering, which can lead to successful technological adoption (Kaufmann et al., 2013). As a result, smart metering technology brings an opportunity to shift consumers towards a smarter and more sustainable energy culture (Stephenson et al., 2010) through the adoption of new technologies and efficiency measures, shifts in energy practices and changes in norms surrounding energy management.

However, the implementation of technology is not the sole contributor to changes in energy behaviours, consumer engagement is also required to establish a culture of CDM. Temporal patterns of energy consumption are highly influenced by consumer behaviour and involve attitudes, awareness and actions towards energy CDM (Abrahamse & Steg, 2009; Abrahamse et al., 2005; Anda & Temmen, 2014). Consequently, the end-user is the key variable in the prediction of smart grid system success (Gaye & Wallenborn, 2014). Energy is 'doubly invisible' since it is an intangible force and governed by unobtrusive habits, which makes it difficult to promote CDM behaviours without increasing awareness (Hargreaves et al., 2010). The parallel delivery of behaviour change programs, alongside the installation of advanced metering infrastructure (AMI), is vital for effective implementation and to gain benefit from the system (Anda & Temmen, 2014). Therefore, smart grid policy must also include provisions for engagement mechanisms.

4.1.2 Complexities of consumption, behaviour, and technical transitions

Transitions in the smart grid incorporate actors at different scales. These socio-technical innovation transitions involve artifacts, knowledge, resources, capital and the interaction of human actors at multiple levels (F. W. Geels, 2002; Frank. W. Geels, 2004). State intervention and policy reform are often mandatory within sustainability transitions (Meadowcroft, 2009) and new conceptualizations of innovations to incorporate user practice across space and time are needed (2007). Therefore, studying detailed user perspectives on smart grid technologies can develop the understanding of niche actors (Ford, Walton, et al., 2017).

Household energy consumption is also complex and is influenced by internal and external factors (Kowsari & Zerriffi, 2011). Differences between identical residential units can be up to 200%, with household behaviours contributing to this extreme variability (Chen et al., 2015; Dietz et al., 2009; Lutzenhiser, 1993; Mills & Schleich, 2012). Behavioural theories view several factors as critical influences, including: attitudes, norms, agency, habits and emotions (Darnton, 2008; Jackson, 2005). Household energy use is also positively correlated to household income (Abrahamse & Steg, 2009; Costanzo et al., 1986; Kowsari & Zerriffi, 2011) and household size (Abrahamse & Steg, 2009; M. Brown, 1984, 1985). Education levels (Mills & Schleich, 2012; Steg, 2008) and energy literacy (M. Brown, 1984; Lutzenhiser, 1993) as well as economic profile (M. Brown, 1984, 1985) positively correlate to the willingness to conserve and invest in efficiency upgrades. In regards to age demographics, households with younger members are more willing to invest in new and efficient technologies (Mills & Schleich, 2012); however, household dynamics and competing attitudes may influence the overall level of conservation (Abrahamse & Steg, 2009; M. Brown, 1984, 1985). Although these socio-economic factors contribute to household energy consumption, additional technical, social, and behavioural factors remain. Habits, routines and behavioural practice have a strong influence over the use of efficient technologies (Mills & Schleich, 2012). Behaviours contribute to two-thirds of household energy use, compared to structural and technological components (Lutzenhiser et al., 2012). Therefore, behavioural 'wedges' are also required to change how consumers use technology and operate household systems to result in consumption shifts (Dietz et al., 2009). Understanding these complexities can give insights for changing energy behaviours.

4.1.3 Complexity in changing energy behaviours

Influencing energy consumption through behavioural interventions has been studied at length in the literature. Encouraging CDM behaviour can be achieved through antecedent interventions, which occur before the behaviour (e.g., goal setting, information and commitments) or consequence interventions, which provide either rewards or penalties after the behaviour has occurred (e.g., feedback and rewards) (Abrahamse et al., 2005). Feedback can be a key method in changing energy behaviours through individual or comparative feedback (Midden et al., 1983). Information-based strategies have experienced average savings of 7.4% (Delmas et al., 2013c). However, changes in energy beliefs or attitudes, not just knowledge, are required to change energy practices (Hargreaves et al., 2013; Wallenborn & Wilhite, 2014). Multiple types of engagement mechanisms are available, and it is essential to assess participant feedback on different smart grid tools to improve our understanding of smart grid engagement and behaviour change potentials. Additionally, it is important for social science research to move beyond studies of hierarchal levels of change and investigate dynamics of energy practices through new frameworks (Walker & Shove, 2007).

4.1.4 Energy cultures: A framework for detailed understanding of energy use

Since factors influencing energy consumption remain complex and incorporate elements within both personal and contextual domains (Kowsari & Zerriffi, 2011), utilizing frameworks to organize these nuances can highlight important details. Stephenson et al.'s (2010) energy cultures framework provides a scalable framework to organize iterative self-reinforcing energy behaviours influenced by social and technical factors (Stephenson, Barton, et al., 2015). The energy cultures framework has been utilized in a variety of contexts, including: photovoltaic adoption (Ford, Walton, et al., 2017); transportation and mobility (Hopkins & Stephenson, 2014, 2016; Stephenson, Hopkins, et al., 2015), timber technologies (Bell et al., 2014); higher education energy behaviours (Ishak et al., 2012); and residential energy interventions (M. G. Scott et al., 2016). The energy cultures framework, however, has not been applied to the Canadian context, nor has it been applied to the smart grid; therefore, this pilot project extends the application of the energy cultures framework to the Canadian residential smart grid.

In this framework, widespread energy behaviours, otherwise called 'energy culture,' are impacted by the interaction of three key elements. Firstly, material culture, involves household technologies, appliances and building materials influencing energy use. Secondly, norms, involves the standards or expectations influencing energy consumption that exist at individual and societal scales (e.g., thermal comfort and convenience). These norms are influenced by beliefs, knowledge, and motivations towards energy consumption. Thirdly, energy practices, involve household activities and processes related to energy consumption (Barton et al., 2013; Stephenson, Barton, et al., 2015; Stephenson et al., 2010). Practices and skills involve the uptake of technology and materials allowing routinized behaviours (Ford, Walton, et al., 2017). In the energy cultures framework practices include infrequent actions, a key differentiating factor from practice as outlined in social practice theory (Stephenson, Barton, et al., 2015). This conceptualization of energy practices complements this pilot project's focus on whole-house energy management, where both repetitive and infrequent energy actions could influence household consumption (e.g., changing thermostat settings, setting automation functions, setting goals, etc.,). External contextual factors (e.g., structural, technical, economic, socio-economic, climactic factors) are also included in the energy cultures framework (Ford, Karlin, & Frantz, 2016). Overall, the energy cultures framework is scalable (Stephenson, Hopkins, et al., 2015) and can be applied to the smart grid context.

4.1.5 Applying the energy cultures framework to the smart grid

As emphasized by Strengers (2013), simply relying on a technologically-driven smart utopia is problematic; instead, elements of user adoption and consumption patterns need to be incorporated through social science approaches (Sovacool, 2014). Utilizing the comprehensive approach of the energy cultures framework (Stephenson, Barton, et al., 2015; Stephenson et al., 2010), allows for these user constructions to be reimagined and to move beyond individual practices through the investigation of in-depth household decision-making and energy culture. Mallett et al. (2018) identify the influence of technological perceptions and adoption in the smart grid context, where policymakers should utilize awareness of local context in the design of smart grid technology and policies. As a result, the energy cultures framework can provide useful framing for understanding complexities surrounding energy use (Stephenson, Hopkins, et al., 2015).

As outlined in Figure 39, transitioning to a smarter and more sustainable residential energy culture involves multiple elements. It involves a change in culture, behaviour and technology, influenced by markets and policy (Ford, Walton, et al., 2017). Firstly, an aspirational shift towards increased energy management through flexibility in consumption patterns; acceptance of technological management and efficiency upgrades; and increased willingness to reduce consumption. Secondly, this transition involves an ‘upgrade’ in material culture through: installing smart grid and smart home technologies; increasing building envelope and appliance efficiencies; and using other home energy management technologies (e.g., control, optimization, and automation) (Karlin et al., 2013; Lamarche et al., 2012). Thirdly, this transition involves adhering to practices that reduce consumption, shift to Off-Peak periods, and align with reduction goals. This includes the use of automation, optimization, and energy management technology, as well as a change in routinized and infrequent consumption actions to shift towards the aspired smart and sustainable energy culture. Thus, the transition involves a change in norms, an adoption of technology, and a shift in actions, which is being attempted in Canada, particularly in the province of Ontario.

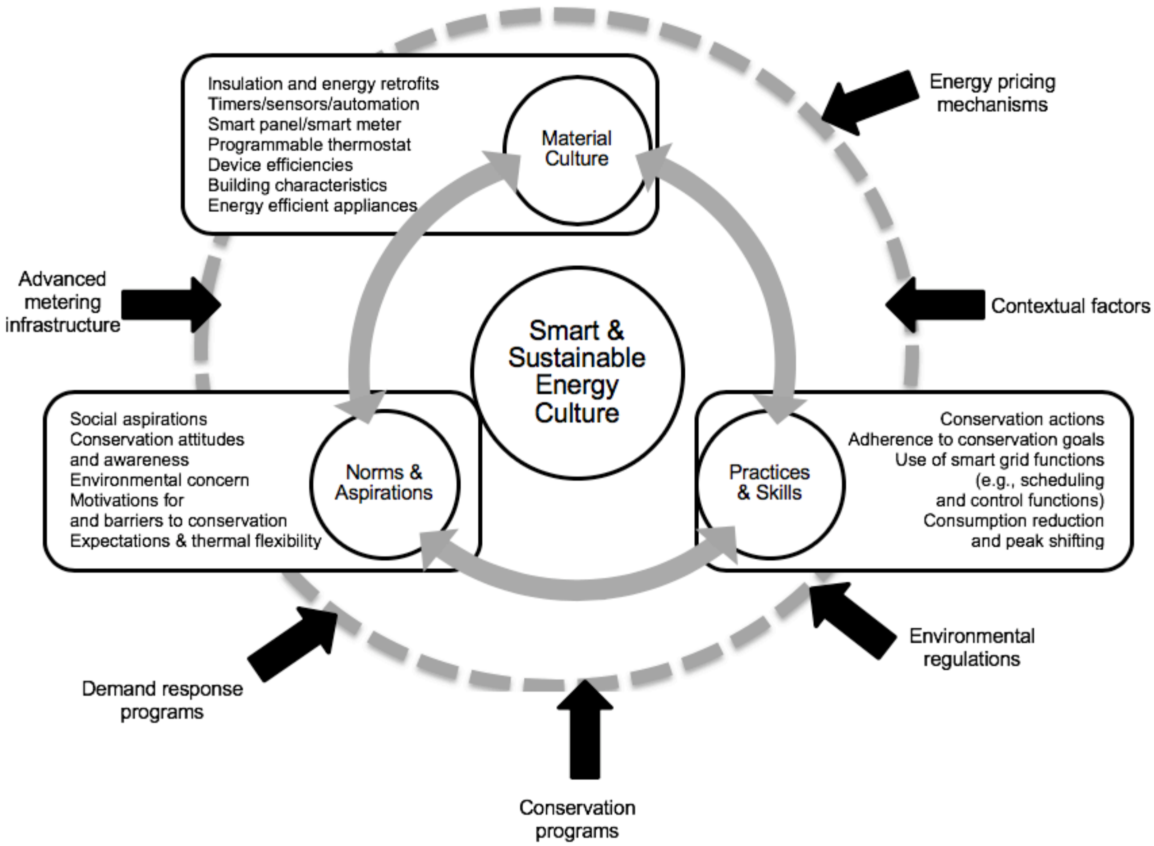

Figure 39 Smart residential energy cultures framework, adapted from (Stephenson, Barton, et al., 2015; Stephenson et al., 2010)

4.1.6 Ontario's smart grid

The province of Ontario is a leader in smart grid deployment in Canada and aimed to shift its provincial energy culture as a result of substantial changes in technology, policy and market rules (Lysyk, 2014; Mallinson, 2013; Winfield & Weiler, 2018). The smart grid is a key element of the province's electricity CDM policies, and was first highlighted in the province's *Electricity Act, 1998*. As part of Ontario's 2004 Smart Metering Initiative, 4.8 million smart meters were installed, resulting in the first and largest Canadian smart meter deployment (Lysyk, 2014). This allowed time-of-use (TOU) pricing to encourage Off-Peak consumption. Ontario's 2013 Long-Term Energy Plan adopted a Conservation First policy involving consumer engagement through smart meter demand response methods to achieve long-term targets (Ontario Ministry of Energy, 2013). As a result, studies of smart grid engagement mechanism effectiveness in Ontario are critical for the successful implementation of smart grid technology and the achievement of CDM targets.

Several elements have established Ontario's leadership in Canadian smart grid development. Ontario has fully operationalized AMI, new rate options (TOU pricing) and has partially implemented demand response for load shifting or ancillary services (2014). Further, distributed energy storage for peak shaving, self-healing grids, microgrids and voltage reactive power control are under study within the province (2014). Consequently, Ontario is the largest actor in the Canadian smart grid landscape. Local Distribution Companies facilitate the interaction of the smart grid between the utility and the consumer, and in particular, standardized electricity data are accessible to approximately two-thirds of Ontario customers for better management and understanding of energy consumption (Hiscock, 2014; Winfield & Weiler, 2018). Therefore, Ontario's phases of smart grid development included a multitude of technological implementation, funds, polices and mechanisms at multiples scales (Table 17). Opportunities remain to examine details regarding how these externalities can shape residential energy cultures.

Table 17 Elements of Ontario's shift to the smart grid and conservation culture

Objectives	Technology	Funds & initiatives	Policies	Additional mechanisms	Actors
Peak shifting; conservation; peak shaving; system efficiencies and security; distributed generation; integration of new technologies; privacy; efficiency; customer value; coordination; reliability; flexibility; innovation	**Established:** Smart meters and AMI; integration of renewables **Testing:** energy storage self-healing grids; microgrids, and voltage reactive power	Smart grid fund; Green Button Initiative	Green Energy and Green Economy Act	TOU pricing; demand response;	Ministry of Energy; Ontario Energy Board; Ontario Power Authority; Independent Electricity System Operator; Hydro One Networks; Local Distribution Companies

To better understand the complexity of residential consumer behavior in the smart grid, this study utilizes a qualitative approach to study the impact of smart grid technologies on participants' energy culture (Stephenson et al., 2010; Stephenson, Hopkins, et al., 2015) within a three-year residential smart grid pilot project. This study aims to: (1) determine whether the project influenced the participants' energy culture; and to (2) determine what factors influenced 'smart' energy management and project engagement. Since this study focuses on the agency of the individual, we utilize the energy cultures framework to gain detailed understanding of the complexity and the nuances surrounding residential energy behaviors (Ford, Walton, et al., 2017).

4.2 Methods

4.2.1 Project overview and research objectives

Twenty-five households in Milton, Ontario were involved in a three-year residential smart grid project to manage their electricity use. This included the installation of a smart panel, which provided circuit-level feedback and monitoring (Aydinalp Koksal et al., 2015). The utility company recruited these households to this opt-in program by email; therefore, these participants could be considered 'early adopters' of smart grid technologies by showing interest in this program. Throughout the project, 13 types of interactions were implemented from June 2011 to March 2014. These mechanisms had multiple purposes (e.g., administrative, behavioural, technical). This paper focuses on six behavioural engagement mechanisms (Table 18).

Understanding the impact(s) of these mechanisms on residential energy cultures can aid in the development of similar programs, policies, and smart grid infrastructure. This paper applies Stephenson et al.'s (2015; 2010) energy cultures framework to provide insights and to discuss the feedback of smart grid engagement mechanisms and the factors influencing their energy culture throughout the pilot project. This study investigates the impact of the engagement mechanisms on residential energy culture (material culture, norms, and energy practices) as well as the identification of factors influencing the adoption of a smart energy culture (motivations and barriers) through qualitative feedback obtained from 15 participating households.

The aims of this study are twofold: (1) to identify whether the project influenced participants' energy culture, and (2) to highlight what factors influenced the adoption of a smart energy management culture within the participating households. The first aim will be met by assessing the changes in attitudes and awareness towards energy management as well as changes in practices and material culture throughout the project. The second aim will be met by examining the major motivations and barriers influencing participants' energy management.

Table 18 Description of the project-led behavioral engagement mechanisms

Item	Description	Classification	Frequency	Timeframe
Goal setting	Self-set goal for consumption reduction monitored on web portal.	Goal setting	Ongoing	December 2011- project end
Web portal	Web-based portal providing access to whole-house and appliance-level consumption feedback. Access to settings for scheduling, goal setting and control also included.	Feedback, monitoring and control	Ongoing	November 2011 - April 2012
Reminder emails	Bi-monthly emails sent to remind participants to log in to the web portal.	Reminder	Bi-Monthly	January 2012- August 2013
Webinar	A webinar to introduce the control feature and other elements of the web portal.	Education	Once	March 2013
Incentivized control program	Households were invited to use the air conditioner 'control' function in return for C$100 for each week's participation for two weeks during the months of July and August 2013.	Control	Twice	July and August 2013
Weekly electricity report	A weekly email sent to participants indicating their total, On-Peak, and appliance-specific consumption. It compared their consumption to other households in the project as well as to the previous year. Conservation tips were provided.	Feedback	Weekly	June-December 2014

4.2.2 Data collection and analysis

The pilot project was located in Milton, Ontario, a suburb approximately 50 km west of Toronto (Aydinalp Koksal et al., 2015; Kantor et al., 2017; Kantor, Rowlands, Parker, & Lazowski, 2015) (Figure 40). Key elements of this town are its rapid population growth, high economic status, and the dominant residential building type (Table 19). This remains consistent with the participant group (Table 22). This study involves an analysis of the participant feedback collected throughout the 3-year pilot project. In particular, data from both an initial project survey and an interview near the end of the project were utilized to assess participant feedback and energy culture at the beginning and end of the pilot project.

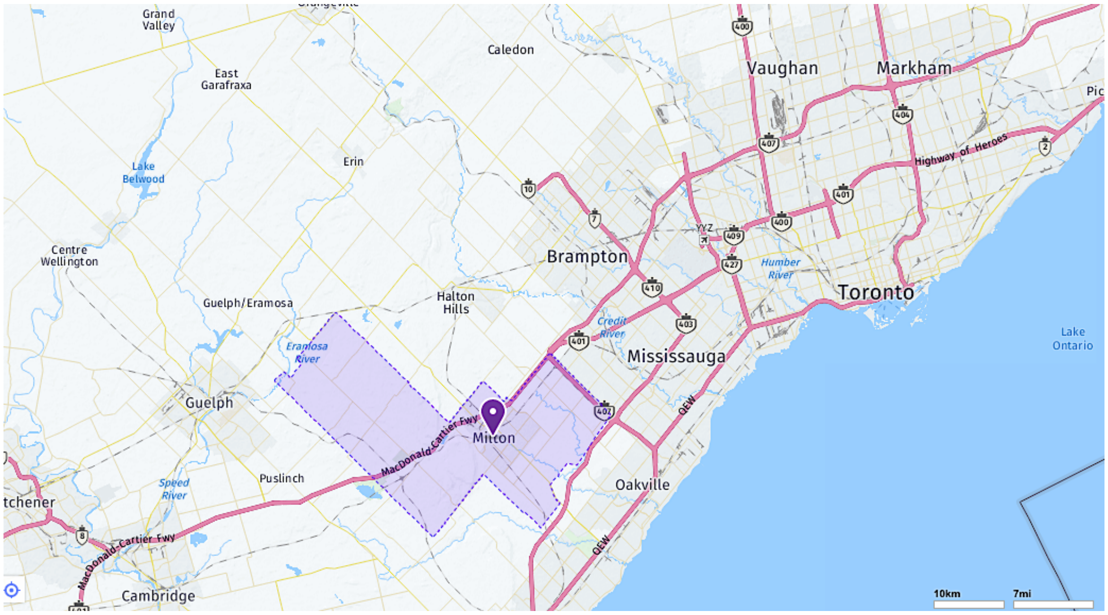

Figure 40 Milton, Ontario map in proximity to Toronto (HereCanada, 2018)

Table 19 Key socio-economic statistics of Milton, Ontario (Statistics Canada, 2013, 2017)

Attribute	Value
Land area (square km)	363
Population density (per square km)	232
Average age (years)	33
Dominant dwelling size by number of bedrooms	3 bedrooms
Average household size by number of people	3
Population 2011	75,880
Population 2016	101,715
Percentage population growth 2011- 2016	34%
Dominant residential building type	Single-detached house
Average income (before tax) CAD	$49,229
Average household income (before tax)	$106,743
Dominant education level	Postsecondary certificate, diploma, or degree

4.2.2.1 Survey Data

Participants were asked to complete an initial project survey at the beginning of the project. Collected on-line through an email, this survey involved a series of Likert scales to measure the baseline factors contributing to the household profile and energy management. This survey involved baseline data collection related to the households' socio-economic profile, household structural and technological profile as well as motivations, attitudes, actions, awareness, and goals towards energy management. The information collected through this survey was used for the baseline elements related to household materials, practices, norms, and contextual factors.

4.2.2.2 Interview Data

To gather the qualitative data for this study, structured interviews were conducted with project participants near the end of the project. Structured interviews provided detailed feedback and responses that aligned with the previous survey and followed up on the motivations, attitudes, actions awareness and goals related to household energy management. The interviews involved close-ended (e.g., Likert and rating scales) and open-ended questions (e.g., rationales and description of experiences with project elements). The initial project began with 25 participants who opted-in to the program after an open call for participants by the utility, however, 7 households had exited the program and were not available to interview. Out of 18 potential interviews, 15 were completed for analysis, resulting in an 83% response rate. One researcher coded the interview transcriptions using NVivo based on the main themes of the research: attitudes, awareness, motivations, and barriers related to energy management; energy management practices and actions; and engagement mechanism feedback (Table 20).

For additional engagement mechanism feedback, participants were asked to rate the effectiveness of the project engagement mechanisms on a scale of 1 to 5 (not effective to very effective). The term 'effective' was defined as providing the participant with the necessary knowledge to actively participate in the project, and to influence their energy culture.
The motivations for and barriers to energy management identified through the interviews were coded using topic-specific codes (e.g., lifestyle, convenience, cost). Upon completion of coding the interviews, frequency counts of each topic-specific code were calculated, and the seven most cited motivations and barriers were determined and presented in the results.

Table 20 Details and procedure for participant feedback

Element	Method	Total sample	Timeframe	Analysis
Initial project recruitment	Email and participant opt-in	25 joined program	Project start	N/a
Initial survey	On-line web survey	12	Project start	Quantitative coding of responses
Interview	In-person semi-structured interviews	15	Year 3	Qualitative coding of transcribed interviews using NVivo Quantitative comparison between responses from interview and initial survey

4.2.2.3 Comparing changes between the beginning and end of the project

To compare initial and final project findings on the residential energy culture, the ratings of statements in the interview were compared to the ratings in the initial survey. Participant baseline attitudes, motivations, objectives, and actions towards energy management were evaluated. The percentages of households that had increased, decreased, or kept the same rating were calculated and summarized in the results. Only 12 of the 15 households participated in both the initial survey and the interview, which were used for comparative analysis.

In the initial survey and the interview, participants were asked how strongly they agreed with statements regarding their attitudes, awareness and energy actions towards energy management in their home by rating them from 1 to 7 (strongly disagree to strongly agree) (Table 21).[31] In the interview, participants were also asked to rate their perceived levels of awareness, attitudes and actions towards energy management before and after the project on a scale of 1-5 (low to high).

[31] These scales were created at the beginning of the pilot project for initial data collection and were continued in this study for consistency and evaluation of changes.

Table 21 Awareness, attitude and action statements from the interview and initial survey

Awareness statements	
1	Currently, I am aware of how much electricity is used by my electric appliances
2	Currently, I am aware of how much money it costs to use each of my electric appliances
3	Currently, I am aware of the carbon footprint associated with using each of my electric appliances
Attitude statements	
4	I believe that it is important to conserve as much energy in my home as possible
5	I believe that it is important to reduce my electricity usage during On-Peak times as much as possible
Action statements	
6	I try to conserve as much energy in my home as possible
7	I try to reduce my electricity usage during On-Peak times as much as possible

4.2.3 Existing participant contextual factors

Household energy cultures are influenced by a multitude of factors including the structural (e.g., built environment and technologies) and socio-economic contexts (e.g., education and income) (Ford et al., 2016). The context is an important consideration in the energy cultures framework (Ford et al., 2016; Ford, Walton, et al., 2017); thus in this section we discuss the contextual factors of the participants. The dominant building type can be classified as 'new suburban build' and detached two-storey (Table 22). These houses had large living areas, with the majority of houses sized 1500-2999 ft^2. Although the participating houses were built between 1970 and 2010, most of the houses were built after 2000 (Table 22). Consequently, these households had newer and more efficient structural elements and appliances. Therefore, limited upgrades were expected in the material culture (e.g., appliances, building envelope, energy systems, heating, and cooling technologies). The households had higher levels of income ($80,000 to $150,000+) and education (Bachelor's or beyond). These contextual factors are consistent with the overall Town of Milton population statistics (Table 19).

Table 22 Household profiles of interview participants

Household	Number of children (0-17 years)	Number of adults (18-64 years)	Total residents	Year house built	Type of house	Approximate house size (ft^2)	Household income (before taxes)	Highest education in household
1	0	3	3	1970-1979	Detached two or more storey	1500-1999	$150,000+	Bachelor's degree
2	1	2	3	2000-2006	Detached two or more storey	3000-3499	$150,000+	University certificate or diploma below bachelor level
3	2	2	4	2007-2010	Detached two or more storey	2500-2999	$150,000 and over	Master's degree
4	2	3	5	2000-2006	Detached two or more storey	1500-1999	$60,000 - $69,999	Bachelor's degree
5	2	2	4	2000-2006	Detached two or more storey	2500-2999	$125,000 - $149,999	Bachelor's degree
6	2	2	4	2000-2006	Detached two or more storey	2000-2499	$150,000+	Degree in medicine, dentistry, veterinary medicine, or optometry
7	1	2	3	2007-2010	Detached two or more storey	2500-2999	$90,000 - $99,999	Bachelor's degree
8	3	2	5	2000-2006	Detached one Storey	1500-1999	$90,000 - $99,999	University certificate or diploma below bachelor level
9	3	5	8	2007-2010	Detached two or more storey	2500-2999	$150,000+	Bachelor's degree
10	2	2	4	2000-2006	Row housing (attached on both sides)	1000-1499	$90,000 - $99,999	Non-university certificate or diploma
11	4	2	6	2000-2006	Semi-detached two or more storey	2000-2499	$80,000 - $89,999	Bachelor's degree
12	2	2	4	2000-2006	Semi-detached two or more storey	1500-1999	$90,000 - $99,999	Bachelor's degree
13	1	2	3	2007-2010	Detached two or more storey	2500-2999	$150,000 and over	Bachelor's degree
14	2	2	4	1970-1979	Detached two or more storey	1500-1999	$125,000 - $149,999	Bachelor's degree
15	0	2	2	1970-1979	Detached two or more storey	2000-2499	$150,000 and over	Bachelor's Degree

4.2.4 Household typologies

The success of the smart grid involves various actors and typologies of end-users (Gaye & Wallenborn, 2014). Classifications of users in technical infrastructures is crucial for the development of energy policies and programs (Summerton, 2004). The application of typologies in the energy cultures context is limited and has only been applied by Lawson et al. (2012). Although this typology could be useful for detailed qualitative analysis, it does not include smart grid considerations. Therefore, smart grid typologies considering materials, norms and practices alongside the smart grid context were used in this analysis. To further understand the profiles of the 15 participant households, Gaye and Wallenborn's (2015) typology of smart grid users for home energy management was used. This typology was selected due to its ability to capture elements aligned with Ontario factors of energy consumption in relation to the smart grid, particularly: thermal flexibility, electricity management, environmental motivations, and technology.

By assessing the motivations and barriers towards energy management and project participation, the four categories (economist, environmentalist, technicians, compromiser) were applied to the participating households. A majority of the interview participants (8) can be classified as 'economists,' as their main motivation for management was to save money while maintaining their lifestyle and comfort, and they had low thermal flexibility. This aligns with typical Canadian comfort standards, considering space heating constitutes the majority (61%) of residential energy usage in Canada (Natural Resources Canada, 2018b). These households were not willing to sacrifice household comfort and convenience to benefit the environment. The remaining households (7) can be classified as 'compromisers' where technology was an important aspect of increasing their awareness to reduce consumption, while being motivated by economic and environmental concerns for current and future CDM actions. It should be noted that there were no 'environmentalists,' as participants did not view environmental protection as their sole and primary motivation for energy management. Additionally, no households were categorized as 'technicians.' Thus, only 'compromiser' and 'economist' households were identified in this study.

4.2.5 Limitations

It should be noted that the intensity of support and capital cost of the technology utilized in this pilot project resulted in sample size limitations. The pilot initially had 25 participants, but by later stages of the multi-year pilot project, 15 participants remained active and willing to participate in the interview. Small sample sizes are predominant in smart metering pilot project studies, especially those with intrusive technologies similar to this pilot project and similar sample sizes have been observed in the peer-reviewed literature in regional contexts beyond Canada (Bager & Mundaca, 2017; Bradley et al., 2016; Hansen & Hauge, 2017). Despite this limitation, the interviews provided detailed understanding of household decision-making and feedback on long-term residential smart grid engagement mechanisms. Consequently, the following results provide valuable insights for residential smart grid research that can be extended with larger samples.

4.2.6 Research contributions

As noted by Abrahamse et al. (2005), relatively little is known about the long-term effects of smart grid engagement mechanisms on energy behaviour. Existing studies have focused on short-term impacts (less than equal to one year) and initial engagement (Delmas et al., 2013c; Faruqui et al., 2010b; Newsham & Bowker, 2010; Rowlands, Reid, & Parker, 2014). Long-term studies (greater than one year) can identify whether interventions encourage sustained behaviours as well as household temporal rhythms of energy consumption (Burchell et al., 2016; Hargreaves et al., 2013; Stromback et al., 2011; van Dam et al., 2010); thus, they are important for smart grid intervention and energy culture studies. Additionally, previous studies that focus on the influence of engagement mechanisms for energy CDM do not include a comprehensive set of smart grid technologies (Abrahamse & Steg, 2009; Abrahamse et al., 2007; Crosbie & Baker, 2010; McCalley & Midden, 2002; Midden et al., 1983). This research provides holistic insights on factors contributing to household energy culture and interaction with multiple smart grid engagement mechanisms over multiple years. Consequently, this study articulates nuances surrounding initial engagement and re-engagement to assess shifts in the energy culture of participating households.

This study acknowledges the complexity and interconnectedness of societal behavior and understands that studying change requires the exploration of these complex environments (Ford, Walton, et al., 2017). Since this study focuses on the agency of the individual, we utilize the energy cultures framework to understand the complexity surrounding residential energy behaviors. This paper extends beyond a critique of public engagement practices by delivering in-depth understanding on household decision-making by utilizing the energy cultures framework (Irwin & Jones, 2012).

4.3 Results and discussion

At the beginning of the interviews, participants were prompted to reflect on consumption changes during the project and participants shared a wide range of responses. Upon exploring factors influencing changes detailed understanding of household energy consumption and energy culture was gained. These nuances are outlined in the following sections, including changes in awareness and attitudes towards energy management, and changes in energy practices and material culture, followed by a discussion of the main motivations and barriers influencing smart home energy management.

4.3.1 Changes in awareness towards energy management

This project aimed to increase awareness towards energy management through multiple mechanisms, including the web portal (disaggregated feedback), weekly newsletter (individual and normative feedback) and webinar (information and education). The majority (73%) of respondents indicated that their awareness had increased due to multiple project interactions, specifically, the web portal, weekly electricity report, and the webinar, due to the information provided. As participant 6 mentioned, “When we actually monitored the web portal, we would be surprised at how much the dishwasher uses, so that I would try to run the dishwasher either less frequently or during Off-Peak hours […] you just don't think about it until you actually see it.” Respondents who reported the same awareness levels (27%) provided rationales such as already having a high level of awareness, or project disengagement.

Participants were asked to rate statements regarding their energy CDM awareness in both the initial survey and the interview (Table 21). In comparing the responses, a trend of increase in awareness can be observed; however, awareness of electricity uses, and associated costs of consumption were raised more than awareness of the carbon footprint associated with electricity use (Figure 41). This corresponds to the trends reported in the interview for increased awareness, as stated above, and the motivations for energy management reported later in this paper.

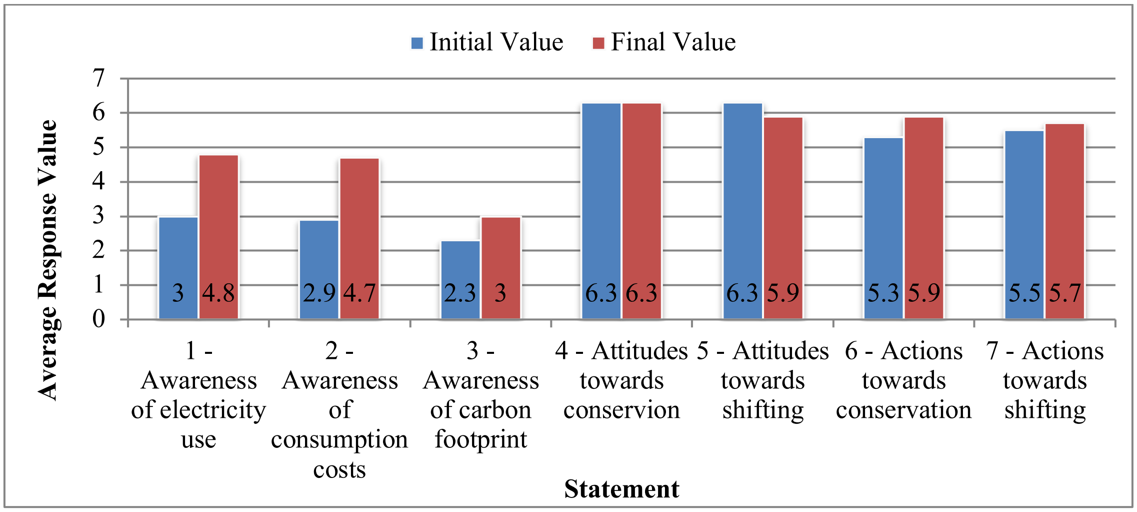

Figure 41 Awareness, attitudes and action statement ratings in the initial survey and final interview. Average response value, on a scale of 1-7 (strongly disagree – strongly agree), n = 12

Information and feedback can stimulate conservation and peak shifting in residential households (Delmas & Lessem, 2014; Ehrhardt-Martinez et al., 2010); however, studies have also highlighted mixed-results with information provision (Abrahamse et al., 2007). The results of this study highlight increased self-reported awareness towards energy management particularly the energy used and associated costs, due to feedback and information gained throughout the project. Individualized, disaggregated feedback was provided through the web portal, whereas, the weekly electricity report provided normative feedback, increasing awareness of their position among their peers. However, as similarly articulated in the literature, the linear approach of the information deficit model is limited and additional factors need to be assessed (Hargreaves et al., 2010; Wilson, Hargreaves, & Hauxwell-Baldwin, 2015).

4.3.2 Changes in attitudes towards energy management

Attitudes towards energy CDM are important to energy policy development, as ineffective policies can be a result of unaddressed attitudes (Stern, 1992). More than half (53%) of participants reported improved attitudes towards energy management during the program due to multiple project interactions, specifically the web portal and the weekly electricity report. In particular, participant 15 found the engagement mechanisms improved their attitudes towards CDM due to, "seeing how much is wasted by poor decisions every day. Especially leaving stuff on. There's a lot of things that will use power when you're not even here." The 47% who stated their attitudes remained the same provided rationales including existing CDM attitudes, cultural background and upbringing, and the inability of the project to change their priorities.

In comparing the attitudes from the initial survey to the interview, the average ratings for statements on conservation and peak shifting remained similar and at a high value from the beginning to end stages of the project. Participants viewed shifting and conserving energy as important throughout the project (Figure 41). External influences and technologies can influence attitudes and perceived behavioural control (Darnton, 2008; Jackson, 2005). Similarly, these results reveal that increased insights and information stimulated positive attitudes towards household energy management and engagement. Social and cultural factors are highly related to energy consumption, and adoption of technologies and management (Shove & Walker, 2014). As seen in this project, homeowners might already have 'highly conservative' attitudes towards their energy management; however, their knowledge about CDM opportunities may be limited. The engagement mechanisms utilized provided a means to reinforce positive attitudes within these households to influence elements related to their energy culture, as articulated in the following sections.

4.3.3 Changes in energy management practices

To assess the impact of the project on household energy practices, households were asked to assess their level of actions towards household energy management before and after the project. Similar to changes in awareness, self-reported increases in actions over the project period were highlighted by a majority of participants (53%). Multiple project interactions, particularly the web portal, weekly electricity report, project tools, and thermostat scheduling were identified as helpful for changing practices. The information provided in the interactions resulted in a more proactive approach to household energy consumption. In particular, participant 11 mentioned that they used the information to, "see what [they] have done, and see the difference [in consumption]." Those who reported the same level of action, 47%, were either already energy conscious, lacked knowledge for reductions or were concerned about comfort. Like participant 9 who noted, "I changed, but not as much as I could have […] because there are a number of things that I could still do." This highlights how certain barriers, discussed later in this paper, can inhibit the adoption of smart energy management practices.

Perceived energy management practices before and after the project remained high. Participants were asked to rate two statements regarding their energy management actions in the initial survey and the interview (Table 21) and similarly high ratings indicate that participants actively used conservation and peak shifting practices throughout the project (Figure 41). Changes in practices involved shifting discretionary loads to Off-Peak, using thermostat programming and appliance timers, highlighting changes in rhythms of consumption (Shove & Walker, 2014) and increased energy management (Karlin et al., 2013). However, limited project devices for management (e.g., control, appliance scheduling) were used. Overall, participants valued direct control over their energy management, and this was restated during the interviews.

Participants who indicated increases in management highlighted project participation increased their knowledge of possible actions (Table 23). These results highlight the ability of these engagement mechanisms, particularly the web portal and weekly electricity reports, to increase perceived CDM actions by households through information provision. Although increased information has mixed effects on consumption changes in the literature (Darby, 2006; Hargreaves et al., 2013; Karlin et al., 2015), these qualitative findings highlight perceived shifts in participants' energy management practices related to feedback provision, and thus increased consumption awareness, as previously articulated. An opportunity is created for future research to analyze the impact of reported increased awareness and action levels on consumption levels.

Table 23 Summary of household changes in level of energy management practices

House-hold	Change	Energy practices	Rationale
1	Increased	Off-Peak use of appliances; overall conservation efforts	Awareness through reminders; increased knowledge of TOU periods
2	Same	Did not change	Convenience and lack of knowledge
3	Same	Small conservation actions where possible; thermostat control	Did not know what to do
4	Increased	Programmed thermostat tried to reduce during On-Peak times; adjusted thermostat by 2°c; thermostat control and optimization	Increased awareness; access to tools to make changes barrier: cannot afford newest and most expensive appliances
5	Increased	Spent more time being energy conscious; turned off lights; tracked and turned off appliances; utilized timers on lights and appliances	Access to consumption data
6	Increased	Ran appliances Off-Peak; turned off lights; turned off devices not in use; thermostat control	Increased awareness
7	Same	Ran major appliances Off-Peak; used timers on laundry machine; thermostat control	Already energy conscious; increased number of people in home
8	Same	Small actions that did not influence comfort; thermostat control	Same actions and attitudes; already energy conscious
9	Increased	Programmed the AC; purchased and used fans; changed daily behaviors related to energy; used timers on smart appliances	Technology available (programmable thermostat); increased awareness
10	Same	Unplugged items; replaced bulbs and appliances; shifted to Off-Peak periods; overall conservation actions; thermostat control	Same actions and attitudes; already energy conscious
11	Increased	Responded to TOU periods (e.g., laundry on evenings and weekends)	Project interactions
12	Increased	Overall conservation and reduced consumption of high-consuming appliances; responded to TOU periods	Increased awareness
13	Same	Reduced consumption of high consuming devices; responded to TOU periods; thermostat control	Same actions and attitudes; already energy conscious
14	Same	Turned off devices not in use; investigated circuit loads for reductions; responded to TOU periods; thermostat control	Comfort
15	Increased	On-Peak consumption and overall consumption reduction; used automation technology to help with day-to-day reductions; thermostat control	Visualization of information

4.3.4 Changes in material culture

Throughout the program, participants had opportunities to upgrade their material culture. As previously mentioned, the majority of participating homes were ‘new suburban build,’ with limited opportunities for large efficiency upgrades; however, some material culture changes were noted (Table 24). Upgrades were mostly limited to small-device replacements (e.g., lighting), appliance replacement (e.g., washer or drier), or related to larger household improvements (e.g., basement renovations). Similar to Attari et al. (2010) households perceived curtailment actions (e.g., turning off lights, reducing use of appliances) as more attainable than energy efficiency improvements. Further, some households identified socio-economic pressures (e.g., income and affordability) and contextual factors (e.g., home ownership) prevented efficiency upgrades, aligning with previous studies (Abrahamse & Steg, 2009; M. Brown, 1984, 1985; Costanzo et al., 1986; Kowsari & Zerriffi, 2011).

Despite the newer home build, some households did make notable changes in their material culture, including smart home devices and automation technologies, solar panels, smart appliances, and large device removal (e.g., servers). There were even changes in actions related to material upgrades. For example, some participants purchased and increased the use of fans during evenings instead of the air conditioner. Participants identified financial and conservation concerns and increased awareness as motivations for material culture changes (Table 24).

Table 24 Summary of household changes in material culture

House-hold	Changes in material culture	Renovations/retrofits
1	Replaced: light bulbs, replaced washer and dryer	Upstairs bathroom; lower bathroom; main bathroom
2	Installed: new computer, pot lights and a television	Basement - pot lights and tv
3	Installed appliances related to new basement: gym equipment, computer, and tv/entertainment centre, added a new printer; replaced light bulbs; installed smart home automation	Basement - added home theater and gym and office; installed smart home automation
4	Replaced light bulbs; installed new HVAC system	n/a
5	Replaced: tv, light bulbs, dishwasher, backdoor; installed light and appliance timers and solar panels	n/a
6	Installed a hot tub	n/a
7	Replaced light bulbs	n/a
8	Installed additional freezer; replaced: tv, light bulbs and appliances	n/a
9	Replaced laundry machine and dryer (more efficient and with timers) and light bulbs; installed light and appliance timers	n/a
10	Replaced light bulbs	n/a
11	Replaced: dishwasher, light bulbs; installed: light and appliance timers, motion sensors, and ceiling fans	n/a
12	Installed new tv; replaced light bulbs	Renovated basement
13	Replaced light bulbs	n/a
14	Installed: hot tub, extra tv, small fridge in basement; replaced: washing machine and light bulbs; installed ceiling fans	Installed solar panels
15	Removed multiple large servers; replaced and added new fridges; replaced light bulbs and HVAC system; installed: weather stripping, light and appliance timers and motion sensors	Smart home and automation technology; completed home energy audit

4.3.5 Motivations and barriers influencing smart energy management

To conclude the assessment of factors influencing participants' energy management and overall energy culture, the motivations to and barriers for project participation in energy management actions were investigated. As articulated by Mackenzie-Mohr (2000, 2011) understanding motivations and barriers for particular behaviours can provide detailed understanding for targeting behaviours and creating effective engagement programs. Further, these motivations and barriers can highlight underlying factors (both internal and external) influencing the overall energy culture (Bell et al., 2014; Ford, Walton, et al., 2017; Stephenson, Barton, et al., 2015).

To assess how underlying motivations changed over time, the motivations for participation identified in the interviews were compared to the original motivations reported in the initial survey. Some motivations remained at similar levels while others decreased over time (Figure 42). The motivations to save money and to reduce the amount of energy consumed were rated the highest by most respondents at the end of the project. This further emphasizes the value of financial feedback for these households. As participant 3 stated:

> "[…] I am not a big 'save the planet' kind of person […] I'm a 'save money,' kind of person. Which, ultimately at the end of the day yields the same result; because electricity costs money, and if you're saving in one area then you're saving in the other."

For many participants, reducing their carbon footprint did not resonate with them, like participant 4, who "[did not] even know what that was." Participant 11 stated, "I don't correlate with that at all […] it is not a factor." Therefore, engaging homeowners through 'carbon footprint' feedback was not broadly effective to achieve shifts without an educational component to the program. Interestingly, an increased and equally high rating was given to 'trying a new web-based energy management technology' at the interview, indicating a positive experience since the start of the project.

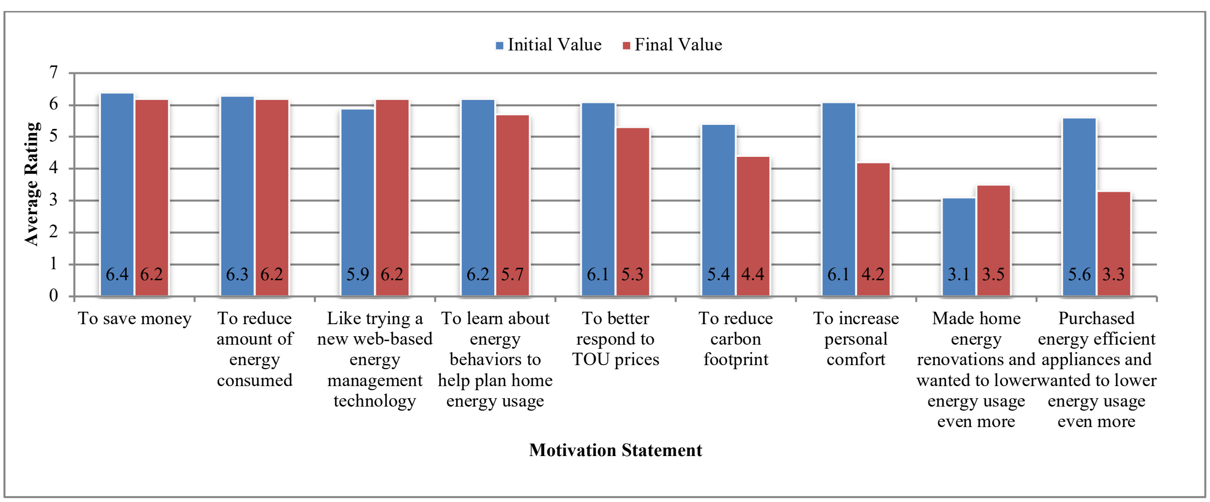

Figure 42 Motivation ratings at initial survey and final interview. Averages of ratings on a scale of 1-7 (strongly disagree to strongly agree), n=12

Additionally, thirty-eight barriers to project participation and energy management were identified throughout the interviews and consolidated into general themes (Table 25). The main barriers were lifestyle and convenience, whereas the main motivations for energy management were to save money and to receive more feedback and information on their consumption levels.

Table 25 Main motivations for and barriers to energy management

Rank	Barriers	Motivations
1	Lifestyle	To save money
2	Convenience	Information on consumption
3	Technical issues with system	Increased awareness
4	Family members	Reduce energy consumption
5	Time	Moral obligation
6	Did not know how else to reduce their consumption	To better respond to time of use prices
7	Lack of flexibility	To reduce environmental impact

These barriers and motivations influenced the engagement with mechanisms throughout the project. Participants were asked to rate the effectiveness of the engagement mechanisms experienced in this study, with the results summarized in Figure 43. It is clear that certain mechanisms were perceived more positively than others; however, certain motivations and barriers related to home energy management influenced these perceptions. The following sections outline main motivations and barriers for home energy management and how they influenced engagement with behaviour-based project interactions (the web portal, the weekly electricity report, goal setting, webinar, reminder emails, and the incentivized control program).

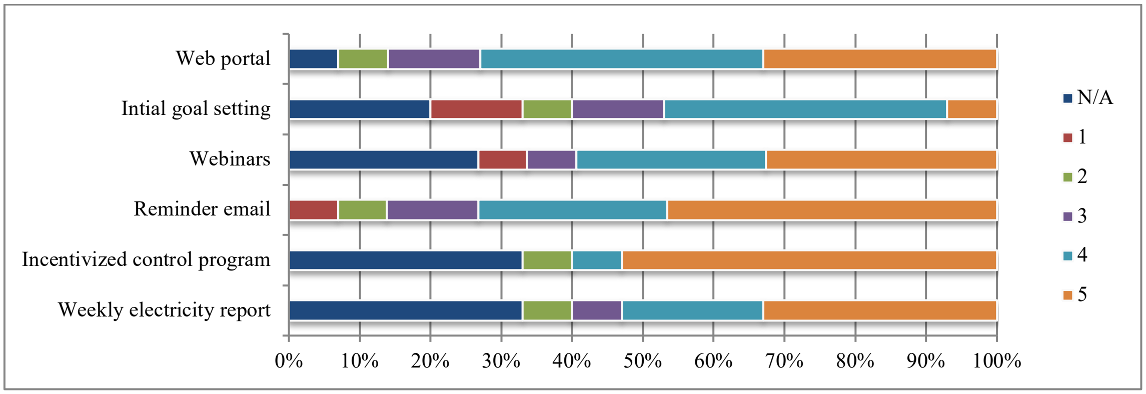

Figure 43 Engagement mechanisms effectiveness ratings by percentage of respondents. Rated on a scale from 1-5 (not effective – very effective), n=15

4.3.5.1 Barriers: Lifestyle and convenience

Throughout the interviews, participants highlighted lifestyle and convenience as substantial barriers for utilizing these smart tools for energy management. Certain participants were not willing to give up their standards of comfort, such as participant 8:

> "I'm not going to change a whole lot. I'm aware that we have to run things at different time periods, because trying to have it running at peak hours when everybody else is using it can result the brownout. So I know that's going to happen, but people have to live, and they have to use their stuff whenever they can."

Interestingly, for some, standards of comfort overrode motivations to save costs, such as participant 9 who articulated, "just because you know convenience and comfort is more important than On-Peak time is. Because I need to use it during the day because it easier, I will just go ahead and use it during the day. Even though I know it's costing me more, I am just going to do it."

For others, it was a matter of using appliances when it was most convenient for them, due to their busy schedules or large families, such as participant 11 "if we need them, we need them […] Being a stay-at-home mom and running a business out of the house, is a little different." These values of convenience are considered barriers to energy consumption changes (Mirosa et al., 2010; Shove, 2003b).

The barrier of convenience was highly articulated in the lack of acceptance and use of the scheduling function. This feature promoted peak shifting practices for discretionary loads through circuit control. Nearly half (46%) of the participants used the scheduling function for energy practices of their thermostat and appliances. Since the scheduling feature conflicted with lifestyle (e.g., people being home during the day) it was perceived as ineffective for energy CDM. Some participants mentioned they would override the feature, showing how norms of convenience inhibited the use of this energy management tool. For example, participant 2 mentioned, “After a while it was unclear […] what the benefit was. Because if I want to use the dishwasher, I will use the dishwasher.” The participants who did not to use the scheduling function chose so due to convenience. As indicated by participant 12, “I am not so sure when you would use the scheduling function. Because we use [our appliances] when we find it convenient. So I left it off and I never used it.” Therefore, norms were the largest barrier to the acceptance of this smart home energy management practice.

Although the project provided opportunities for scripting behaviour through technological changes, household standards for energy use remained prominent barriers to engagement. Personal obligations related to lifestyle and comfort were highly valued and highlight a challenge for engagement to reduce the consumption of ‘invisible’ resources (Shove, 2003b). The participant feedback aligns with Leadbetter and Swan (2012), where appliance control has limited abilities to modify demand before negatively impacting comfort. This emphasizes how norms can highly impact energy practices and adoption of smart home energy management tools.

4.3.5.2 Barriers: Technical issues and preferences

Another set of substantial barriers for participation was technical issues. In particular, these participants identified accessibility issues and difficulty in learning to use the web portal. This was also the case for the scheduling function, including accessibility issues for making quick setting changes. Many respondents expressed preferences for mobile web applications with ‘push notifications’ instead of a passive portal only accessible by computer. In particular, participant 15 stated:

> “The worst part for me is not having access to the web portal in as many forms as necessary for me. A site that would work on your phone when you're running around doing stuff would be great. It would be really interesting to just jump in and see how your house is doing, or if you're going on the train and you just want to look at some graphs because you're thinking about something. That was really difficult to do on the web portal. I think that is the part that would need the most work [...]”

Consequently, technical issues limited participation in smart energy management.

4.3.5.3 Barrier: Family members

As a contextual factor, household profiles were identified as a substantial barrier for energy management. As identified by Ford et al. (2017), contextual factors can considerably influence the energy culture. Household changes were identified through the interviews and most households expressed consumption fluctuations due to household population changes. Households experienced certain family members entering or leaving the home, including members home during peak periods (Table 26).

For example, participant 9 highlighted competing norms and attitudes towards energy management with in-laws living in the home: "There are more adults in the house so it is hard to […] I guess we could communicate that, so it's really our fault […] so it takes that flexibility away. Like more people are using things now." When asked about whether their attitudes reflect those of others in the home, participant 9 further identified "No […] because they do not pay the bill […] it is honestly because we have not really talked about it that much. It all comes down to balancing convenience versus efficiency." Participants with growing families were involved in this study, where 5 out of 15 homes experienced childbirth during the study. This is consistent with the Milton area, which had a population growth of 34% between 2011 and 2016 (Statistics Canada, 2017). Those with newborns and adults home for childcare emphasized the importance of maintaining comfort during this time. As a result of changing profiles, homes experienced changes in norms and practices surrounding energy management.

Table 26 Summary of changes to household population

Household	Change in household population	Energy usage influence	Change to number of people home during peak hours
1	Two adults moved out	Less consumption	2 less people
2	1 child born	Increased peak-hours consumption	1 adult & 1 infant - on maternity leave
3	No changes	No changes	No changes
4	No changes	No changes	No changes
5	1 child born; 1 adult home for childcare	Increased peak-hours consumption	1 adult & 1 infant - working from home
6	No changes	No changes	1 less adult - went from part-time to full-time work
7	1 child born; 1 adult home for childcare	Increased peak-hours consumption	1 adult & 1 infant- on maternity leave
8	1 less adult - adolescent moved out	Increased peak-hours consumption for tv, stove	1 less adult - stopped working from home
9	2 adults moved in	Increased peak-hours consumption	1 child, 2 adults home during the day
10	No changes	No changes	No changes
11	1 more adult, then 1 less adult	Increased fluctuations in consumption due to changes	1 less child, went to school
12	Change in work schedule	Used computer when home	1 adult worked from home (6 months) (used computer)
13	1 child born; 1 adult home for childcare	Increased peak-hours consumption	1 adult & 1 infant - on maternity leave
14	School schedule	Increased peak-hours consumption during the summer	Children home during summer (4 people home) 1 adult – childcare during summer
15	No changes	No changes	No changes

Household dynamics and competing attitudes may influence the overall conservation (Abrahamse & Steg, 2009; Boudet et al., 2016; M. Brown, 1984, 1985), so this was probed in the interview. A majority of participants (60%) expressed that CDM attitudes and actions were the same across household members. However, 27% said that the adults in the household had similar actions and attitudes, while the children did not. Since 13 participating households had children (between 0-17 years), it highlights an opportunity to engage children/teens in this study group to adjust their norms and to improve their energy practices. Existing studies have highlighted tremendous opportunities for residential energy savings by engaging children (Boudet et al., 2016; Lane, Floress, & Rickert, 2014; Ntona, Arabatzis, & Kyriakopoulos, 2015). Interviewees mentioned possible engagement techniques, including a 'kids web portal,' to engage their children, as well as relating their child's consumption to their allowance and activities. Although these contextual factors may be specific to the participants' circumstances, they highlight a substantial factor influencing consumption.

4.3.5.4 Barrier: Time

Participants highlighted that energy management became secondary due to more pressing issues requiring their time, which is consistent with barriers observed in other residential energy cultures studies (M. G. Scott et al., 2016). As indicated by participant 11, certain issues became more important: "Just [issues] happening at the house […] and dealing with the extra stress. Lots of stuff has happened, that is beyond the control of anything so this sort of takes the back burner for some of it."

Additionally, mechanisms requiring additional time to operate and learn to use, or did not align with their time, were not utilized, further highlighting the social challenge of coordination and strong values of convenience inhibiting energy management among households (Shove, 2003b). Therefore, due to competing interests, participants' efficiency measures were not prioritized.

4.3.5.5 Barrier: Lack of knowledge and skills to make additional changes

The lack of knowledge and skills for making additional changes was clearly articulated as a barrier for energy management. In particular, this barrier was strongly related to the goal setting function. Goal setting is identified as a promising form of antecedent intervention (Abrahamse et al., 2005). Although 80%, of respondents set goals, three-quarters of these respondents found goals ineffective due the lack of knowledge to set and meet goals. As participant 3 noted, "I don't know what a proper goal would be. And then again steps to achieve them." Participants also mentioned that they were not motivated to change when unable to meet their goals. As participant 7 stated, "from an initial standpoint, it was hard to know where to start because you don't really know where you were, and what it translated into, in terms of where you wanted to be." Another respondent, participant 15, identified how difficult it was to reach their goals, "I remember setting my goals and quickly realizing that I was never really going to make them." Lack of knowledge is consistent with barriers in other energy cultures studies (M. G. Scott et al., 2016). Providing additional guidance was suggested as a key area to reduce this barrier.

In this study self-determined goals caused confusion and disengagement. This contradicts McCalley and Midden (2002), where self-determined goals were more successful than assigned goals. External factors, such as low electricity prices, may limit the willingness to set and monitor goals in jurisdictions, such as Ontario, with On-Peak prices of C$0.161/kWh at the time of the project (Ontario Energy Board, 2015). Although participants identified that their awareness had increased, careful consideration for engaging consumers on *how* to make additional changes was needed in regard to goal setting.

4.3.5.6 Barrier: Lack of flexibility

As a result of high standards for comfort and convenience, and household contextual factors, participants indicated a lack of willingness to make substantial changes in practices. Consequently, limited use of mechanisms for energy management (e.g., scheduling and control functions) occurred. Participants who did not utilize the thermostat control function mentioned concerns about flexibility and accessibility of the settings, similar to participant 3 who said:

> "I know they wanted to take over my thermostat […] I'm sorry, but I refuse to let that happen. Because you know what they talk about doing this automatic optimization, whether shutting on and off appliances so I can and cannot use them […] With two kids, I cannot deal with that. So I think part of it is my inflexibility […]"

This highlights the challenge of changing conventions and expectations (Shove, 2003b) of homeowners in order to adopt home energy management technologies.

4.3.5.7 Motivation: To save money

As articulated earlier, households' financial motivations strongly influenced their overall energy culture. Participants highly valued that consumption feedback was provided in financial terms (consumption could be shown in kWh, dollars or $kgCO_2$). As noted by Delmas et al. (2013c), information on monetary savings can be useful for engagement. In particular, financial feedback motivated participants to make changes in both material culture and practices. Increased information on appliance consumption costs provided households with opportunities to increase their savings by switching to Off-Peak periods, as well as to remove appliances. For two households, this meant removing servers contributing to higher energy bills (Table 24). Consequently, increased financial information led to some changes in material culture and energy practices, specifically peak shifting.

4.3.5.8 Motivation: Increased consumption information and awareness

Participants highlighted the value of gaining more information consumption data and the ability to see historical appliance-level consumption through the web portal. This aligns with Chen et al. (2014), who found that high-granularity consumption feedback can help to facilitate energy conservation. The importance of awareness and increased information was discussed thoroughly by participants in relation to the weekly newsletter electricity report, which provided a summary of household-level consumption as well as comparative feedback (average and best quintile). As participant 15 mentioned, "[…] it was really nice bites of information based on information from your account that did not require you to log in to the web portal." Others also liked that it was 'very high level.' As noted by Delmas and Lessem (2014), comparative feedback can create social norms for electricity usage, and the combination of public and private feedback can lead to energy savings of up to 20%. The frequency of the electricity reports allowed households to see end-use impacts of their actions. Participant 11 reported, "The weekly piece that lets me know how I've done was very effective […] it was not until then that we really started paying attention." However, those participants with larger households or who operated home businesses considered it inappropriate to be compared to 'average' consumers. Presenting household consumption on a 'per person' measure for comparative feedback was suggested.

This highlights how weekly electricity reports aligned with participants' motivations for changing consumption, providing information comparing the household consumption to others (average and best quintile), along with energy saving tips, engaged consumers and increased their consumption awareness; thus, influencing participants' energy culture.

4.3.6 Instilling a smart energy culture beyond the pilot project

All interviewees identified the continued importance of managing energy consumption beyond the project, aligning with their previously articulated motivations, including saving money, improving efficiency, and reducing waste and environmental impacts. Additionally, participants throughout the interviews mentioned their willingness and desire to continue utilizing disaggregated feedback to understand their energy use. In particular, participant 6 moved to a new home without this technology, and identified interest to install similar technologies to increase awareness and opportunities for management:

> "[Looking at] our first hydro bill [at our new home] I almost vomited, thinking how is that so much money? Because the house was heated floor in the kitchen, which we didn't have at the other place, so my thought was like, did someone turn it on? And then the kids were playing with the controls? And then I was like did someone turn it on and leave it? And, if I have it on all winter how is it going to impact our energy, I have no idea. There's no way to see it. So we were happy to move, but we were not happy that we were unable to monitor our usage at all […] it was a very positive experience."

This highlights an example of how one household's energy culture shifted during the program due to increased awareness and management, facilitated by smart technologies, only to readjust when moving to a different home with different material culture and contextual factors. Additionally, during the program two households installed more advanced home automation and smart home optimization technologies (Table 24). Participants valued this technology to improve their consumption awareness and their potential for increased energy management; therefore, highlighting a few cases of an aspirational shift in household energy culture.

To reduce the main barriers discussed, program elements for conserving energy should not interfere with lifestyle and convenience by being accessible, timely, and concise. For example, participants became disengaged with project mechanisms, such as scheduling and goal setting, if they were 'inconvenient' or interfered with their lifestyle. In addition, participants mentioned a need for a mobile web portal application, along with 'push' notifications for alerts of approaching goals or On-Peak hours.

To maximize the key motivations, smart grid engagement mechanisms for these particular individuals can be aimed at providing 'money-saving' tips or alerts through reducing consumption or transitioning to Off-Peak consumption. Providing more direct feedback on particular strategies for CDM could also aid in reducing the barrier of not knowing how to improve. Setting this into the broader context of Ontario's smart grid development, important considerations can be made and tested with larger cohorts of participants, including: the provision of disaggregated and real-time feedback utilizing financial data, and control, scheduling, and optimization functions.

4.4 Conclusions

This study applied Stephenson et al.'s (2015; 2010) energy cultures framework to understand detailed nuances of household energy behaviours during a multi-year residential smart grid pilot project. This is the first pilot project to utilize the energy cultures framework in both a Canadian and smart grid context – extending the application of the framework both technologically and geographically. Additionally, the depth of qualitative feedback from the three-year pilot project and the multiple engagement mechanisms used to engage and re-engage participants allows for further understanding of household decision-making processes in regard to energy consumption. In this project, participants increased their awareness and practices towards energy management. However, minimal changes in material culture took place due to the 'new suburban build' classification of the homes.

Key findings indicate that although these smart grid early adopters were interested in using this form of smart grid technology for managing their energy consumption, contextual factors and normative standards of lifestyle and convenience strongly inhibited the adoption of both a smarter and more sustainable energy culture within these households (Figure 44). In particular, low energy prices and high standards of comfort resulted in less flexibility for shifting and reducing energy practices. Additionally, the range of household energy cultures within a house, and the fluctuation of household members, caused additional difficulties for changing practices. Although consumption awareness was gained, there remained a large lack of knowledge on how to make substantial and lasting changes in the home, which is consistent with other energy cultures studies (M. G. Scott et al., 2016). In particular, households identified that more hands-on help would have been beneficial. Although a combination of tailored information goal-setting and feedback was used in this pilot project, which is considered effective in the literature (Abrahamse et al., 2007), it was not enough to substantially change participants' energy culture towards smarter and more sustainable energy management. Competing motivations and barriers reduced the perceived effectiveness of these mechanisms, and overall management. These insights derived from a small-scale pilot project, highlight some important nuances that may be missed in larger studies.

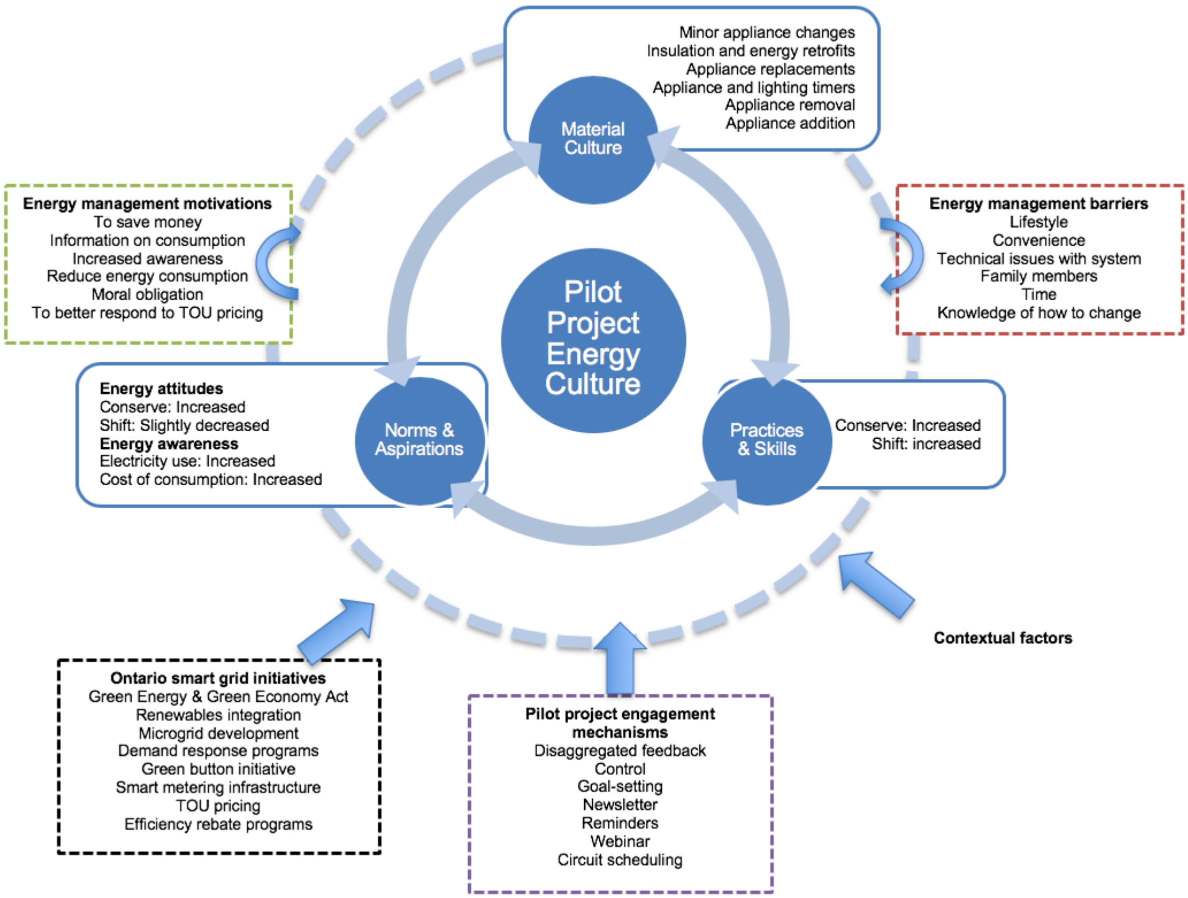

Figure 44 Summary of changes in and influences on participant energy culture experienced during the pilot project. Adapted from (M. G. Scott et al., 2016; Stephenson, Barton, et al., 2015; Stephenson et al., 2010)

Outcomes from this pilot project highlight some of the challenges for changing longer-term energy practices and uptake of smarter energy management. Consumers, although motivated to make changes and to save money, can also be motivated by 'stone-aged psychological biases,' such as self-interest, short-sightedness, status, social imitation and ignorance of problems (Van Vugt et al., 2014). These conventions and personalized standards can inhibit change in practice and materials (Shove, 2003b). This reinforces the importance of integrating social and technical approaches for conservation approaches (D. Scott et al., 2001; Shove, 2003b, 2004). Thus, opportunities exist to extend beyond behavioural theories and intervention approaches to conceptualize the complexity of socio-technical factors influencing household energy consumption, such as the energy cultures framework.

As Ontario is the most advanced province in AMI establishment across Canada, influenced by both landscape and regime level factors, it is important to look into these niche-level forces involved in the uptake of 'smarter' energy practices. The smart grid transition has been driven by the increased capabilities facilitated by the revolution in information and communication technologies as well as the increased emphasis on reducing energy-related climate change impacts (Meadowcroft, Stephens, Wilson, & Rowlands, 2018). However, particular attention needs to be paid to the engagement of consumers with these technologies to create long-lasting socio-technical change at the societal level (Abrahamse et al., 2007; Gangale et al., 2013; Stephens et al., 2013). Although the landscape factors of policies and infrastructure may support an AMI-driven energy culture, consumer norms need to support the uptake of additional changes in practices and material culture to facilitate smarter and more sustainable household energy management. Therefore, using a scalable framework for studying niche-level adoption factors that goes beyond consumption levels can provide detailed nuances related to energy consumption in particular areas. Gaining deeper understanding of regional contexts is integral for smart grid policy development (Mallett et al., 2018), thus, additional studies focusing on these nuances with larger participant groups can be beneficial for smart grid development in Ontario and other jurisdictions.

5. Chapter 5 – Re-engagement in a long-term smart grid study: Influences on household energy management practices

This paper explores the impacts of two feedback mechanisms (electricity report and mobile tablet) on home energy management for re-engagement in a residential smart grid study. Household electricity consumption at whole-house and appliance levels is assessed alongside two phases of participant interviews. This study aims to: (1) determine whether the weekly electricity report and mobile tablet feedback resulted in energy management changes; (2) identify particular energy practices contributing to those shifts, and; (3) highlight underlying factors and participant insights on re-engagement and 'smart' energy management. In this study, household re-engagement through both a weekly electricity report and a mobile tablet resulted in significant changes in laundry consumption, particularly conservation (-16%), and reductions in On-Peak (-31%) and Mid-Peak (-33%) periods during a 10-week autumn monitoring period ($p<0.05$) (n=14). Participant interviews offered a detailed understanding of 'smart' energy management. Participants' Peak shifting flexibility was not equal across different appliance groups, despite On-Peak prices. Whole-house and laundry consumption changes were strongly correlated with participants' self-reported energy management actions. Interviews highlighted mobile device 'overload,' existing energy awareness, and needing action-oriented guidance as key considerations for mobile smart grid re-engagement. For electricity reports, participants acknowledged the 'competitiveness' of normative feedback, the preferences for 'snapshots' of feedback, and the importance of appliance-level suggestions. Therefore, slower forms of feedback (e.g., weekly report) were preferred and changes in laundry practices were evident during autumn re-engagement. The nuances surrounding energy management and long-term engagement presented in this case study bring opportunities to test in larger cohorts.

Keywords: Feedback, demand response, smart grid, electricity, technology, home energy management.

5.1 Introduction

Residential energy conservation and demand management (CDM) is a prominent focus area for achieving climate change goals. The importance of sustainable energy developments is evident globally, but especially in Canada, where the national climate goals involve substantial energy system shifts. In 2016, Canadian residential electricity consumption contributed to 21.4 Mt of CO_2e and presents a substantial opportunity for consumer engagement to achieve climate change policy objectives (Natural Resources Canada, 2019b). The modernization of the electricity grid delivers new strategies for engaging consumers and facilitating these shifts. The smart grid, which brings information and communication technologies (ICT) into the traditional electricity grid, is viewed as the future of the energy grid (Lysyk, 2016; Tuballa & Abundo, 2016). Although residential smart grid technologies bring opportunities to control and shift consumption, the responsibility of residential energy management remains in the hands of consumers. Studies have identified a wide range of consumption differences in energy use (e.g., 200%) in households with identical technical and socio-demographic profiles; therefore, signalling the strong influence of behaviours and the importance of engagement mechanisms to shift consumers' behaviours (Anda & Temmen, 2014; Lutzenhiser, 1993). Encouraging conservation behaviour can be achieved through multiple types of engagement mechanisms for end-users (Abrahamse et al., 2005; Dwyer et al., 1993).

Identifying new methods for engaging and re-engaging consumers over the long-term can deliver insights for long-term residential energy management. The provision of feedback is a promising technique for energy demand response (DR), where different types of feedback can contribute to distinct consumer responses. Various studies have identified a wide range of household energy management impacts associated with the provision of energy feedback (0-25%)(Darby, 2006; Karlin et al., 2015; Sovacool et al., 2017). Smart grid technological developments have brought additional mechanisms for energy management and feedback (e.g., disaggregated feedback, in-home displays (IHDs), and home energy management technologies). However, consumer engagement is crucial for achieving the potentials of smart grid technology (Anda & Temmen, 2014). The Province of Ontario, Canada has made advancements in smart grid infrastructure, with time-of-use (TOU) pricing and large-scale smart metering integration; therefore, Ontario has become a prominent testing ground for residential smart grid feedback and engagement methods (Hiscock, 2014; Lazowski et al., 2018; Lysyk, 2016; Winfield & Weiler, 2018). This smart grid progress presents opportunities for mixed-methods research on long-term consumer engagement with these technologies for favourable CDM shifts, aligning with climate change objectives.

This paper presents a mixed-methods analysis of two forms of feedback provided for re-engagement at the end of a long-term[32] Ontario residential smart grid study. Initial project engagement for energy management (e.g., scheduling and control) and feedback, came in the form of

[32] In this paper the authors define long-term as greater than one year.

a web portal. The levels of portal engagement reduced after the first seven months of use; therefore, providing an opportunity for re-engagement (Khorrami, 2014). This study aims to: (1) determine whether re-engagement through a weekly report and mobile tablet influenced participants' energy management; (2) identify specific energy practices contributing to the observed changes, and; (3) highlight underlying factors influencing energy management and users' experiences with smart grid re-engagement mechanisms.

This paper integrates both qualitative and quantitative findings to demonstrate the effect of both aggregate (whole-house) and disaggregated (appliance-level) feedback to re-engage participants. This paper also assesses whether participants' self-reported consumption changes aligned with observed changes. The following sections will (1) provide an overview of the literature pertaining to the residential smart grid, energy feedback, demand response and consumer engagement; (2) highlight the methodology used for the analysis; (3) present the findings, and; (4) integrate the findings with the literature to offer insights for research and practice in residential smart grid engagement and energy management.

5.2 Literature review

5.2.1 The smart grid

The smart grid involves the integration of ICT in the energy grid and comprises of a network of smart meters and new technologies to facilitate the sensing, control, and optimization of energy flows. (Ford, Pritoni, et al., 2017; Karlin et al., 2013). Although less than 10% of meters utilized globally are smart meters, they are expected to be rapidly introduced into global energy grids (Karlin et al., 2015). The United Kingdom has targeted to have smart gas and electricity meters in combination with in-home displays in all homes by 2020; the United States are expected to roll-out 65 million smart meters by 2020; and the European Union has aimed for 80% of all meters to be smart meters by 2020 (Faruqui et al., 2010a; Karlin et al., 2013; Sovacool et al., 2017). Ontario installed 4.2 million smart meters across the province as of 2014, becoming a Canadian leader in smart meter deployment (Lazowski et al., 2018; Lysyk, 2016; Winfield & Weiler, 2018).

Research has identified opportunities for engaging households in the smart grid for DR (Anda & Temmen, 2014; Chen et al., 2014; Sovacool et al., 2017). As noted by Anda and Temmen (2014), and further emphasized by Ellabban et al. (2016), benefits from the smart grid can only be achieved through the cooperation and engagement of end-users. These benefits can be achieved through engaging end-users with multiple intervention types, including feedback devices, analytical tools, mobile and web applications, normalization of feedback between peers, optimization and control, and dynamic pricing mechanisms (Anda & Temmen, 2014; Stephens et al., 2015; Strengers, 2013). Therefore, the smart grid has introduced increased capabilities for energy data collection, feedback provision, and engagement at different scales than previously available.

Although smart grid technologies bring potential opportunities for household electricity management (HEM), a multitude of factors influence both household consumption and the effectiveness of these technologies. These factors occur within personal and contextual domains and include technological efficiencies, routines, capabilities, and behaviours (Kowsari & Zerriffi, 2011). Stephenson et al. (2010) frame this complexity as an 'energy culture' influenced by material cultures (i.e., technological efficiencies and the built environment); norms and aspirations surrounding energy use, and; the practices and skills contributing to consumption patterns (Ford, Pritoni, et al., 2017; Stephenson, 2018; Stephenson, Barton, et al., 2015). Since a wide range of factors influence household energy consumption, assessing types of energy practices shifts and collecting household perspectives can provide insights into how energy cultures change over time.

Domestic energy consumption is embedded within activities and routines. Grouped by function (e.g., food; mobility; cleanliness; leisure and work; comfort and ambiance) these energy actions can exist in short-term patterns, cycles or rhythms of consumption, and converge at societal synchronicities of temporal demand (Naus, 2017; Shove, 2003a; Shove & Walker, 2014; Walker, 2014). Norms, materials, and skills influence these energy practices (Shove et al., 2012). Furthermore, the emergence of smart grid technologies has introduced additional scalable practices for home energy management, such as energy monitoring, the timing of demand, energy conservation, energy sharing, energy storage, and co-/self-production (Naus, 2017). Empirical analysis on the temporalities of energy practices is integral and remains limited within the existing literature (Greene, 2018). Furthermore, analysis of feedback and long-term appliance-level consumption changes in the smart grid can develop knowledge on smart grid engagement and re-engagement and related smart grid practices among residential consumers.

5.2.2 Feedback

Feedback refers to the provision of information that can be used to shape end-use behaviour and has been considered an essential dimension of behaviour change. The influence of energy feedback on consumption is widely studied. Studies have reported mixed results on savings (0 to

25%), with a wide range of participants (approximately 11-2000), and a variety of timeframes (approximately 0.5-42 months) (Becker, 1978; Darby, 2006; Dobson & Griffin, 1992; Gleerup, Larsen, & Togeby, 2007; Grønhøj & Thøgersen, 2011; Harries et al., 2013; Houde, Todd, Sudarshan, Flora, & Carrie Armel, 2013; Karlin et al., 2015; Mountain, 2012; Oca, Corgnati, & Buso, 2014; Schleich, Klobasa, Gölz, & Brunner, 2013; Vassileva, Odlare, Wallin, & Dahlquist, 2012; Winett, Neale, & Grier, 1979). Longer-term engagement studies (over 1 year), with a range of 11-72 participants, have observed either insignificant or mixed savings (Hargreaves et al., 2013; Nilsson et al., 2014; Smeaton & Doherty, 2013). Wemyss et al. (2019), found energy application savings were not realized one year after the intervention; however, some studies observed long-term success. For example, a program applying social integration and feedback in the Netherlands resulted in long-term energy and water conservation (Staats, Harland, & Wilke, 2004). Furthermore, studies have shown the effectiveness of combining types of smart grid feedback on energy consumption, such as paper statements and web portal feedback (-4.5%) (Schleich et al., 2013). Overall, this highlights the inconsistency of energy feedback effectiveness, over short- and long-term scales for CDM.

A variety of characteristics can cause the variability of feedback effectiveness for promoting demand management. They include elements such as immediacy, data collection, comparisons, the integration of control devices, calls to action, data granularity, content, and presentation (Karlin et al., 2015). Feedback can either be direct (immediate feedback provided from the meter, e.g., in-home display) or indirect (not immediate, e.g., monthly bill or report) (Darby, 2006). Savings of direct feedback range from 5-15%, whereas a range of 0-10% was evident with indirect feedback (Darby, 2006; Ehrhardt-Martinez et al., 2010). Direct feedback has been observed as more effective due to its provision of, potentially, real-time and disaggregated consumption feedback (Darby, 2006).

Feedback can also be comparative or individualized. Normative feedback compares private consumers' feedback with societal levels (Darby, 2006; Delmas, Fischlein, & Asensio, 2013a; Karlin et al., 2015). Delmas and Lessem (2014) identified a 20% savings from a combination of normative and private feedback. However, these benefits have been contested in the literature with the potential for a rebound effect (K. Buchanan et al., 2015; Karjalainen, 2011). Normative feedback can appeal to participants' competitive nature and has been identified as effective in contests with rewards (Abrahamse et al., 2005; Delmas & Lessem, 2014; Midden et al., 1983; Peschiera et al., 2010; Wood & Newborough, 2007). Therefore, the implementation of different types of HEM feedback can occur at different scales.

The frequency of feedback can also influence consumption, where more frequent feedback can provide more behaviour-specific information and is more effective (Abrahamse et al., 2007; Darby, 2006; Karlin et al., 2015). The granularity of energy feedback can also influence the level of consumption change(s). A variety of feedback levels for energy feedback can be provided, including fuel consumption, appliance use, historical consumption, room comparisons, and energy use predictions (Wood & Newborough, 2007). Evidently, multiple factors influence the effectiveness of feedback on HEM, emphasizing the importance of design features when studying the influence on demand response and consumer engagement.

Understanding participants' perspectives on feedback mechanisms for CDM is vital for effective program development and related behaviour change (Crosbie & Baker, 2010). Existing studies provide insights on interventions, where a majority of studies focus on intervention effectiveness and quantitative outcomes, either through surveys or pre-post consumption analysis (Asensio & Delmas, 2015; Chen et al., 2014, 2015; Delmas & Lessem, 2014; Ek & Söderholm, 2010; Gangale et al., 2013; Harring, 2015; Jacobsen & Kotchen, 2011; Jain et al., 2012; McCalley & Midden, 2002; Ueno et al., 2006; Wood & Newborough, 2003). Since energy consumption is rooted in daily activities, understanding consumers' interactions and user experiences through qualitative methods can deliver insights for feedback development (Chen et al., 2015; Dietz et al., 2009; Karlin et al., 2017; Mills & Schleich, 2012). Qualitative methods deliver additional insights on contextual factors influencing energy consumption (e.g., barriers, motivations, socio-demographics etc.,) (M. Brown, 1984). Utilizing mixed-methods research approaches also provides a comprehensive overview of behavioural impacts and intervention effectiveness. It is crucial to develop the understanding of energy and demand management practices to identify additional CDM opportunities (K. Buchanan et al., 2015; Wilhite, Shove, Lutzenhiser, & Kempton, 2000). At the time of this study, limited qualitative studies focused on intervention implementation, effectiveness, and impact(s) on household decision-making in the smart grid (Burchell et al., 2016; Crosbie & Baker, 2010; Hargreaves et al., 2010, 2013; Karjalainen, 2011; Nilsson et al., 2014). Recent studies have incorporated mixed-methods approaches for understanding consumer engagement with energy (Ford, Walton, et al., 2017; Wemyss et al., 2019), which provide increased opportunities for studying user experience with smart grid technology for energy management.

Opportunities to integrate user experiences and energy efficiency in research are available (Karlin et al., 2017). Although users' preferences have a significant influence on intervention effectiveness (T. Brown & Wyatt, 2010; Karjalainen, 2011), many studies focus on behavioural impacts (e.g., attitudes and awareness), rather than integrating intervention usability, design or users' preferences with these findings (Abrahamse et al., 2007; Delmas et al., 2013c). Additionally, studies focusing on quantitative consumption effectiveness often analyze short-term effects (less than one to one year), and provide limited analysis of re-engagement; therefore, presenting an opportunity to assess long-term smart grid engagement and re-engagement (Abrahamse et al., 2007; Chen et al., 2014; Crosbie & Baker, 2010; Delmas et al., 2013c; McCalley & Midden, 2002). Long-term studies convey insights on lasting trends and long-term capabilities of interventions (K. Buchanan et al., 2015; Hargreaves et al., 2010). Consequently, insights on the influence of re-engagement in long-term smart grid studies are limited in existing research and deliver opportunities for development.

5.2.3 Ontario's smart grid

The province of Ontario became a leader in smart grid transformations within Canada as a result of the *Smart Metering Initiative* and related implementation of smart metering infrastructure (Lysyk, 2014, 2016). Additionally, the province established CDM programs to manage electricity consumption, utilizing smart metering infrastructure for the implementation of a TOU pricing structure to encourage Peak shifting (Kantor et al., 2015; Lazowski et al., 2018; Winfield & Weiler, 2018). Ontario's TOU pricing utilizes a three-level pricing structure where On-Peak prices are 1.8 to 2 times more compared to Off-Peak periods (Table 27) (Ontario Energy Board, 2015). Therefore, CDM opportunities were key motivations for Ontario's smart metering infrastructure implementation.

Table 27 Ontario historical electricity commodity prices during the study

Time frame start	Off-Peak price (¢/kWh)	Mid-Peak price (¢/kWh)	On-Peak price (¢/kWh)
May 1, 2013	6.7	10.4	14.0
Nov 1, 2013	7.2	10.9	13.5
May 1, 2014	7.5	11.2	12.9
Nov 1, 2014	7.7	11.4	12.4

Source: (Ontario Energy Board, 2015)

5.2.4 Energy Hub Management System study

The Energy Hub Management System (EHMS) study was an opt-in residential smart grid study from 2010 and 2016 in Milton, Ontario. Participants for the study were recruited through email by the utility company. Twenty-five households opted-in and during the study, households received aggregate and disaggregated (appliance-level) consumption feedback. Participants also received technologies to monitor and control their circuit-level electricity consumption. Although conservation through appliance load-shifting was observed after the first study year, levels of initial project web portal engagement declined after seven months (Kantor et al., 2017; Khorrami, 2014). Therefore, presenting a strong an opportunity for project re-engagement.

In the final year, participants were prompted to re-engage with two feedback mechanisms: a weekly electricity report and a mobile tablet. This paper assesses the influence(s) of these two engagement mechanisms on HEM practices and highlights users' experiences with these mechanisms. This paper highlights whole-house and appliance-level consumption changes to assess the impact(s) of the re-engagement mechanisms. Overall, the combination of both participant interviews and long-term high-resolution consumption data provides a thorough assessment of re-engagement influences on HEM practices.

5.2.5 Contributions

A multitude of complex factors influence household energy consumption. As identified by Stephenson et al. (2010), consumption is influenced not only by technological efficiencies and the built environment, but also energy actions and skills, as well as related energy management norms and aspirations. Similarly, Darby et al. (2018) identify that technologies, activities, and service expectations influence HEM, and coexist and coevolve over time. Therefore, a detailed understanding of consumer responses can bring valuable insights into consumers' engagement with smart grid technologies for making aspired DR shifts. Furthermore, there is a need for understanding intervention impacts on disaggregated consumption loads to develop knowledge for managing appliance uses (Kantor et al., 2017). These elements offer opportunities to focus on user-centred feedback through qualitative or mixed-methods smart grid research studies and to investigate long-term influences of CDM interventions.

At the outcome of this review, there are three key areas to contribute to the literature. First, assessing long-term smart grid energy management practices at both aggregate and disaggregated levels; second, applying mixed-methods approaches to understand impacts on energy management practices, and; third, assessing the influence of multiple types of feedback on consumer re-engagement in long-term smart grid residential programs.

Three elements of this study specifically fulfill the previously articulated gaps in the literature. Firstly, by investigating the impact(s) of two types of energy feedback with smart grid study participants (tablet, and electricity reports) at the end of a long-term smart grid study for re-engagement. Secondly, by assessing changes in consumption during the re-engagement period at both whole-house and appliance levels. Thirdly, by assessing qualitative feedback gathered from participant interviews in conjunction with consumption patterns. These three elements fully integrate detailed information on changes in energy management practices as well as related influencing factors.

5.3 Methods

5.3.1 EHMS study: Participant household profiles

The EHMS study was set in Milton, Ontario, a growing suburban town outside of Toronto. Participating households could be classified as ‘new suburban build’ where the majority of households were detached two-storey homes, built after 2000, and over 1500 ft^2 in size (1500–2999 ft^2). Households also had incomes between CAD 60,000 - 150,000 + before taxes, had post-secondary education levels (Bachelor’s degree or higher), and had average household sizes of four people. These participant attributes align with the census population data for Milton, Ontario (Lazowski et al., 2018; Statistics Canada, 2017) (Table 28). Although household changes (e.g., population, schedules, building envelope upgrades, appliance upgrades etc.,) occurred during the study, participant interviews identified limited changes that would substantially influence consumption in the re-engagement period.

Table 28 Household profiles

HH	Age (Years)					Total	Household Income (Before Taxes)	Highest Education in Household	Dwe-lling size	Year built	Style of dwelling
	0-5	6-13	14-17	18-64	65+						
1	0	1	1	3	0	5	$60,000-$69,999	Bachelor's Degree	1500-1999	2000-2006	Detached two or more storey
2	1	0	0	2	0	3	$150,000 +	University Certificate or Diploma below Bachelor Level	3000-3499	2000-2006	Detached two or more storey
3	2	0	0	2	0	4	$150,000 +	Master's Degree	2500-2999	2007-2010	Detached two or more storey
4	2	0	0	2	0	4	$125,000-$149,000	University Certificate or Diploma below Bachelor Level	2500-2999	2000-2006	Detached two or more storey
5	0	2	0	2	0	4	$100,000-$124, 999	Bachelor's Degree	3000-3499	2000-2006	Detached two or more storey
6	2	0	0	2	0	4	$125,000-$149,999	Bachelor's Degree	2500-2999	2007-2010	Detached two or more storey
7	0	0	0	3	0	3	$150,000 +	Bachelor's Degree	1500-1999	1970-1979	Detached two or more storey
8	1	1	0	2	0	4	$90,000-$99, 999	Bachelor’s Degree	1000-1499	2000-2006	Row housing (attached on both sides)
9	1	2	0	5	0	8	$150,000 +	Bachelor's Degree	2500-2999	2007-2010	Detached two or more storey
10	1	0	0	2	0	3	$90,000-$99,999	Bachelor's Degree	2500-2999	2007-2010	Detached two or more storey
11	1	1	0	2	0	4	$90,000-$99, 999	Bachelor's Degree	1500-1999	2000-2006	Semi-detached two or more storey
12	0	2	1	2	0	5	$90,000-$99,999	University Certificate or Diploma below Bachelor Level	1500-1999	2000-2006	Detached one storey
13	2	2	0	2	0	6	$80,000-$89,999	Bachelor's Degree	2000-2499	2000-2006	Semi-detached two or more storey
14	0	0	0	2	0	2	$150,000 +	Bachelor’s Degree	2000-2499	1970-1979	Detached two or more storey

Re-engagement with the tablet and electricity reports occurred following the initial study engagement mechanisms, including detailed electricity feedback through a web portal that enabled scheduling, optimization, and goal-setting features. Reminder emails and webinars also engaged participants during the initial study stages (Lazowski et al., 2018). This study utilizes feedback collected through two phases of interviews and electricity consumption data collected following re-engagement in the summer and autumn of year 3 in the multi-year study.

5.3.2 Weekly electricity report feedback

Active participants received weekly whole-house and appliance-level electricity reports in the summer and autumn of year 3. The reports, delivered as a PDF file over email, provided weekly consumption feedback at whole-house and appliance-levels in comparison to the previous year. Additionally, the reports provided appliance-level conservation tips and normative feedback compared to other participants (Figure 45). Technical issues related to meter logging connectivity resulted in data constraints during the feedback periods; therefore, only certain houses were available for analysis. Seven households received the newsletter in the summer of year 3 (June – August) for a 12-week period. An additional 7 households, 14 households in total, received both the weekly electricity reports and a tablet in the autumn of year 3 (September – December). The electricity report design incorporated 7 main elements: normative/historic comparison, consequent and direct information, tailored and appliance specific feedback, multiple measures of consumption, persistent and consistent delivery, reinforcement of sustainable behaviours, and presentation clarity and attractiveness (Huber, 2016).

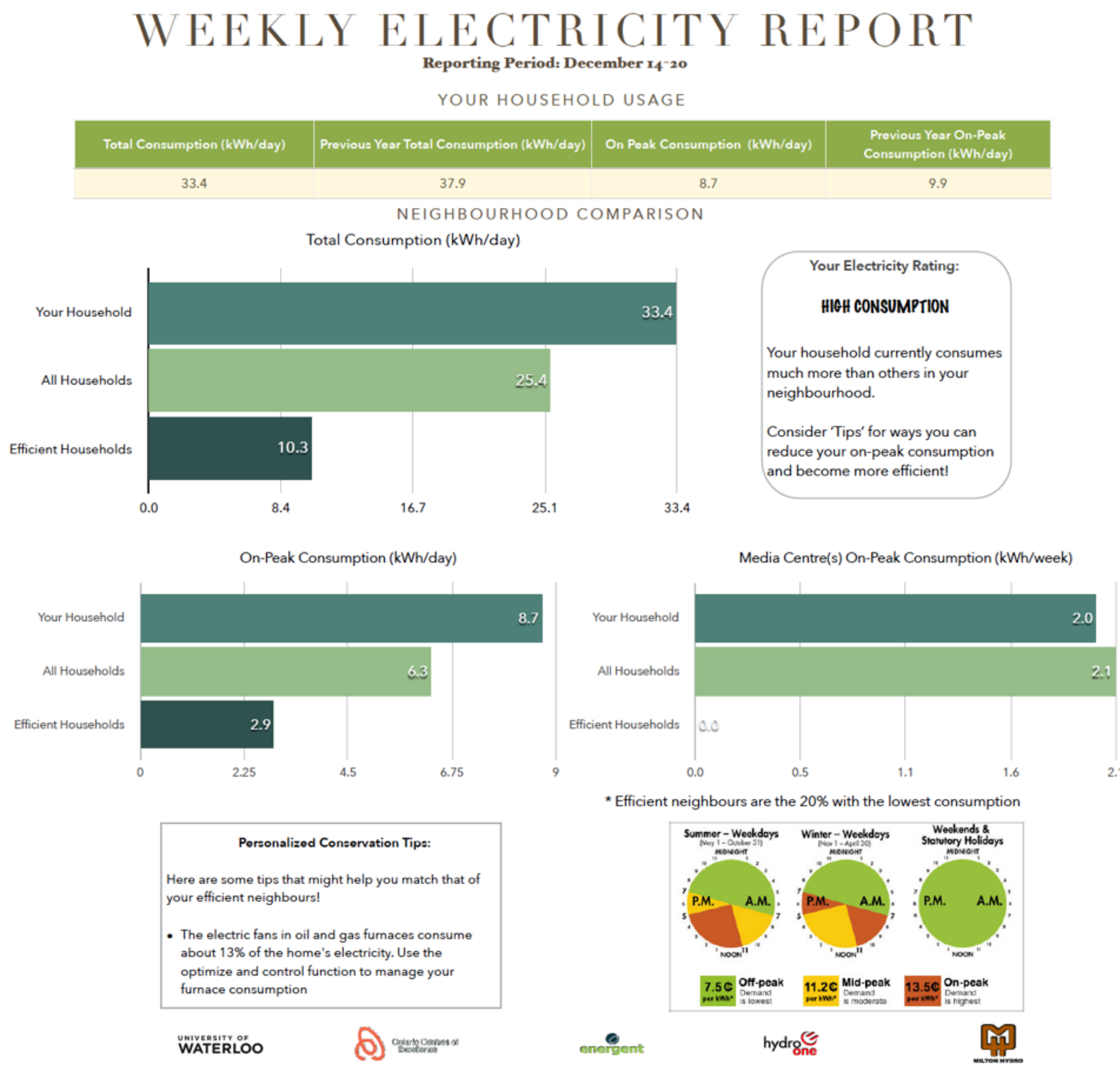

Figure 45 Example of weekly electricity report

5.3.3 Mobile tablet feedback

All fourteen participants received the tablet near the end of the study (autumn, year 3). The tablet provided access to a mobile version of the initial web portal[33] engagement mechanism introduced in year 1 (Figure 46). The tablet provided participants with access to the mobile application, which was also accessible on other devices. The tablet can be classified as a sensor display and closed management network by Karlin et al.'s (2013) typology of HEM technologies. The tablet had multiple features, including a dashboard home page, TOU clock, appliance usage feedback (individual and multi-appliance), goal-setting functions, control settings, and optimization settings. The tablet was not 'locked' and, therefore, could be utilized for functions other than energy feedback (e.g., searching the internet, checking emails, entertainment, etc.,). Table 29 provides a summary of the tablet's elements alongside the weekly electricity report.

Figure 46 Mobile tablet feedback device

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[33] The web portal was an online portal where participants could access their circuit-level feedback in near real-time (five-minute intervals) and adjust settings related to the study.

Table 29 Design dimensions of study feedback mechanisms, adapted from: (Froehlich, 2009)

Design dimension	Electricity report	Tablet
Information delivery	Emailed PDF	Digital display, tablet
Accessible information	Normative comparison (average, below average, above average); Total weekly consumption; Total weekly On-Peak consumption; Specific weekly appliance consumption; Personalized consumption tip; TOU period chart	Optimizer; Appliance-level feedback; Scheduling settings; Energy goals; Main page: carbon footprint, total daily electricity, goal progress, current TOU period
Feedback frequency	Weekly	Real-time from circuit readers and smart meter
Measurement unit	Consumption (kWh)	Consumption (kWh); monetary ($/kWh); CO_2 emissions; and TOU period
Data granularity	Whole-house, On-Peak, and appliance-level for 1 week, and historical comparison (previous year)	5-minute intervals at whole-house and appliance-levels for all time periods
Presentation medium	Coloured PDF document	Colour screen; digital display
Location	On the computer or printed	Tablet
Recommending action	Personalized tip for consumption change	No specific call to action
Comparisons	Time comparison: previous year; Normative comparison: study participants, average & high-efficiency; Appliance-level comparison	Time comparison: multi-year - consumption history over the entire study; Circuit-level comparison

5.3.4 Consumption data collection[34]

The utility and study partners collected participants' whole-house and appliance-level consumption data from the beginning of the study until closure. The local electricity company obtained hourly smart meter data for the study period. Compared to the Ontario average, these households are considered a suitable representation of Ontario urban residential consumers, where the annual consumption for participant households was 9931 kWh, and the Ontario average was 9250 kWh in 2013 (Figure 47) (Kantor et al., 2017) (Statistics Canada, 2018).

[34] The participant ID utilized throughout this paper was randomly assigned to ensure participant anonymity.

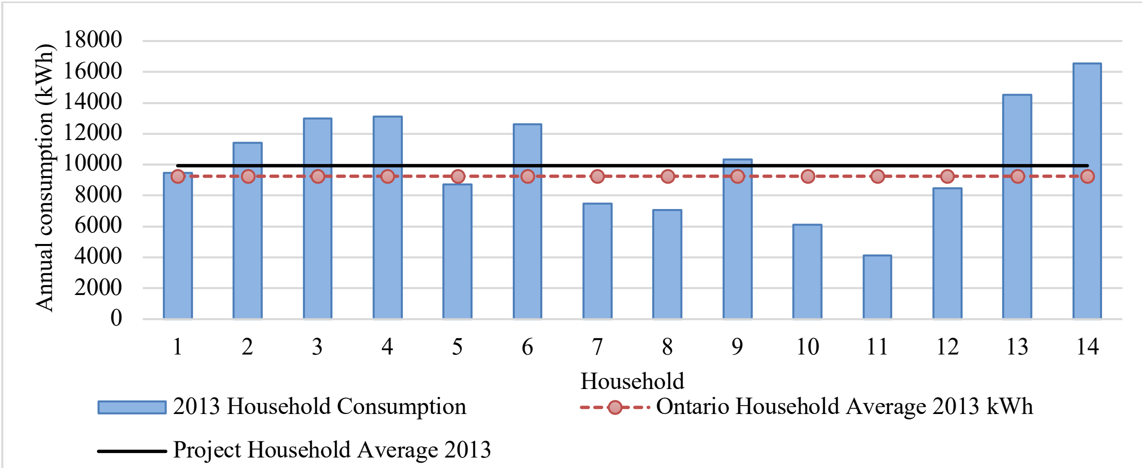

Figure 47 Annual household consumption (2013), kWh, source: (Statistics Canada, 2018)

A partnering company, Energent, obtained hourly appliance consumption data through circuit-level data readers through either the smart panel or Brultech-level devices (Kantor et al., 2017).[35] The hourly appliance-level consumption data allowed for a detailed assessment of temporal changes in HEM practices related to cooking, dishwashing, cooling, laundry, and entertainment (Table 30).

Table 30 Overview of energy practices assessed, sources: (Milton Hydro, 2019; Toronto Hydro, 2017)

Practice	Appliance(s)	Typical range of monthly usage (Milton, Ontario)
Cooling	Air Conditioner (A/C)	A/C Central 850-3000 kWh
Entertainment	Media systems and centres, gaming devices	Television – 5-35 kWh Computer – 5-32 kWh
Cooking	Oven and stove	125-625 kWh
Laundry	Washer and drier	Washer 33-196 kWh Drier 30-140 kWh
Dishwashing	Dishwasher	20-102 kWh

5.3.5 Consumption data analysis

The consumption analysis was divided into two seasonal periods groups to assess the HEM impacts of the re-engagement mechanisms. The first period was a 12-week summer period (within June – August) for seven households introduced to only the report. The second period was a 10-week

[35] The data collection process and technological details are presented in detail by Kantor et al., (2017).

autumn period (within September – December) where 14 households had both the tablet and the weekly electricity report. The particular timeframe differed per household (Table 31). The number of participants for each appliance-level consumption measure varied, based on data collection availability and circuit or plug-level connection. Since this analysis included disaggregated consumption loads (such as laundry and entertainment appliances), which are largely independent of outside temperature, weather normalization was not performed, similar to Kantor et al. (2017).

Data analysis between both monitoring (year 3) and baseline periods (year 2) assessed changes in consumption (Table 31). Hourly data were aggregated to weekly levels to assess changes in average weekly consumption between the baseline and monitoring periods. The monitoring period was calculated during the weeks following the re-engagement introduction (either 10 or 12 weeks, year 3). Baseline consumption was calculated for each household for the same period in the year prior to re-engagement (year 2). Baseline and monitoring consumption were calculated for the total and TOU period consumption for whole-house and disaggregated loads

Paired t-tests between the baseline and monitoring periods assessed changes in consumption. This procedure assessed whether the mean of the baseline consumption was the same as the mean of the monitoring period consumption and whether these differences were significant. This analysis is assessed by the hypothesis below, where *L is* the particular energy load:

H_0: Weekly Mean Consumption $_{\text{Monitoring}L}$ = Weekly Mean Consumption $_{\text{Baseline}L}$

This study also determined whether participants' self-reported level of energy management correlated to consumption levels. Spearman's rank-order correlation assessed the relationship between household energy consumption and interviewees' (n = 12) rankings on energy management action and awareness. Average weekly consumption for the 10-week autumn period was used to compare consumption with participants' ratings, to test the hypothesis:

H_0: $\rho = 0$, the correlation coefficient is equal to zero; there is no association between the variables.

Table 31 Summary of consumption analysis periods

Engagement	Base period	Monitoring period	Households
Electricity report introduction in summer	12 weeks summer year 2 (June – September 2013)	12 weeks summer year 3 (June – September 2014)	n = 7 (1, 3, 4, 6, 11, 13, 14)
Electricity report and tablet introduction in autumn	10 weeks – autumn year 2 (September – December 2013)	10 weeks – autumn year 3 (September – December 2014)	n = 14 All households

5.3.6 Tablet interaction and engagement: Google analytics

Google Analytics data analysis services were used to assess the engagement with the mobile web application. Google analytics collected tablet log-in and user interaction data from January 1, 2015 to project closure. This directly measured: (1) user interaction, in general and per page visit; (2) length of user interaction in general, and per page visit, and; (3) access location and device used.

5.3.7 User experience interviews

Qualitative feedback was gathered and utilized to gain detailed insights on the households' engagement with study interventions. Two phases of semi-structured participant interviews were conducted. The first phase of interviews took place in the Autumn of year 3 of the study and assessed participant feedback and HEM changes. The second phase of interviews took place 1 year after tablet introduction (Autumn year 4). These interviews collected participant feedback on the study and the impact of re-engagement mechanisms on household energy management (Table 32). Both interviews were approximately one-hour, and questions were both structured (e.g., Likert scales, rating, and multiple choice) and open-ended questions. One researcher coded the transcribed interviews with NVivo to analyze main findings.

Table 32 Data collection and intervention procedure

Element	Method	n	Timeframe	Analysis
Re-engagement Part 1	Electricity reports	7	Summer Year 3	12-week comparison between monitoring and baseline years
Re-engagement Part 2	Electricity reports and tablet	14	Autumn Year 3	10-week comparison between monitoring and baseline years
Interview 1	Semi-structured interviews, in person and over the phone	13	Autumn Year 3	Qualitative coding of transcribed interviews using NVivo Quantitative comparison between responses from the interview and initial study survey
Interview 2	Semi-structured interviews over the phone	12	Autumn Year 4	Qualitative coding of transcribed interviews using NVivo Quantitative comparison between responses from interview and initial survey
Consumption data collection	Circuit-level consumption data and whole-house consumption data	14	Year 1 to study closure	Quantitative analysis utilizing excel and SPSS
Google analytics data collection	Mobile web application	14	Year 3 to study closure	Quantitative analysis using data from Google analytics

5.3.8 Limitations

This analysis was subject to certain limitations. There was a limited sample size due to technical issues (e.g., connectivity and data transmission) and participants withdrawing from the multi-year study. These factors resulted in limited participants for both qualitative and quantitative analysis. For the electricity report, these technical issues resulted in inconsistent participation. Thirteen re-engaged participants participated in the first interview, and twelve were available for the second interview. For whole-house consumption, 14 households were available for analysis; however, due to technical issues and variability of appliances in participants' homes, the numbers for appliance-level data varied. Limited sample sizes remain consistent with other smart grid pilot projects in various jurisdictions, due to the intrusive nature of some smart grid technologies and the financial resources required for obtaining these technologies (Bager & Mundaca, 2017; Bradley et al., 2016; Hansen & Hauge, 2017).

Additionally, the Google analytics data measured mobile engagement from January 1, 2015, until project closure. Consequently, this only collected device engagement 1-4 months after the tablet introduction (September – November 2014). Although initial portal engagement data are not available, long-term engagement levels can be assessed to compare tablet re-engagement with web portal engagement. Despite these limitations, the depth and longevity of the data available provide a triangulated analysis of consumer re-engagement in a long-term residential smart grid study.

5.4 Results

The following sections outline the changes in whole-house and appliance-level consumption, an assessment of reported actions and awareness levels in comparison to these changes, followed by an overview of the participants' qualitative feedback from two stages of participant interviews.

5.4.1 Consumption changes in the summer period

5.4.1.1 Whole-house consumption

The 12-week summer analysis included seven households. The majority of household consumption during the monitoring period (66%) was during Off-Peak periods (M = 181.40 kWh, SD = 72.19 kWh), which remains consistent with Ontario households, where 65% of household electricity consumption is during Off-Peak periods (Toronto Hydro, 2017). Participants during the summer period reduced their total whole-house weekly consumption by an average of 7% (-19.73 kWh), mostly during On-Peak Periods (-10%); however, these shifts were not statistically significant ($p>0.05$).[36]

5.4.1.2 Disaggregated consumption

Appliance consumption practices during the 12-week summer period did not experience statistically significant reductions or shifts; however, some interesting trends can be highlighted (Figure 48). Observed reductions occurred in entertainment consumption (-25%, n=6), particularly during On-Peak periods (-33%). Although overall laundry consumption increased, a shift was visible, specifically in On-Peak and Mid-Peak consumption reductions (-54%, and -21%, respectively, n=7), and Off-Peak consumption increases (+23%, n=7). Substantial increases in On-Peak and Mid-Peak dishwasher usage were also evident. Air conditioning (A/C) consumption was significantly less in the

[36] The results tables for each circuit-level are in Appendix C.

12-week monitoring period (M= 74.06, SD = 27.15) compared to the base period (M=107.02 SD, 30.68); t (5), *p*=0.03.[30] However, climatic influences were evident where more cooling degree days (CDDs) were present in the base period (274 CDDs) compared to the monitoring period (215 CDDs). Therefore, although not statistically significant, a story of shifting, particularly in laundry practices, was observed in households re-engaged with the electricity report during the summer (Table 33).[37]

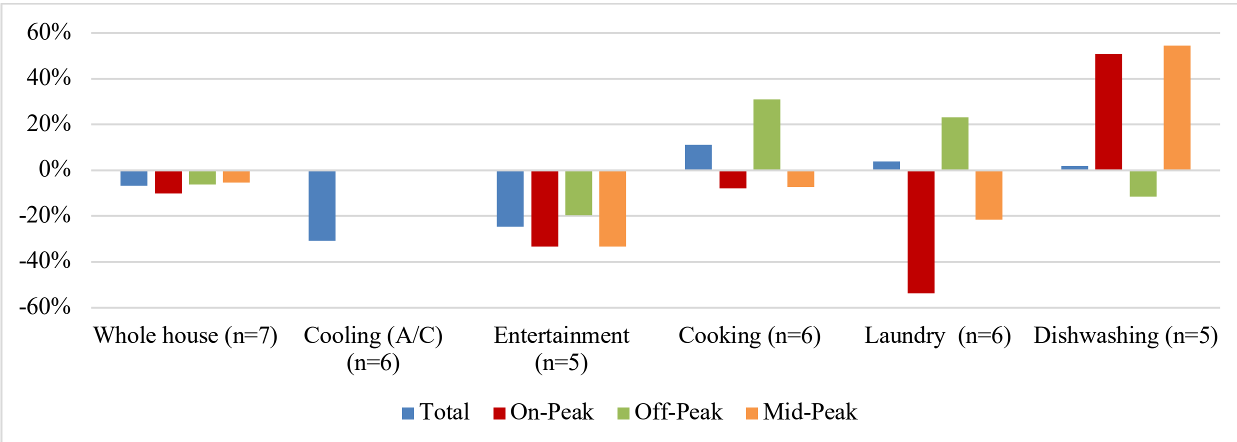

Figure 48 Percent change in average weekly consumption (%) by appliance and TOU period, 12-week summer[38]

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[37] The results tables for each circuit-level are in Appendix C.
[38] Only total AC consumption was analyzed since Peak shifting is difficult for this appliance.

Table 33 Summary of household consumption changes, 12-week summer period, average weekly kWh

Appliance	Total			On-Peak			Off-Peak			Mid-Peak			
	M	SD	Δ	M	SD	Δ	M	SD	Δ	M	SD	Δ	n
Whole House Base	293.19	113.93	-19.73	50.09	22.25	-5.06	193.38	83.67	-11.98	49.72	17.60	-2.69	7
Whole House Monitoring	273.45	104.14		45.03	21.84		181.40	72.19		47.03	17.29		
AC Base	107.02	30.68	-32.96 *										6
AC Monitoring	74.06	27.15											
Media Centre Base	28.73	28.02	-7.09	5.06	5.42	-1.68	18.09	17.26	-3.55	5.59	5.40	-1.85	5
Media Centre Monitoring	21.65	18.38		3.38	2.78		14.55	12.91		3.73	2.76		
Cooking Base	4.07	3.13	0.45	0.59	0.68	-0.05	1.96	1.67	0.61	1.53	1.18	-0.11	6
Cooking Monitoring	4.52	2.92		0.54	0.56		2.57	2.08		1.42	1.05		
Laundry Base	21.40	12.76	0.83	3.66	5.04	-1.96	14.77	8.55	3.42	2.95	2.68	-0.63	6
Laundry Monitoring	22.23	13.14		1.70	1.84		18.20	10.65		2.32	1.77		
Dishwasher Base	3.43	3.77	0.07	0.35	0.46	0.18	2.71	2.94	-0.31	0.37	0.50	0.20	5
Dishwasher Monitoring	3.49	4.23		0.52	0.96		2.40	2.45		0.57	0.85		

Note: shading and * indicate a significant difference in means, (p<0.05) as presented in the text above.

5.4.2 Consumption changes in the autumn period

During the 10-week autumn period, a similar story of conservation and shifting was observed. Re-engagement occurred with 7 more households through both an electricity report and a tablet. Additionally, the 7 households initially re-engaged with the electricity report also received a tablet alongside reports. Therefore, the assessment during the 10-week autumn period involved 14 households, re-engaged with both a tablet and energy reports.

5.4.2.1 Whole-house consumption

Similar to the summer period, households in the autumn predominantly consumed energy during Off-Peak Periods (69%). Additionally, whole-house consumption reduced by 8%, particularly during On-Peak periods (9%); however, conservation and Peak shifting were not statistically significant (p>0.05) (Table 35).

5.4.2.2 Disaggregated consumption

A clear story of changes in appliance-level energy management practices was observed in the autumn period (Figure 49).

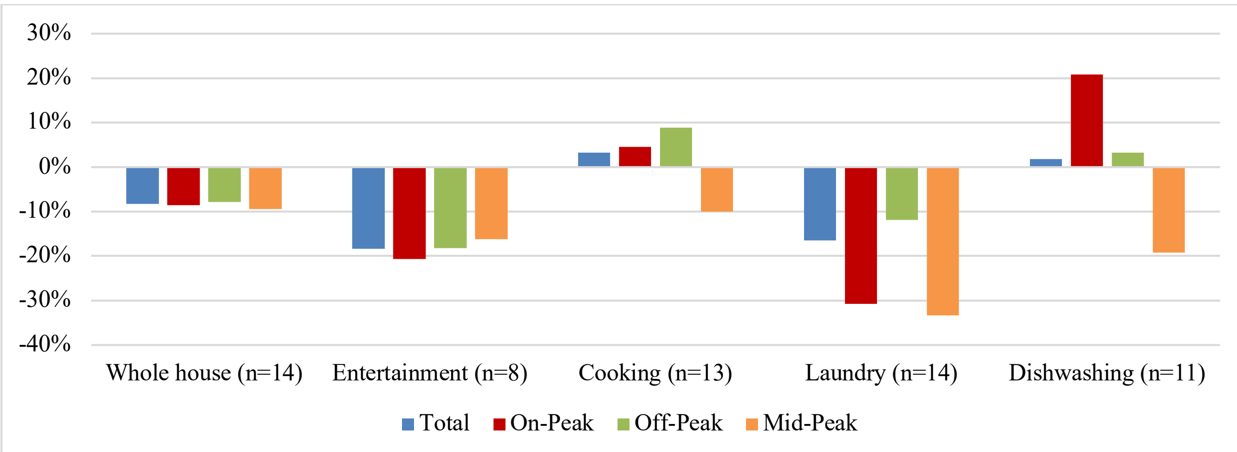

Figure 49 Percent change in average weekly consumption (%) by appliance and TOU period, autumn

In particular, laundry consumption reductions and shifts were evident. Households significantly reduced overall laundry consumption (-16%, p=0.015) in addition to reducing On-Peak (-31%, p=0.048) and Mid-Peak (-33%, p=0.002) consumption (Table 34). Other discretionary load appliances, however, did not significantly reduce and shift consumption.[39] Therefore, these findings indicate that shifts in laundry practices were evident during the autumn re-engagement with both the tablet and the electricity report (Table 35).

[39] The results tables for each circuit-level are in Appendix E.

Table 34 Laundry consumption paired t-test outcomes, 10-week autumn period, average weekly kWh

Pair	Time Period: Base Period			Time Period: Monitoring Period			Mean Difference	95% CI for Mean Difference						
	M	SD	n	M	SD	n					t		df	*p*
Total	18.7	12.4	14	15.6	10.9	14	-3.1	-5.4	,	-0.7	-2.8	*	13	0.015
On-Peak	1.8	1.6	14	1.2	1.2	14	-0.6	-1.1	,	0.0	-2.2	*	13	0.048
Off-Peak	14.5	10.2	14	12.8	9.2	14	-1.7	-3.8	,	0.3	-1.8		13	0.089
Mid-Peak	2.4	1.7	14	1.6	1.7	14	-0.8	-1.2	,	-0.3	-3.8	*	13	0.002

*p<0.05

Table 35 Summary of household consumption changes, 10-week autumn period, average weekly kWh

Appliance	Total			On-Peak			Off-Peak			Mid-Peak			n
	M	**SD**	**Δ**	**M**	**SD**	**Δ**	**M**	**SD**	**Δ**	**M**	**SD**	**Δ**	**n**
Whole House Base	181.71	62.80	-14.95	28.74	10.95	-2.47	124.02	44.50	-9.74	28.95	10.09	-2.73	14
Whole House Monitoring	166.77	56.96		26.27	9.40		114.28	39.53		26.22	8.71		
Media Centre Base	27.10	28.46	-4.97	4.58	5.23	-0.94	18.07	18.27	-3.29	4.44	5.02	-0.72	8
Media Centre Monitoring	22.13	22.95		3.64	4.02		14.78	14.98		3.72	3.99		
Cooking Base	4.64	3.57	0.15	0.94	0.93	0.04	2.51	2.06	0.22	1.19	1.20	-0.12	13
Cooking Monitoring	4.79	2.98		0.99	0.94		2.73	1.71		1.07	0.85		
Laundry Base	18.68	12.39	-3.07 *	1.80	1.57	-0.56 *	14.52	10.17	-1.73	2.36	1.75	-0.79 *	14
Laundry Monitoring	15.61	10.90		1.25	1.19		12.79	9.17		1.57	1.75		
Dishwasher Base	5.70	9.49	0.10	0.86	1.86	0.18	3.74	5.11	0.12	1.10	2.62	-0.21	11
Dishwasher Monitoring	5.80	10.13		1.04	2.45		3.87	5.49		0.89	2.24		

Note: shading and * represent a significant difference in means, (p<0.05) as presented in the text above.

5.4.3 Preferences for peak shifting practices: Not equal across appliance groups

During the interviews, households expressed a certain level of flexibility for shifting specific appliance usage to Off-Peak. To measure this flexibility, households were asked how much higher On-

Peak electricity price would need to be in comparison to Off-Peak prices to motivate shifts (e.g., 2x, 3x, 4x, 5x, 6x). Certain appliances were easily or already shifted to Off-Peak periods, or had low financial thresholds for shifting (e.g., laundry) (Figure 50). Households had mixed financial motivations for entertainment practices. At least one-third of interviewees expressed no flexibility to shift home office use, cooking, and cooling, despite On-Peak prices. Therefore, although TOU pricing promotes discretionary load shifts, these participants expressed unequal peak shifting flexibility across appliances, despite financial incentives.

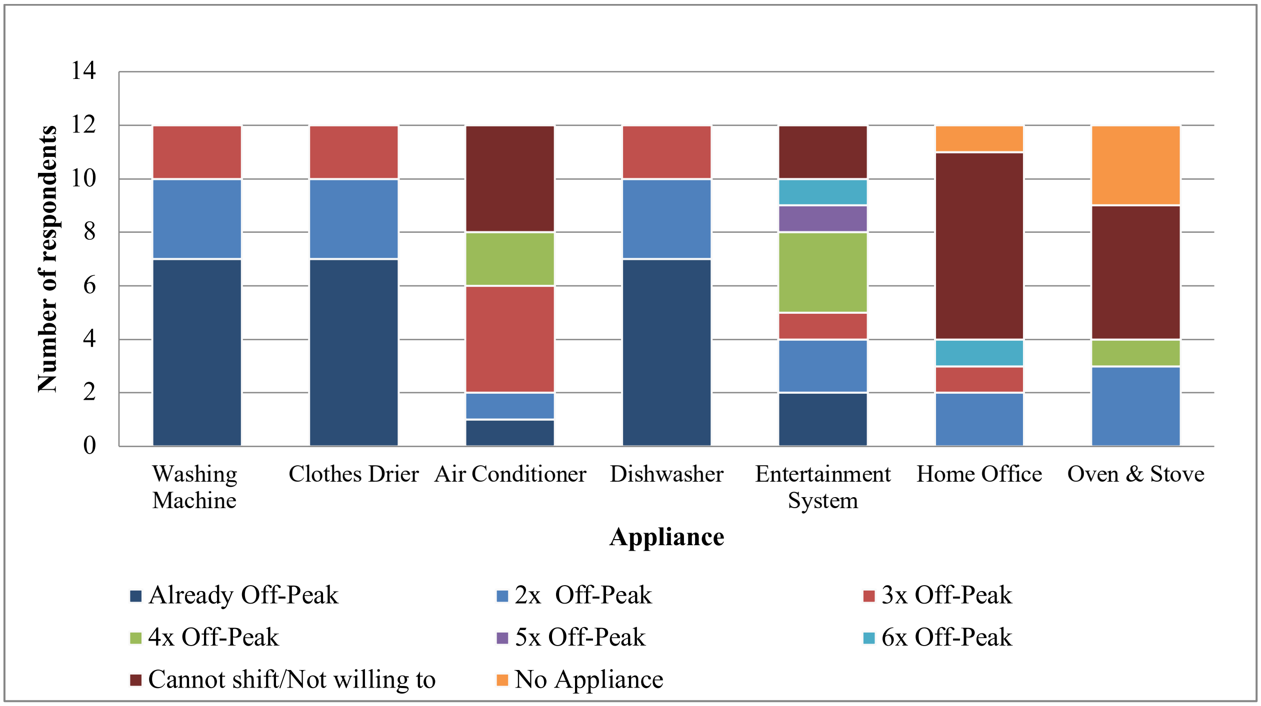

Figure 50 How much higher would the price of On-Peak electricity need to be compared to Off-Peak electricity[40] to cause you to shift from On-Peak to Off-Peak usage for the following appliances? n= 12

5.4.4 Comparing self-reported actions and observed consumption levels

As an outcome of user-interviews and consumption data collection, there was a strong opportunity to test whether participants' self-reported levels of energy management aligned with observed consumption. Households reported their levels of HEM actions on a five-point scale, (low to high levels of action). An assessment determined whether these self-reported ratings correlated with

[40] The selection details assessed in the interview question are as follows: 2x Off-Peak (15¢/kWh), 3x Off-Peak (22.5¢/kWh), 4x Off-Peak (30¢/kWh), 5x Off-Peak (37.5¢/kWh), 6x Off Peak (45¢/kWh).

observed consumption during the 10-week autumn period. Whole-house consumption change aligned with participants' HEM action ratings, where a strong negative correlation between consumption changes and ratings occurred. Therefore, increased action ratings aligned with whole-house consumption reductions in On-Peak periods (r_s=-0.705, n=12, p=0.010), and total consumption (r_s=-0.734, n=12, p=0.007). Additionally, a strong negative correlation was observed between action rankings and On-Peak share of whole-house consumption (r_s=-0.646, n=12, p=0.023); therefore, households with higher self-reported HEM actions consumed proportionately less electricity during On-Peak periods. Similarly, a strong negative correlation was observed between action rankings and On-Peak share in laundry consumption. Thereby, households with higher self-reported HEM action had less On-Peak laundry practices (r_s=-0.666, n=12, p=0.018). Therefore, the households' self-reported HEM activity ratings aligned with the observed consumption levels for whole-house and laundry energy consumption.

5.4.5 'Zooming-in' on weekly energy feedback

During the two rounds of interviews, participants highlighted their experiences with the electricity report. The following sections outline the key themes articulated by participants regarding their experience with the electricity report.

5.4.5.1 'Bite-sized feedback' for targeting actions

Providing feedback and a 'call to action' were notable strengths of the weekly report. Specifically, since households had already seen their detailed consumption, the weekly 'tip'[41] or focus provided a quick action to complete. As Participant 8 mentioned, "It is the most targeted feedback, so it's the best feedback." Although participants were previously provided detailed energy feedback in a web portal, receiving weekly targeted summaries gave opportunities to address specific actions.

5.4.5.2 Comparative feedback: creating a competitive nature

Participants mentioned the motivation from the report's comparative feedback. As expressed by Participant 14, "I like the competitive aspect - yes I am very competitive. And I'm losing," and as

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[41] Tips were provided on weekly energy reports to encourage households to moderate specific appliances and reduce consumption to align with the more efficient households. Examples of tips include: switch your washer/dryer schedule to 'Off-Peak'; run your dishwasher after 7pm and before 7am; plug home electronics, such as TVs and DVD players, into power strips; turn the power strips off when the equipment is not in use—TVs and DVDs in standby mode still use several watts of power.

Participant 6 articulated, "[…] great now I know that I stink." Participant insights identified the motivation to manage energy when observing poor performance in comparison to other participants. However, for some participants, neighbourhood comparisons were not relatable when their household profile differed from the neighbourhood norm (e.g., operating home businesses, large family sizes). Therefore, comparative feedback provided motivations for HEM, if it was relatable.

5.4.5.3 Feedback preferences: accessibility and digital delivery

Households expressed the ease of the weekly report compared to logging into the study web portal. The ability to easily see their consumption and to make some changes, 'closed the loop' between their behaviours and the feedback. Since receiving the report provided digestible feedback without requiring additional analysis, receiving a weekly report allowed for participants' HEM exploration alongside busy schedules. The importance of accessible feedback was articulated by Participant 3, "If you asked me to sit down at the computer and log in, yeah… I work, got the kids, my own business as well. So, between all of those things, if I don't see them in front of my face, it usually doesn't get done." In general, an emailed consumption summary was favoured by interviewees. Participant feedback reinforced the seven categories utilized for the report design (Section 5.3.2), highlighting crucial elements viewed as 'effective' for re-engagement.

5.4.6 'Zooming-in' on tablet engagement

To further understand the tablet influence(s) on HEM practices this section highlights feedback collected during user experience interviews with available tablet participants (n=12). Primary tablet users were the principal household energy managers, who were in their 30s (n=5) and 40s (n=5) and 50s (n=2). The tablet was primarily used for energy feedback and monitoring, whereas, utilizing other features (e.g., optimization and goals), were minimal. Although the tablet could spark family discussions on energy use, it also remained a minimal purpose of use.

5.4.6.1 Limited awareness changes despite 'closing the feedback cycle'

The tablet had a mixed influence on awareness, where half of participants indicated no awareness changes. For some participants, energy feedback at this stage was not as meaningful as at the beginning of the study. As identified by Participant 13 "[…] once I saw what the numbers were, and there wasn't much of a change from a day-to-day aspect or month-to-month, the only changes would be when I did a drastic change." Participants' homes were considered 'new build,' with limited opportunities for substantial changes (Lazowski et al., 2018). On the other hand, interviewees who reported increased awareness identified the tablet's role for re-examining HEM. As identified by Participant 6 "it helped to re-energize our focus," since they were able to re-assess energy performance later in the study.

Although the tablet was more convenient to access than a computer, increased accessibility had limited influence on participants' awareness to make HEM changes. Participants emphasized the importance of additional information (e.g., suggestions and tips) to increase their capabilities to change, such as Participant 3 who expressed, "[…] what was missing was guidance" for implementing substantial HEM changes. Therefore, the presentation of similar information as the web portal resulted in mixed influences on participants' HEM awareness.

5.4.6.2 Difficulty making substantial changes in practice despite increased feedback

Most participants also identified the tablet's limited influence on household energy practices. Some had difficulties making changes throughout the program, such as Participant 6 who found "it was really hard to move the needle" and the tablet did not help. Others had already made HEM changes and the tablet enforced and encouraged their existing 'shifts', such as Participant 10 where the tablet "…solidified […] rather than changed our habits, like instead of running the dryer every day at 2 o'clock in the afternoon let's run it at 8 o'clock at night." Similarly, for some, since the tablet did not provide new information in comparison to the web portal, it was not a significant motivation for HEM changes. Busy schedules and competing priorities within the household were substantial HEM barriers, such as Participant 13 who expressed, "[…] it's trying to get the kids to change their habits for laundry, which was the biggest piece." Although the tablet was more accessible, and provided ease for engagement, engaging family members was not the primary tablet function.

However, for a couple of households, the tablet had some impacts. For example, for Participant 4, this involved gaining better insights on performance, where they purchased a new television and scheduled dishwasher usage to Off-Peak in conjunction with the tablet. Therefore, although the majority of participants had difficulty using the tablet for HEM, some households re-enforced, re-examined, and re-configured their HEM practices.

5.4.6.3 Technological preferences: 'mobile device overload'

A critical barrier to tablet use was the issue of 'mobile device overload' and the logistical issues of the tablet. In particular, locating and charging the device and the related inconvenience were highlighted. With many devices in the home, including other tablets, this specific tablet became 'lost in the noise' of other household devices (e.g., iPads, computers, and smartphones). For example, for Participant 13, each of the 6 people in the household (2 adults, 4 children) already had a tablet or computer before the study, explicitly stating "I have tech everywhere I turn… my entire household has tech up the wazoo." Therefore, mobile device overload was a substantial issue for tablet re-engagement.

The interviews also explored participants' technological preferences. The majority of interviewees would have preferred a dedicated, centralized device, or IHD,[42] to the tablet (n=8). The specific rationales for IHD preference were visibility, location, and immediate feedback. Participants in favor of an IHD expressed it could engage others in the home and enable energy use feedback in a central location without the logistics of an additional mobile device. Although not verified in this study, this option could have engaged multiple people in the home without logging-in to a tablet.

5.4.7 Mobile web portal engagement

Tablet engagement insights from the Google Analytics provided insights on user activity on the mobile web portal. Throughout re-engagement, the main pages visited were the: homepage (27.5%), usage page (12.5%), goal page (9.7%), TOU clock page (9.5%), and scheduling options (5.3%). Therefore, aligning with participant insights on main the tablet function: assessing whole-house consumption. However, Google Analytics engagement data also clearly shows minimal active users over the long-term. Over a seven-month period (January 1 – July 31, 2015),[43] a total of seven users were active at approximately 8.86 sessions per user, with each user having an average session log-in of 8 minutes 29 seconds. As seen in Figure 51, over a 7-month period, limited long-term project re-engagement with the mobile application is evident. During the first month, 6 users logged in, falling to 3 users over the second and third months, and to 2 users in the final 4 months. Although Google Analytics data were only available 1 to 4 months following tablet introduction, it presents essential information on long-term engagement: the tablet was not enough to motivate long-term re-engagement.

[42] An in-home display (IHD) is a dedicated device for feedback on energy consumption.
[43] The January – July 2015 timeframe was utilized since several participants exited the study in August 2015.

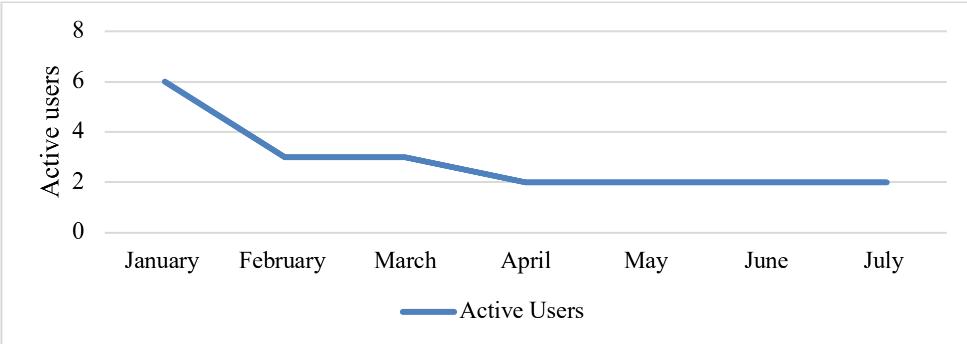

Figure 51 Mobile web portal Google analytics for active users per month (January – July 2015)

5.5 Discussion

5.5.1 User preferences: 'Slow' vs 'smart' feedback

Although the introduction of two mechanisms for re-engagement occurred at similar timeframes, the qualitative feedback indicates user preferences for weekly reports over the tablet. Design features, including targeted action, snapshots of information, comparative feedback, and delivery method influenced this preference. Although the tablet provided more detailed feedback than the report, the logistics and lack of accessibility were barriers for use. Smart technologies and feedback are promoted for household energy management and engagement; however, assumptions of increased CDM from 'smart' technologies and feedback needs to be approached with caution (McKenna, Higginson, Grunewald, & Darby, 2017). As raised in participant interviews, over the long-term, 'smart' feedback and HEM 'fell to the backburner' of daily routines, which is similar in other long-term smart feedback studies (Hargreaves et al., 2013). The elements of targeted and normative feedback with particular calls to actions were preferred. Similarly, Delmas and Lessem (2014) found private feedback ineffective in changing electricity use in university residences; however, combining private feedback with public feedback resulted in 20% electricity reductions. Normative feedback as a 'nudge' to change consumption has also been found effective through the provision of smile and frown faces on energy bills (Sunstein & Thaler, 2008). Therefore, social norms for electricity usage can be established through comparative feedback (Delmas & Lessem, 2014).

In this study, participants highlighted preferences for the report as a 'slower' mechanism of HEM feedback at the later study stage. Although participants requested mobile app-based feedback in earlier stages of the study (Lazowski et al., 2018), when the requested device-based feedback was provided, limited engagement occurred. Alternatively, the indirect feedback from electricity reports received positive feedback for re-engaging participants in energy management. Recent studies have identified the challenges and lack of clarity surrounding of smart devices for HEM and engagement (Darby, 2018b; Gram-Hanssen & Darby, 2018; Hargreaves et al., 2018; Strengers & Nicholls, 2017; Tirado Herrero et al., 2018). A challenge of this case study is the lack of separate engagement dates for both re-engagement mechanisms; however, the participant interviews bring substantial insight into their use and implementation. Therefore, the interviews highlighted critical considerations for feedback provision.

5.5.2 The challenge: TOU prices are not a 'latte' to motivate

External policy mechanisms also influence household energy management practices. The Province of Ontario enabled TOU energy prices as part of the *Smart Metering Initiative*, providing a financial incentive for Peak shifting. Although the majority of participants were motivated to adopt this technology to 'save money' on their energy bill (Lazowski et al., 2018), occasionally On-Peak prices were not enough for Peak shifting. This concern was highlighted by Participant 2, "I mean at the end of the day, after looking at the data, switching [to Off-Peak] really only saves me a few lattes a month… that's not a lot to motivate me." Laundry consumption was more flexible, and this willingness directly aligns with households' Peak shifting during the autumn monitoring period, as expressed earlier. However, flexibility for load shifting was not equal across appliances, where most participants were not willing to shift consumption related to cooling comfort, cooking and home office use, despite the On-Peak price. Similarly Lysyk (2016), highlighted Ontario's anticipated smart metering CDM targets were not reached partly due to limited On-and-Off-Peak price differences. During the study, On-Peak commodity prices remained below 15¢/kWh and fell during the study (Table 27). Although TOU prices promote discretionary load shifts, not all loads had equal opportunities or preferences for flexibility in this study. While this feedback does not represent all Ontario consumers, it provides considerations for HEM financial incentives. Similarly, in a small-scale UK case study, Hargreaves et al. (2013) found limited changes from energy feedback as a result of limited market mechanism support. Overall, these incentives play an essential role in transforming HEM practices and enabling the effectiveness of feedback.

5.5.3 Feedback, design, and long-term engagement

The effectiveness of feedback can be impacted by multiple design and delivery elements, as articulated in this study. Specifically, participant insights echoed factors previously identified by

Karlin et al. (2013), including immediacy, comparisons, calls to action, data granularity, content, and presentation mode. The electricity report insights also reiterated design features utilized for report development. Studies have identified the effectiveness of combining feedback and engagement mechanisms (Abrahamse et al., 2007; Karlin et al., 2015; Smeaton & Doherty, 2013). Although significant reductions and shifts in laundry consumption were observed following re-engagement by two mechanisms, this study also highlighted participants' preference for a 'slower' form of feedback for re-engagement (e.g., electricity report) with targeted and normative feedback alongside specific calls to action.

Applying assumptions on individuals' roles and responses to energy feedback can be precarious for program design. First, is the assumption of residential energy consumers being proactive energy 'resource managers' (Strengers, 2011a, 2011b). A similar issue is the simplistic assumption of the linear information deficit model. These assumptions view households as 'black boxes' failing to account for complex factors influencing consumption (Darby, 2003). Qualitative energy feedback studies have highlighted issues of these assumptions (Hargreaves et al., 2010, 2013). This study further articulates these issues, where households identified HEM challenges due to household complexities (e.g., competing values and standards of convenience). In this study, long-term engagement yielded limited changes, despite self-reported increased awareness from study feedback (Lazowski et al., 2018). Priorities of comfort and routines presented difficulties for determining next steps after initial and obvious changes. Additionally, peak shifting flexibility was stronger for certain appliance groups, regardless of TOU tariffs. However, re-engagement through the electricity report re-shaped laundry practices, highlighting how nudges, competition and suggestions can trigger additional changes.

This study emphasizes the challenge of re-engaging consumers with long-term HEM projects. As similarly identified by Hargreaves et al. (2013), competing household habits can overshadow increased awareness from energy monitors. Similarly, Wemyss et al. (2019) found that savings related to an energy application were not realized one year after its introduction. However, some studies have observed long-term success (Staats et al., 2004). Overall, mixed results on savings (0 to 25%), have been identified in energy feedback studies over both the short- and long-term and varying participant numbers (Darby, 2006; Grønhøj & Thøgersen, 2011; Harries et al., 2013; Houde et al., 2013; Karlin et al., 2015; Mountain, 2012; Oca et al., 2014; Schleich et al., 2013). Our study highlights not only the mixed effect on whole-house consumption, but also within appliance-levels, in conjunction with feedback over the long-term. Combining feedback and engagement mechanisms have been identified as beneficial for CDM responses (Abrahamse et al., 2007). In smart grid feedback research, paper statements and web portal feedback resulted in significant reductions in Austrian homes (-4.5%) (Schleich et al., 2013), and real-time displays combined with smart meters resulted in 2-4% savings in the UK (Raw & Ross, 2011). Although our study only showed favourable significant laundry shifts, with combined smart grid engagement mechanisms, the detailed feedback delivers users' experiences and insights on mechanism effectiveness for additional testing in larger cohorts.

In previous analysis related to this study, no relationship between web portal engagement and energy conservation was identified, with low web portal engagement overall. Participant engagement was highest in the first three months, with reduced engagement after seven months (Khorrami, 2014; Shulist, 2013). Tablet engagement declined after the first month of Google Analytics collection. Within the first year of the EHMS study, households reduced energy consumption and had Peak shifting, where Off-Peak periods shifts were a result of changing specific appliance loads (Kantor et al., 2017). With re-engagement, households continued to shift specific loads, mainly laundry. However, when combining quantitative with qualitative we understand the *why,* or more importantly, the *why not* behind these shifts corresponding with engagement and re-engagement. In comparing the results of this study to the literature, our results highlight nuances for smart grid engagement and appliance-level consumption changes. Re-engagement through both a tablet and a report stimulated changes laundry consumption, with limited significant whole-house changes. The outcomes of this small-scale case study can be tested with larger audiences to further understand the role of smart energy feedback for long-term shifts in household energy practices.

5.6 Conclusions

This study investigated household re-engagement for electricity conservation and demand shifting at the end of a long-term smart grid study. Although households reduced their consumption (-7% summer, -8% autumn), the mean differences were not statistically significant from the base periods. Findings identify nuances surrounding re-engaging residential consumers within the long-term. Household re-engagement by a tablet and targeted weekly reports resulted in significant shifts in autumn laundry practices, specifically, notable reductions (-16%) and peak shifting (-31% On-Peak and -33% Mid-Peak consumption). Reductions in Autumn whole-house consumption and changes in laundry practices strongly correlated with participants' self-reported HEM actions. User experience interviews highlighted preferences for targeted feedback, utilizing normative values, and specifying calls to action. Participants also highlighted the issue of device overload and preferences for an IHD in comparison to a mobile application or tablet. Additionally, households expressed barriers of household complexities and schedules for preventing HEM. These particular households identified the lack of financial motivation for making shifts and the preference of convenience for appliance usage in central areas of the home (e.g., cooking, cleaning, and entertainment).

Although participants requested the mobile device and indicated preferences for mobile applications and feedback from a previous interview (Lazowski et al., 2018), the tablet delivered limited capabilities for participant re-engagement. While the tablet tightened the feedback cycle, it had a limited impact on household energy management, as identified in participant interviews. Although not solely contributed to the tablet, this brings an essential consideration for assessing 'smarter' forms of home energy feedback. Participants positively reacted to snapshots of report feedback that emphasized a 'call to action.'

The nuances highlighted in this paper identify difficulties for utilizing smart grid energy feedback to re-engage residential participants for increased household energy management. Although laundry consumption practices were significantly reduced and shifted, whole-house and other appliance changes remained insignificant. The interview responses identified preferences for and experiences with specific elements of feedback (e.g., units, delivery, comparisons), thereby highlighting the importance of user-centred feedback for smart metering program design to understand relevant preferences and barriers for developing effective solutions. Furthermore, the results of this study emphasize the call made by Hargreaves (2018) of going 'beyond' energy feedback and focusing on feedback that shapes everyday life, integrating a diverse range of actors within the process, and utilizing novel approaches for energy-related feedback.

Although this study had a small sample size, the outcomes present opportunities and developments for future research. Small sample sizes bring benefits by identifying unique areas within larger system dynamics for policymakers to focus on and by highlighting insights to test in larger studies (Hargreaves et al., 2013). Moreover, small sample sizes in smart grid research are typical, especially in studies with intrusive technologies similar to this study. Smart grid studies with small sample sizes, and in various regions, have been observed in the literature (Bager & Mundaca, 2017; Bradley et al., 2016; Hansen & Hauge, 2017). Additionally, the benefits of the long-term and re-engagement aspects of this study, alongside the qualitative feedback, bring detailed nuances for studying temporal changes in HEM in the smart grid. Furthermore, this study emphasizes appliance-level changes, associated HEM practices impacted by re-engagement, and highlights the preferences for HEM flexibility within appliance groups. These outcomes bring insights into long-term temporalities of HEM practices within the smart grid and develop the literature on smart grid engagement for HEM. Therefore, the results provide valuable insights for future research development with larger samples. Specifically, these outcomes emphasize the importance for future studies to investigate strategies for engaging and re-engaging residential consumers for long-term HEM and to implement mixed-methods approaches, including consumer feedback, alongside the quantitative evaluation of smart grid engagement mechanisms.

6. Chapter 6 – Who's responding anyway? Assessing segment-specific responses to real-time energy displays

The advancement of smart metering infrastructure introduces increased capabilities for near-real time feedback to households; however, studying the types of users and how they respond to feedback delivers valuable insights for smart metering program development. This study investigates the influence of a large-scale implementation of in-home displays (IHDs) on electricity consumption in central Ontario households (n=5274) compared to a control group (n=3020). This study utilizes thermal sensitivity and household electricity profiles to cluster households into 78 different consumer segments based on both thermal and behavioural consumption patterns. A multiphase analysis is conducted to determine whether: (1) the IHD influenced the overall population; (2) the consumer segments responded differently to real-time feedback, and; (3) the segmentation of households can generate insights for smart grid consumer engagement. Significant impacts on consumption were not evident within the general population; however, different consumer segments responded differently to the real-time feedback. Evidence of overall peak shifting, and conservation was limited. Five notable segments were identified. Those notable segments inclined to reduce peak consumption were specifically those with high heating sensitivities and who consumed more energy during the evening and night-time periods. This study provides four key insights for program development: (1) behavioural and thermal consumption patterns influenced intervention responses; (2) audience segmentation and target market analysis deliver key insights for producing effective programs to the right consumers; (3) consumption data can be used for understanding energy consumers and their preferences in the absence of socio-demographic data, and; (4) smart grid engagement strategies need to extend beyond information and feedback provision.

Keywords: In-home displays (IHDs), smart grid, consumption profile, clustering, conservation, and demand management (CDM).

Highlights:

1. Applies segmented analysis of smart meter-enabled feedback in Ontario homes
2. Identifies thermal and behavioural load shape clusters of consumers
3. Compares the influence of IHD installation in 5274 homes
4. Observes that households exhibiting peak consumption reductions had sensitive heating consumption patterns and consumed more of their energy during the evening and nighttime periods

6.1 Introduction

Energy conservation and management is a crucial pathway for clean energy transitions and reducing carbon emissions. Significant opportunities for electricity consumption management exist at the residential scale, which contributes to 27% of global electricity consumption (International Energy Agency, 2017; McKinsey & Company, 2019; Parker et al., 2003). Developments in advanced metering infrastructure (AMI) present new opportunities to encourage residential demand-side management (DSM) (Meadowcroft et al., 2018; Stephens et al., 2015). The smart grid has the potential to develop a residential 'demand-side intelligence' through near-real-time consumption feedback for active consumer management, enabled by information and communication technologies (ICT) (Miler & Beauvais, 2012; Stephens et al., 2015). Since 2010, smart meters have been installed rapidly worldwide, increasing residential feedback capabilities (Schultz, Estrada, Schmitt, Sokoloski, & Silva-Send, 2015). To achieve the potentials of the smart grid; however, consumer engagement is crucial and, therefore, various feedback technologies have been developed (Abrahamse et al., 2007; Anda & Temmen, 2014; Karlin et al., 2015).

Residential energy feedback mechanisms come in many forms. In-home displays (IHDs) are one common method and dedicated to providing direct electricity consumption feedback. Various regions have implemented IHDs alongside smart metering infrastructure as a critical element of their energy demand management strategy, including the European Union, United States, Japan, New Zealand, Australia, and Canada (Burchell et al., 2016; Darby, 2010; Sovacool et al., 2017). Studies show that IHD engagement can increase the visibility and awareness of energy consumption. However, different types of consumers may respond differently to this increased visibility, and there is a need to assess the impact of IHDs on different consumer segments (van Dam et al., 2010).

Residential energy consumption is complex and influenced by a multitude of factors. Influential elements can include building efficiency, household profile, standards of comfort, and energy actions (Greene, 2019; Kowsari & Zerriffi, 2011; Stephenson, Barton, et al., 2015). Consequently, the energy 'context' governing decisions towards household energy consumption and management is multifaceted and, therefore, studies incorporating emerging forms of household data can develop understanding into household decision-making (Stephen, 2016). A number of factors can influence residential engagement with feedback such as information provision, feedback timeframes, granularity, energy literacy (Darby, 2006; Froehlich, 2009; Karlin et al., 2015). The province of Ontario, Canada has become a favourable testing ground for residential smart grid engagement as a result of AMI development (Lazowski et al., 2018; Meadowcroft, Stephens, Wilson, & Rowlands, 2017; Winfield & Weiler, 2018). As of 2014, 4.1 million smart meters were installed within Ontario homes and small businesses, which facilitated time-of-use (TOU) pricing to incentivize peak shifting.

This paper presents a residential smart meter-enabled IHD case study in Ontario, Canada,[44] to determine whether near real-time feedback influenced recipient households (n=5274). Additionally, this study assesses the influence of the IHD (i.e., conservation and peak shifting outcomes) on different types of consumers, based on thermal and behavioural consumption patterns. The objectives of this study are three-fold and assess whether: (1) the IHD influenced the overall population; (2) different consumer segments responded differently to real-time feedback, and; (3) segmentation of households can generate insights for smart grid consumer engagement. The following sections will provide an overview of the research background and literature related to smart grid engagement, IHDs and segmentation research; highlight the research methodology; present the research findings, and; incorporate the findings with the literature to offer perceptions and suggestions for IHD research and consumer engagement.

6.2 Literature review and research background

6.2.1 The complexity of residential energy consumption

A multitude of complex factors within personal and contextual domains influence residential energy consumption (Kowsari & Zerriffi, 2011). Behavioural actions influencing consumption interact and involve a range of activities (e.g., heating, entertaining, cooking, cleaning etc.,) (Zhang, Shen, Yang, Tang, & Wang, 2019). Additionally, the efficiency of technologies and the built environment, and how they are managed, influences residential energy consumption (Dietz et al.,

[44] The particular municipality is not provided due to non-disclosure agreements made with the partnering organization.

2009; Parker et al., 2003). These levels of consumption, and relative efficiency measures are also impacted by socio-demographic factors including household size, income, education and energy literacy (Abrahamse & Steg, 2009; M. Brown, 1984, 1985; Costanzo et al., 1986; Kowsari & Zerriffi, 2011; Lutzenhiser, 1993; Mills & Schleich, 2012; Steg, 2008). Stephenson et al. (2010) conceptualize these consumption behaviours in the scalable energy cultures framework, which is influenced by three interrelated factors: norms, and aspirations surrounding energy consumption; material culture, or the efficiency and use of physical and technical elements (e.g., infrastructure and appliances); and actions and skills revolving around energy consumption and behaviours (Barton et al., 2013; Stephenson, Barton, et al., 2015; Stephenson et al., 2010). Therefore, these factors derived from physical, contextual, psychological, physiological, and social domains, influence residential energy consumption and the respective capacity to manage energy consumption in the smart grid.

6.2.2 Feedback and IHD studies

IHDs have been introduced for communicating near real-time smart meter feedback with smart grid customers for increased energy management (Anda & Temmen, 2014; Strengers, 2011b). IHDs facilitate immediate smart meter consumption feedback consumption through an independent display (Darby, 2008; Ehrhardt-Martinez et al., 2010; Karlin et al., 2013; Lamarche et al., 2012). These devices consist of both a sensor and a display to collect and portray smart meter data in near real-time at different scales (e.g., whole-house and/or appliance-level) and measurements (e.g., kWh, MJ, $) (Anda & Temmen, 2014; Darby, 2006; Ehrhardt-Martinez et al., 2010; Gangale et al., 2013; Karlin et al., 2013). These real-time displays can facilitate consumers' ability to: make immediate responses to feedback, make more rational decisions to their energy use and make conservation 'spill over' to other habits (Hargreaves et al., 2010). Thus, AMI-enabled feedback can facilitate active consumer engagement and create a 'demand side intelligence' by increased awareness, empowerment, and more informed consumption decisions (K. Buchanan et al., 2015; Stephens et al., 2015).

IHDs are often deployed in combination with energy pricing mechanisms to stimulate conservation and demand management (CDM). Time-sensitive pricing has shown potential for energy reductions in both peak and overall demand (Darby, 2006). Time-of-use (TOU) structures are the focus of this study, and divide the day into defined periods, each with specific prices to curb On-Peak consumption (Harding & Sexton, 2017; Sintov & Schultz, 2015). Studies have indicated a 3-6% reduction in peak demand from TOU rate structures (Faruqui & Sergici, 2010; Newsham & Bowker, 2010). In general, information-based strategies (e.g., education, feedback, pre-action information) have achieved average savings of 7.4% in energy consumption (Delmas et al., 2013c). Several studies have assessed IHD feedback effectiveness on household consumption (Faruqui et al., 2010a; Nilsson et al., 2014; Schultz et al., 2015) with average consumption reduced by 3 to 19% (Burchell et al., 2016; Darby, 2006, 2010; Ehrhardt-Martinez et al., 2010; Faruqui et al., 2010a; Hargreaves et al., 2010; Stromback et al., 2011). Other studies, however, have identified no significant effect of IHD feedback on consumption (Alahmad, Wheeler, Schwer, Eiden, & Brumbaugh, 2012; Allen, Janda, & College, 2006; Nilsson et al., 2014; B. A. Scott, 2009); therefore, highlighting the uncertainty of IHD feedback to influence consumption behaviours.

Feedback form and framing can also influence the level of response. For instance, IHDs can provide individualized or comparative consumption feedback (Abrahamse et al., 2007; Delmas & Lessem, 2014). Using both comparative and individualized feedback can stimulate more substantial consumption reductions. Schultz et al. (2015) also found significant influences of comparative feedback, with 7% reductions over three-weeks compared to a control group. Comparative feedback can create social norms for electricity usage (Delmas & Lessem, 2014), and can be an appealing IHD feature to consumers (Hargreaves et al., 2010). Overall, the type of feedback provided, and the framing of feedback are essential considerations in IHD provision.

Studies investigating long-term engagement with IHDs also suggest varied results. Hargreaves et al. (2013), identify short-term engagement with IHDs, followed by long-term disengagement. Additionally, van Dam et al. (2010) highlight short-term savings of 7.4% in residential IHD programs could not be sustained over the medium- to long-term. However, Stromback et al. (2011) suggest that long-term engagement with IHDs is possible, with a potential for reductions over time. Long-term engagement was also confirmed by Burchell et al., (2016), identifying continued long-term IHD engagement throughout a two-year project. Therefore, highlighting the variability of IHD feedback in temporal studies.

Although IHDs can increase the visibility and awareness of energy consumption, different types of consumers may respond differently to this increased visibility. As identified by van Dam et al. (2010), certain groups of consumers are more responsive to energy-saving interventions than others; however, limited studies have investigated cohort-specific responses to the introduction of IHDs. Therefore, since a multitude of factors influence IHD effectiveness, including the household profile, there is a need to assess the impact of IHDs on segment-specific responses to IHD installations.

6.2.3 Studying consumer segments

Consumer segmentation has been used in energy research to understand user preferences and program effectiveness. A variety of variables can be used to segment consumers, such as energy consumption data, socio-demographic factors, lifestyle, and consumption preferences (Al-Otaibi, Jin, Wilcox, & Flach, 2016; Chicco, 2012; McLoughlin, Duffy, & Conlon, 2015; Wang et al., 2015). For example, Russell-Bennett et al. (2017) identified six segments based on socio-demographic, energy preferences, and energy attitude information to develop a detailed market understanding of Australian households. Similarly, consumer segmentation has been previously applied to Ontario energy consumers. Key demographics (e.g., education, income level, home ownership status), as well as energy and environmental attitudes and awareness, were utilized to create four consumer segments (green champions, pragmatic conservers, budget driven, and live for today consumers), where the largest cohort of Ontario consumers were classified as budget driven (34%) (Collins, 2008). Consumer segmentation is also used in smart grid research. Gaye and Wallenborn (2015) identify four consumer groups based on smart grid goals, technological knowledge and skill-level, economic values, and thermal flexibility. The Smart Grid Consumer Coalition (2016b) identifies five segments of the new 'empowered' consumer, based on large-scale consumer surveys. Consequently, these consumer segments can generate detailed market insights.

Utilizing the wealth of smart-metering data in meaningful ways can reduce the 'triad of anonymity' among utilities, consumers, and their practices (Summerton, 2004). In particular, load shape profiles can be used to study particular consumer types (Aydinalp Koksal et al., 2015; Beckel, Sadamori, Staake, & Santini, 2014; Kwac et al., 2014) and have been identified as important for policy and program design (Ge, Zhou, & Hepburn, 2016; SGCC, 2016a). Consumers can be segmented for effective CDM program targeting and delivery to harness the value of smart metering data (Sintov & Schultz, 2015). Advanced household characterization and analysis techniques have been developed to identify policy opportunities. These advanced models can incorporate load shape profiles, thermal profiles, and household characteristics for detailed understanding of end-user consumption patterns (Do Carmo & Christensen, 2016). Load-shape profile analysis can reveal consumer responsiveness to demand response programs (Jang, Eom, Park, & Rho, 2016). Thermal consumption profiles can deliver opportunities to disaggregate consumption into particular end-uses (Birt et al., 2012). Companies have also utilized advanced consumption analytics to identify market segments for efficiency programs. Most notably, Oracle clustered 812,000 households into five consumption categories based on load-shape profiles (e.g., night owls, twin peakers, steady eddies, evening peakers, and daytimers); therefore, demonstrating the power of advanced analytics for a detailed understanding of behavioural patterns (Frades, 2016; Oracle, 2015). Since there is no 'one-size-fits-all' approach for the smart grid and IHD program development (K. Buchanan et al., 2015; Hargreaves et al., 2013; Rowlands, 2012), separating users into different groups to identify strategic consumer profiles is crucial for program design (Stromback et al., 2011), and consumption analytics can deliver these insights.

As an outcome of the literature review, three key themes are presented to develop the existing literature and to advance detailed insights on household responses to IHD feedback. First, to further identify consumption-level factors influencing household responses to real-time feedback; second, to apply consumer segmentation utilizing smart metering data and consumption patterns (i.e., behavioural load shape and thermal profiles) to discover holistic consumption 'contexts' of consumers; and third, to apply these segmentation techniques to IHD participants to determine how different types of consumers respond to real-time feedback displays.

6.2.4 Research overview and objectives

This study examines the influence of an IHD in a large number of households (n=5274) in Ontario, Canada. These households had an electric water heater and were also participants in the PeakSaver Plus program.[45] The IHD connected to the existing smart meter and provided real-time whole-house consumption data, the respective costs, and TOU period. This study also investigates the influence of the IHD on different consumer segments within the study. As a result, this study assesses how the introduction of an IHD influences the energy culture of the participant group, and how different consumer segments responded to IHD feedback. Additionally, this study applies clustering methods to smart metering data to understand segments of residential customers for effective smart grid policy design. The research objectives are three-fold to address the aforementioned opportunities for research: (1) to assess whether the introduction of smart meter-enabled feedback influenced the overall energy culture within the recipient households; (2) to determine whether different consumer segments respond differently to the introduction of an IHD, and; (3) to highlight opportunities to utilize smart grid data for effective smart grid engagement and design.

[45] During critical periods on summer days (May 1st to September 30th), participating households of the PeakSaver Plus program are alerted to the surge in demand and their thermostat, electric water heater, or pool pump is adjusted for a maximum of four hours during the periods of 12:00 PM to 7:00 PM, Monday-Friday.

6.3 Data and methods

This study applies a multiphase analysis, outlined in the following sections, including data collection, aggregation and cleaning; household characterization; behavioural, thermal and thermo-behavioural clustering; and impact regression analysis for the total population and consumer segments (Figure 52).

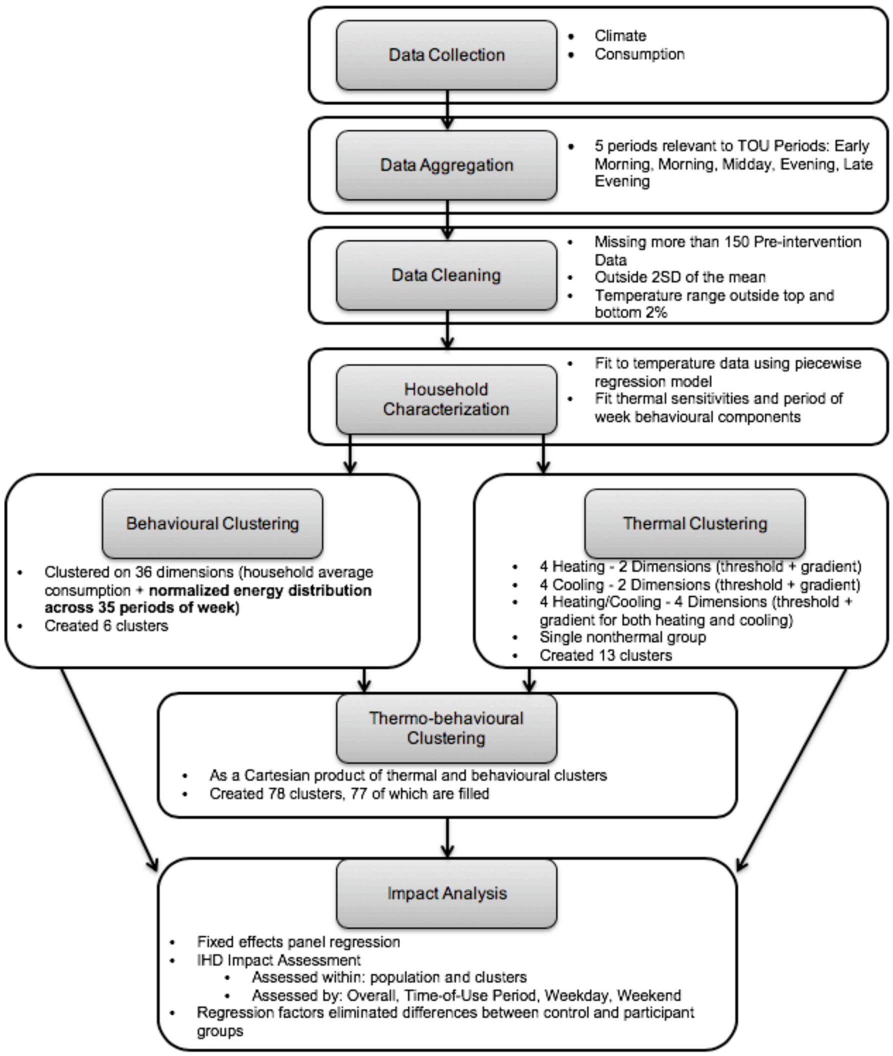

Figure 52 Analysis procedure

6.3.1 The IHD

The IHD used in this study was directly connected to the smart meter for each home and can be classified by Karlin et al.'s (2013) taxonomy of feedback technology as a 'grid display,' since it provided whole-house electricity consumption data for the past month and 24-hours (Figure 53). The display was a simple black-and-white display with individualized whole-house feedback for both consumption levels (kW) and cost of consumption ($/hour) in real-time. A cycling light arc also provided real-time feedback, where the colour symbolized the TOU period (green for Off-Peak, yellow for Mid-Peak and red for On-Peak) and level of consumption (fast movement for high-level consumption, and slow movement for low-level consumption) (Table 36).

Figure 53 IHD utilized in the study

Table 36 Froehlich's (2009) 10 design dimensions applied to the study IHD

Design dimension	Study IHD component
Feedback frequency	Real-time from smart meter
Measurement unit	Consumption (kW) and monetary ($/kW)
Data granularity	Hourly consumption and cost information at whole-house level Historical (last 24 hours, last month)
Presentation medium	Black and white screen, simple display, light-arc
Visual design	Black and white screen, simple display, light-arc
Location	Decided by user
Recommending action	No specific call to action Speed of light arc could be interpreted as a signal to change consumption
Comparisons	Time comparison: last 24 hours and 1 month provided No social feedback comparison No plug-load comparison No energy type comparison
Push/pull notification(s)	None
Social sharing	None

The IHDs were delivered by mail and installed by connection to a standard outlet. Recipients could install the IHD in any part of the home. This study utilizes the delivery date as the 'installation' date and assumes that each household activated their IHD and placed it within a centralized location in the home, beginning on the IHD delivery date.

6.3.2 Data collection

This study analyzes two years of hourly energy consumption data and climate data (September 9, 2012 – September 9, 2014). This involved consumption data collection for a participant group (n = 6879 houses), which received the IHD, and a control group (n=3359 houses), which did not receive the IHD. After data cleaning the final participant and control groups are 5274 and 3020, respectively. The participating households are not a randomized sample since it was an opt-in program with particular participation requirements (e.g., electric water heater installed and PeakSaver Plus participant). The households in the control group were randomly selected and not PeakSaver Plus participants.

The climate data used for this study were from Environment Canada's Climate Weather Database weather station in closest proximity to the municipality[46] of this study (Environment Canada, 2015). The heating degree days (HDD) and cooling degree days (CDD) were studied using a base temperature of 18°C, which is the standard used by Environment Canada.

6.3.3 Aggregation of the data

The consumption, temperature, heating, and cooling degree hour data were aggregated (averaged) from hourly data, into five daily periods (early morning, morning, midday, evening, late evening) to reduce computational requirements. These periods aligned with the Independent Electricity System Operator (IESO) TOU rate-based consumption periods. The data used in the following stages of the study used these aggregated periods.

6.3.4 Data cleaning

Following the aggregation, several steps took place to remove outliers and households with insufficient data to ensure accurate analysis and clustering outcomes. Households, with less than 150 pre-intervention readings, approximately one month, were removed. The average household-level consumption was assessed and those outlier households that had significantly higher, or significantly lower consumption compared to average household-level average hourly consumption were removed. To do this, households that were outside two standard deviations of the mean hourly consumption data were removed from the dataset, (0.26 kWh, 4.7 kWh). Lastly, the outdoor temperature range of the households were assessed, and those households with an insufficient observed temperature range to reliability fit thermal models were removed. Specifically, at least 2% of the pre-intervention data in

[46] The site remains undisclosed for non-disclosure agreement purposes.

periods with average temperature were 8°C or lower, and at least 2% were 26°C or higher. As a result, the final counts of the participant and control groups are 5274 and 3020, respectively, with a total of 8294 households used within this study after data cleaning.

6.3.5 Household characterization

Following the aggregation and cleaning of the data, household consumption data were fit to outdoor temperature data, according to four different piecewise regression models based on notable loads: (1) heating load, (2) cooling load, (3) heating and cooling load, and (4) non-thermal load This facilitated consumption characterization in relation to outdoor temperature creating linear fits to determine heating, cooling, and passive consumption loads (Birt et al., 2012; Fels, 1986). As identified by Birt et al. (2012), disaggregating different loads from whole-house electricity consumption data can identify end-use parameters relevant to different demand-side management (DSM) policies. This type of information could be used, for example, to target particular homes suitable for retrofit and replacement incentives (Birt et al., 2012). Similarly, in this study, thermal characterization provided insights into dominant thermal uses for households in the dataset. Since technical details of each home were not available in the dataset, this analysis delivered additional insights into the households' consumption patterns. Households with dominant heating profiles utilized electricity loads for heating purposes, in relation to outdoor temperature. Similarly, households with dominant cooling profiles, exhibited consumption patterns relative to outdoor temperatures for cooling purposes, whereas, households with Heating/Cooling profiles exhibited consumption patterns to outdoor temperatures related to both heating and cooling. Where 61% of residential energy in Canada is utilized for space heating, assessing thermal contributions to energy consumption gives essential details on the energy 'context' of household energy consumption (Natural Resources Canada, 2018b; Stephen, 2016).

As an outcome of this thermal disaggregation of consumption, the thermal consumption profile, or consumption relative to outdoor temperature (gradient[47] and activation threshold[48]), as well

[47] The gradient is the slope of the power versus temperature fit lines or the sensitivity of power consumption to changes in temperature past the heating/cooling activation thresholds (in kW/°C).
[48] The activation threshold is the external temperature in which either the cooling or heating system is activated or the external temperature threshold for HVAC system activation (°C).

as base loads[49] and activity loads[50] were identified. Non-thermal characterization identified the dominant consumption related to non-heating/cooling needs.[51] Overall, this sorted households into four categories based on their sensitivity to outdoor temperature: heating, cooling, heating/cooling, or non-thermal.

Heating and cooling thresholds were fit with gradient-free nonlinear optimization via the subplex nonlinear optimization method of Rowan (1990) as implemented by Johnson (2008). The objective function for each optimization consisted of the root mean square error of a non-negative least squares regression on heating/cooling degree days and period of the week. Thresholds were bound by the 2nd and 98th percentile of the thermal dataset corresponding to each household. Within each optimization iteration, thermal sensitivities and period-of-week behavioural components were fit within a non-negative least squares regression. After the four models were fit, they were compared according to the Aikake Information Criterion corrected (AICc) to select the most appropriate model for the household in question, subject to Heating/Cooling thresholds within predetermined bounds. For the heating model, the bounds were 3°C-18°C, and for the cooling model the bounds were 16°C-31°C. This characterization delivered a comprehensive approach to fitting the households within the four thermal models, in addition to providing numerical parameters, this process also created four discrete categories of households, based on the best-fit model for each house.

6.3.6 Household clustering

Following the household thermal model characterization, households were clustered into consumer segments using the model outputs. K-means clustering method was used to segment the households within heating load, cooling load, heating/cooling load thermal archetypes, over two or four dimensions, depending on the model selected in the previous step. K-means clustering was also used for behavioural patterns, utilizing the consumption mean and the normalized energy distribution across the 35 periods of the week (36 dimensions total). Final thermo-behavioural clusters were generated as a Cartesian product of thermal and behavioural clusters (Chicco, 2012). This process

[49] The base load refers to the typical power utilized outside of appliance and space thermal uses (Birt et al., 2012).
[50] The activity load is the standard maximum power not accumulated in space thermal uses or base load. This can be an accumulation of loads related to the operation of other appliances (e.g., laundry appliances, entertainment appliances, lighting, cooking appliances, etc.,) (Birt et al., 2012).
[51] The outcomes are an assumption of the analysis since data are not available to confirm households' technical profiles.

created 78 thermo-behavioural clusters as an outcome from the 6 behavioural and 13 thermal clusters previously generated.

6.3.7 Regression analysis

During this stage both standardization and IHD impact assessment took place. The following sections outline the phases of analysis.

6.3.7.1 Control versus treatment group standardization

In order to accurately analyze the post-treatment data, an assessment of the pre-treatment data took place to determine whether the treatment and control groups had substantial differences. In investigating the consumption data before the IHD installation at the household level, the control and treatment groups exhibited systematic differences in the average load profile across the pre-intervention observation period. The participant groups showed different average responses to temperature fluctuations and daily usage patterns. The difference in hourly group averages was correlated with external temperature in the study site with a Pearson correlation coefficient of 0.71 during the heating season. Factoring out the effects of heating season temperatures at a household level (for all households, regardless of groups) significantly reduced seasonal variation in between-group differences. Finally, applying household-level hour-of-week correction factors eliminated much of the remaining cyclical variation between control and treatment group averages, possibly resulting from systematic differences in average occupant behavioural patterns between groups.

In summary, to ensure both the control and sample consumption data were appropriate for comparison and analysis, a four-factor standardization took place: first, the weekly profile correction, to control for period of week averages; second, the household average consumption correction; third, the temperature correction; and, fourth, the overall time period correction. The standardization procedure was included in the regression, which is also incorporated in the overall IHD impact assessment.

6.3.7.2 IHD impact assessment

An impact regression was utilized to identify the IHD impacts on overall and TOU consumption at various scales. Specifically, the IHD impact assessment involved a multi-stage analysis to assess: first, the effect on overall average consumption; second, the effect on TOU period consumption; third, the effect on day type (i.e., weekend and weekday) consumption. This assessment took place at two scales: total population and cluster-level. The linear regression model was used with household and temporal fixed effects to understand the influence of the IHD installation on household consumption levels for the overall population, and the different cluster levels at each stage of analysis. Global time correction, as well as household specific factors, were also included (average consumption, hourly time correction, average heating degree hours, average cooling degree hours) (Equations listed below).

Legend for Equations

$I_{x,y}$ = 1 When index x corresponds to grouping y,

= 0 otherwise

$IHD_{i,t}$ = 1 if HH_i has IHD enabled at time *t*

= 0 otherwise

HDH_t → Average hourly heating degree hours in time period *t*

CDH_t → Average hourly cooling degree hours in time period *t*

μ_t → Fixed temporal effect for time period *t*

α_i → Fixed household effect for household *i*

β → Intervention effect size (specific to particular time period (e.g., β_w), cluster (e.g., β_{c_b}) or both (e.g., $\beta_{c_t,w}$)

h_i → HDH coefficient for HH_i

c_i → CDH coefficient for HH_i

$s_{i,p}$ → Behavioural schedule effect for household *i* in period of week *p*

$\varepsilon_{i,t}$ → Error/uncertainty term

$y_{i,t}$ → Consumption of HH_i at time *t*

P → Set of all of the households in the population

W → Set of all of the weekend and weekday periods

D → Set of all of the TOU periods

$C_{t,b}$ → Set of all thermo-behavioural clusters

Equation 1 Overall Population-Wide

$$y_{i,t} = \alpha_i + \beta\, IHD_{i,t} + h_i\, HDH_t + c_i\, CDH_t + \sum_{p \epsilon P} s_{i,p}\, I_{t,p} + \mu_t + \varepsilon_{i,t}$$

Equation 2 Weekday/Weekend Population-Wide

$$y_{i,t} = \alpha_i + \sum_{w \epsilon W} \beta_w\, IHD_{i,t}\, I_{t,w} + h_i\, HDH_t + c_i\, CDH_t + \sum_{p \epsilon P} s_{i,p}\, I_{t,p} + \mu_t + \varepsilon_{i,t}$$

Equation 3 TOU Period Population-Wide

$$y_{i,t} = \alpha_i + \sum_{d \epsilon D} \beta_d\, IHD_{i,t}\, I_{t,d} + h_i\, HDH_t + c_i\, CDH_t + \sum_{p \epsilon P} s_{i,p}\, I_{t,p} + \mu_t + \varepsilon_{i,t}$$

Equation 4 Overall by Thermo-behavioural Cluster

$$y_{i,t} = \alpha_i + \sum_{c_{tb} \epsilon C_{tb}} \beta_{c_{tb}}\, IHD_{i,t}\, I_{i,C_{tb}} + h_i\, HDH_t + c_i\, CDH_t + \sum_{p \epsilon P} s_{i,p}\, I_{t,p} + \mu_t + \varepsilon_{i,t}$$

Equation 5 Weekday/Weekend by Thermo-behavioural Cluster

$$y_{i,t} = \alpha_i + \sum_{c_{tb} \epsilon C_{tb}} \sum_{w \epsilon W} \beta_{c_{tb},w}\; IHD_{i,t}\, I_{i,C_{tb}} I_{t,w} + h_i\, HDH_t + c_i\, CDH_t + \sum_{p \epsilon P} s_{i,p}\, I_{t,p} + \mu_t + \varepsilon_{i,t}$$

Equation 6 TOU Period by Thermo-behavioural Cluster

$$y_{i,t} = \alpha_i + \sum_{c_{tb} \epsilon C_{tb}} \sum_{d \epsilon D} \beta_{c_{tb},d}\; IHD_{i,t}\, I_{i,C_{tb}} I_{t,d} + h_i\, HDH_t + c_i\, CDH_t + \sum_{p \epsilon P} s_{i,p}\, I_{t,p} + \mu_t + \varepsilon_{i,t}$$

6.3.8 Study limitations

Limitations of this study should be highlighted. First, hourly consumption data were only available for this study. Household profiles, qualitative feedback, or details on routines and lifestyle changes were not available; consequently, limitations exist for making concrete conclusions on the effectiveness and influence(s) of the IHD on the participants' decisions. Future studies can incorporate socio-demographic data, qualitative feedback, and details on technological and social household profiles. Second, participants in this study were not a random sample of the overall population, since they were PeakSaver Plus participants with electric water heaters. The control group was randomly selected. Third, this study assumes that the 'installation' date was the IHD delivery date and that each household activated and placed their IHD within a central location in the home.

6.4 Results

The following sections outline the results of the introduction of the IHD[52] on the overall consumption culture of the study population. Additionally, the following sections also define and highlight the IHD impacts.

6.4.1 IHD influence on overall consumption

As an outcome of the regression analysis on the general participant group, no statistically significant change in consumption (overall, day type and TOU period) was observed in conjunction with the IHD installation (Table 37) ($p>0.05$). Therefore, a substantial opportunity was available to assess the IHD effect on particular consumer segments.

Table 37 IHD effect on consumption across different periods (estimate in hourly kWh). * is significant where $p<0.05$

Period	Estimate	Standard Error	*p*
Overall	0.0023	0.0061	0.635
Weekday	0.0027	0.0062	0.664
Weekend	0.0034	0.0062	0.580
Mid-Peak	0.0031	0.0065	0.629
Off-Peak	0.0007	0.0060	0.905
On-Peak	0.0088	0.0073	0.231

$R^2 = 0.668$

6.4.2 Behavioural segments

Households were divided into six behavioural segments based on the periods of the week in which energy was consumed (evening peakers, midday consumers, steady eddies, twin peakers, high-level night-timers, night-owls). These six clusters highlight distinct behavioural patterns (e.g., magnitudes and consumption distribution) within the study population, similar to Oracle's behavioural clusters (Fischer, 2014; Frades, 2016) (Table 38 and Figure 54). These patterns could suggest particular lifestyles, routines, or habits. For example, midday consumers (Cluster 2), could be home during the day (e.g., parents or seniors), twin peakers (Cluster 4) could have a '9-to-5' schedule and consume most daily energy before and after work, whereas evening peakers (Cluster 1), could also have a '9-to-5' schedule, but consume most weekday energy after work (e.g., cooking or other

[52] As mentioned in the methods, this study utilizes the delivery date as the 'installation' date and assumes that each household activated their IHD and placed it in a central location in the home.

post-work activities requiring energy). Although these speculations in routines and habits cannot be confirmed with the data available, these segmented archetypes based on period-of-week consumption deliver critical insights into distinct consumption patterns in the population.

Table 38 Summary of behavioural segments, IHD recipients

Behavioural cluster[53]	Description	Cluster Size
1 Evening peakers	Peak consumption in evening periods. Consumption below average. Weekend consumption larger in midday.	538
2 Midday consumers	Rounded consumption with midday-evening peak consumption. Above average all week. Fridays have a midday peak. Weekend consumption is lower.	199
3 Steady eddies	Flattened consumption with evening to late evening peak. Increased evening consumption on weekends. Consumption stays below average.	1399
4 Twin peakers	Peak consumption in morning and evening periods. Consumption below average, except mornings (average). Larger weekend midday consumption.	996
5 High-level night-timers	Evening peak consumption. Larger midday consumption during weekends. Always above average consumption.	1147
6 Night-owls	Steep late evening peak consumption with more midday consumption on weekends. All periods below average, except for late evening periods on weekdays.	995

Specific DSM techniques can be directed to different load shape profiles. Strategies such as strategic conservation, load shifting, peak clipping, and valley filling can be targeted towards certain load shapes that align with particular benefits (Alagoz, Kaygusuz, & Karabiber, 2012; Ellegård & Palm, 2011; Gellings, 1985; Macedo, Galo, Almeida, & Lima, 2015; Palensky, Member, Dietrich, & Member, 2011; Patterson, 1996). For example, energy efficiency and conservation policies could be applied to consumers with constant consumption, or in flatter load shapes, such as cluster 3 (steady eddies). Policies can be also be targeted to consumers with peak loads. Profiles with two distinct

[53] These cluster names were adapted from Oracle's behavioural load shape cluster names (Fischer, 2014; Frades, 2016; Oracle, 2015).

peaks (e.g., cluster 4, twin peakers) can benefit from policy mechanisms to reduce the peak loads (e.g., tariffs, direct load controls, consumer power generation). Those with peaked and constant consumption, such as cluster 2 (midday consumers), could benefit from consumer power generation or storage. Sharp peaks, as exhibited in clusters 1 (evening peakers), 5 (night-timers), and 6 (night-owls), can benefit from policies targeting peak loads, such as direct load control, storage, distributed generation, or tariffs (Ellegård & Palm, 2011; Frades, 2016; Gellings, 1985; Macedo et al., 2015; Patterson, 1996). Therefore, these load-shape profile segments bring insights into consumption use patterns and potential relevant CDM approaches; however, these load-shape archetypes present limited information on thermal constraints of energy demand.

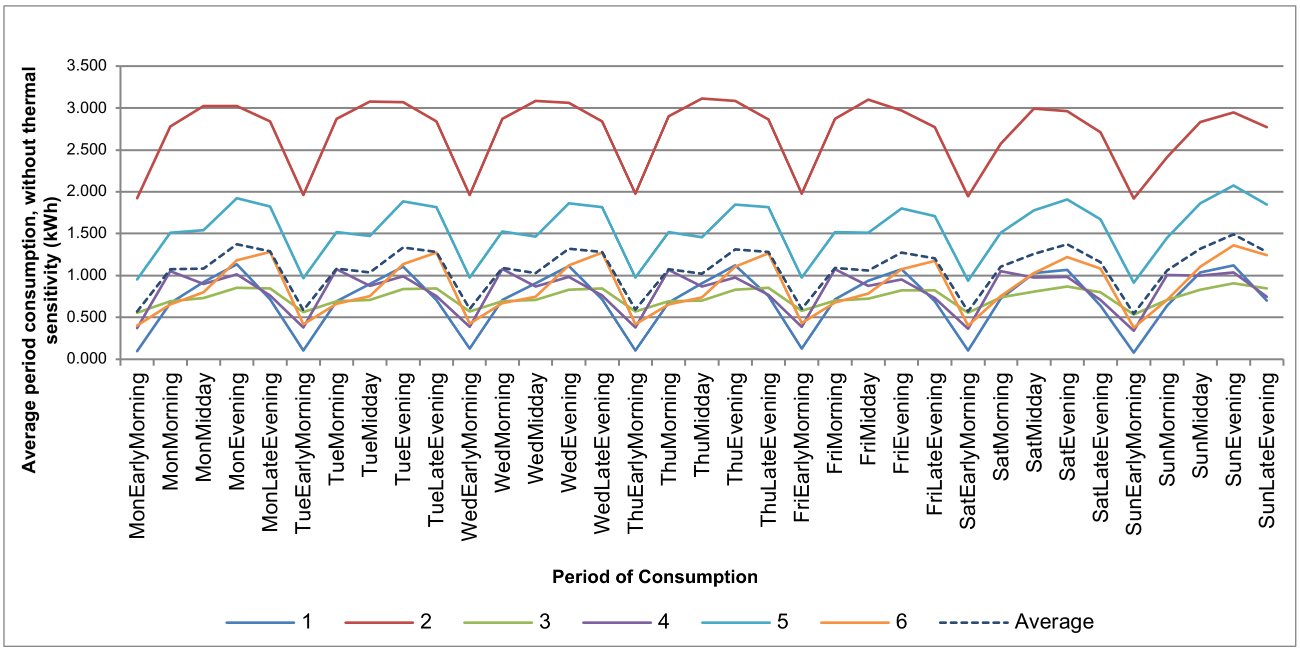

Figure 54 Summary of 6 behavioural segments' load shape

6.4.3 Thermal segments

Identifying the thermal clusters offers additional understanding about participants' thermal flexibility and sensitivity, as well as potential household-level efficiencies, therefore gaining more insights on consumption patterns. Disaggregating thermal consumption patterns provides insights on electricity end-use categories related to heating and cooling and identifies households relevant for particular DSM strategies (e.g., retrofit and replacement incentives) (Birt et al., 2012). Participants were clustered based on their heating and cooling gradient[54] and their cooling and heating activation threshold[55], resulting in twelve thermal clusters and one non-thermal cluster (thirteen clusters in total). Based on their model fit, households were characterized by their activation thresholds, gradient and consumption between each of the four heating, cooling and heating/cooling clusters (Table 39). Through clustering, distinct thermal segments are evident, where certain customers experienced specific levels of thermal responses based on their levels of sensitivity, activation thresholds, and thermal model fit.

Table 39 Summary of thermal clusters, IHD recipients

Cluster	Cluster description	Heating activation threshold (avg °C)	Heating gradient (avg kW/°C)	Cooling activation threshold (avg °C)	Cooling gradient (avg kW/°C)	Cluster Size
Cooling 1	High-level sensitive coolers	-	-	20.2	0.178	111
Cooling 2	Low-level non-sensitive coolers	-	-	24.7	0.113	201
Cooling 3	Low-level sensitive coolers	-	-	25.3	0.278	81
Cooling 4	High-level non-sensitive coolers	-	-	18.3	0.070	185
Heating 1	Low-level sensitive heaters	13.3	0.170	-	-	245
Heating 2	High-level non-sensitive heaters	15.7	0.026	-	-	479
Heating 3	High-level sensitive heaters	14.3	0.088	-	-	539
Heating 4	Low-level non-sensitive heaters	8.5	0.051	-	-	334
Heating/ Cooling 1	Sensitive and low-level thermals	11.9	0.140	23.9	0.136	241
Heating/ Cooling 2	Non-sensitive high-level thermals	12.6	0.024	18.8	0.088	334
Heating/ Cooling 3	Mixed sensitivity (high cool, low heat) with mixed thermals (high heat & low cooling)	14.1	0.027	23.5	0.163	515
Heating/ Cooling 4	Mixed sensitivity (high heat, low cool) with mixed thermals (low heat & high cooling)	7.8	0.037	22.2	0.110	521
Non-thermal	Non-thermal consumers	-	-	-	-	1488

[54] As previously mentioned, the gradient is the slope of the power versus temperature fit lines or the sensitivity of power consumption to changes in temperature past the heating/cooling activation thresholds (in kW/°C).
[55] As previously mentioned, the activation threshold is the external temperature in which either the cooling or heating system is activated or the external temperature threshold for HVAC system activation (°C).

6.4.4 Thermo-behavioural energy culture segments

Bringing together the thermal (13) and behavioural (6) segments created 78 thermo-behavioural segments; however, only 77 segments were filled.[56] This segmentation delivered detailed insights on household consumption decisions in the absence of socio-demographic data (Stephen, 2016; Stephenson, Barton, et al., 2015; Stephenson et al., 2010). Consequently, this model provides detailed insights into consumption culture influenced by thermal and behavioural consumption patterns by integrating the households' load shape profile and respective thermal model.

6.4.5 Influence of the IHD on thermo-behavioural clusters

The analysis identifies that different thermo-behavioural clusters responded differently to the IHD. Thirty-four clusters (44%) experienced significant influences on consumption ($p<0.05$) as an outcome of the regression analysis on overall, TOU and day type (weekend/weekday) consumption levels.[57]

Of the clusters with significant effects ($p<0.05$) (n=34),[58] patterns in overall reductions were evident, with limited evidence of favourable peak shifting.[59] The majority of segments with significant reductions (n=11) were heating groups (n=5). Limited TOU shifting occurred where over half of the clusters with On-Peak reductions consumption (n=7) also had Off-Peak reductions (n=4). On-Peak reductions were distributed evenly in Heating (n=3) and Cooling groups (n=3). Similarly, the majority of households with Off-Peak reductions (n=10) had On-Peak increases (n=7); however, heating groups experienced the most significant Off-Peak increases.

Although 10 segments significantly reduced their weekday consumption, 4 also reduced weekend consumption at similar scales ($p<0.05$). Half of these effects were in Heating clusters. Similarly, although 7 clusters had increased weekend consumption, they also increased weekday consumption. The majority were in Heating groups (n=4). Thus, shifts to weekends and Off-Peak consumption periods were limited, with the Heating groups experiencing the majority of significant effects in conjunction with the IHD installation.

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[56] Details for all 77 thermo-behavioural clusters located in Appendix F.
[57] Regression results for all clusters located in Appendix G, with notable clusters identified in the following sections.
[58] n refers to the number of segments.
[59] The authors define favourable peak shifting as shifting consumption from On-Peak and Mid-Peak periods to Off-Peak.

The effect on behavioural clusters was not as uniform as thermal clusters. The majority of significant influence(s) were experienced in behavioural groups 3 (steady eddies), 5 (high-level night-timers) and 6 (night-owls) ($p<0.05$). Significant influences were experienced across most thermal groups. Although the trends for the majority of the thermo-behavioural clusters show limited favourable changes in consumption, ten clusters with favourable consumption changes should be highlighted (Table 40).

Table 40 Summary thermo-behavioural cluster characteristics with significant favourable changes, *Significant effect (*p*<0.05) ♦ notable clusters[60]

Cluster		Characteristic	n	Influence	Total consumption effect (hourly kWh)	TOU consumption effect (hourly kWh)	Day type consumption effect (hourly kWh)
A♦	Heating/ Cooling 2, 2	Midday consumers with Non-sensitive high-level thermals	22	Largest reductions	-0.47*	Mid-Peak: -0.48* Off-Peak: -0.50* On-Peak: -0.39	Weekday: -0.46* Weekend: -0.49*
B♦	Heating 3, 1	Evening peakers with High-level sensitive heating	294	Peak reductions	-0.05*	Mid-Peak: -0.10* Off-Peak: -0.01 On-Peak: -0.08*	Weekday: -0.06* Weekend: -0.02
C♦	Heating 4, 4	Twin peakers with Low-level non-sensitive heating	97	Off-Peak increases	0.08	Mid-Peak: 0.09 Off-Peak: 0.07* On-Peak:0.11	Weekday: 0.09 Weekend: 0.08
D♦	Heating 1, 1	Evening peakers with Low-level sensitive heating	126	Peak reductions	-0.10*	Mid-Peak: -0.17* Off-Peak: -0.06 On-Peak: -0.11*	Weekday: -0.11* Weekend: -0.06
E♦	Heating 1, 6	Night-owls with Low-level sensitive heating	82	Peak reductions	-0.08	Mid-Peak: 0.07 Off-Peak: -0.10 On-Peak: -0.20*	Weekday: -0.09 Weekend: -0.06
F	Cooling 1, 1	Evening peakers with High-level sensitive cooling	2	Largest non-Peak increases	0.21*	Mid-Peak: 0.35* Off-Peak: 0.20* On-Peak: 0.09*	Weekday: 0.20* Weekend: 0.24*
G	Heating 3, 3	Steady eddies with High-level sensitive heating	66	Increases in non-Peak	0.13*	Mid-Peak: 0.23* Off-Peak: 0.11* On-Peak: 0.06	Weekday: 0.12* Weekend: 0.14*
H	Cooling 4, 1	Evening peakers with High-level non-sensitive cooling	3	Peak period (Mid-Peak, On-Peak) and weekday reductions	-0.19*	Mid-Peak: -0.46* Off-Peak: -0.08* On-Peak: -0.20*	Weekday: -0.26* Weekend: -0.01
I	Cooling 2, 2	Midday consumers with Low-level non-sensitive cooling	8	Reductions On-Peak, weekend, Mid-Peak	-0.06	Mid-Peak: -0.19* Off-Peak: 0.00 On-Peak: -0.09*	Weekday: -0.07 Weekend: -0.04*
J	Cooling 3, 2	Midday consumers with Low-level sensitive cooling	8	Large Peak reductions	-0.49	Mid-Peak: -0.45* Off-Peak: -0.45 On-Peak: -0.64*	Weekday: -0.47 Weekend: -0.54*

[60] Thermo-behavioural clusters are identified with their thermal cluster and number and followed by the behavioural cluster number (e.g., Cooling 1, 1, is the cluster with Cooling 1 and Behavioural Cluster 1 characteristics).

Of the ten segments highlighted (Tables 40 and 41), five segments were notable due to their cluster size and peak consumption changes (Clusters A – E, Tables 40 and 41). First, cluster A had the largest consumption reductions across periods; however, significant On-Peak reductions were not experienced. Second, cluster B experienced substantial Peak Period reductions. Third, cluster C only experienced significant Off-Peak consumption increases. Fourth, cluster D, experienced reductions across periods (except Off-Peak), showing potential peak reductions. Lastly, cluster E showed potential signs of peak shifting, with significant On-Peak reductions, and non-significant Mid-Peak increases. Therefore, these notable clusters showcased On-Peak reductions and potential for peak shifting patterns, corresponding to the IHD introduction.

These five clusters with notable consumption differences had certain thermo-behavioural characteristics. In particular, evening, and night-time consumption peaks were evident where two groups were evening peakers (behavioural cluster 1), one was night-owls (behavioural cluster 6), and one had night-time as well as morning peaks (twin peakers, cluster 4). Additionally, heating thermal models experienced the most notable influences in consumption, with the majority of heating groups having high heating sensitivities. These five notable segments consisted of 621 households or 12% of the IHD recipients. As expressed in Section 6.4.2, certain load shapes are favourable for specific DSR policy mechanisms (Alagoz et al., 2012; Ellegård & Palm, 2011; Gellings, 1985; Macedo et al., 2015; Palensky et al., 2011; Patterson, 1996). Tariffs or direct load control can be applied to load-shapes with single or dual peaks to encourage peak shifting. In this case, households that favourably responded to the IHDs had particular evening peak patterns, highlighting potential peak reductions, and shifted responses through real-time TOU feedback. Understanding the particular thermal model can bring insights for specific DSR techniques for shifting, and seasonality of these shifts. As expressed in these thermo-behavioural results, households who, according to the thermal model, utilized energy during heating periods could be targeted for direct load control or peak shifting. Therefore, the most notable consumption influences were evident in heating clusters and evening peak consumption; however, these notable clusters were a small fraction of IHD recipients (12%), highlighting challenges with engaging large numbers of consumers with smart meter-enabled IHD feedback.

Table 41 IHD effect on notable thermo-behavioural clusters, (estimate in average hourly kWh, standard errors reported in parentheses). * is significant where *p*<0.05

	Cluster	Overall	Weekday	Weekend	Mid-Peak	Off-Peak	On-Peak
A	Heating/ Cooling2,2	-0.47* (-0.19)	-0.46* (-0.19)	-0.49* (-0.2)	-0.48* (-0.21)	-0.50* (-0.18)	-0.39 (-0.23)
B	Heating 3,1	-0.05* (-0.02)	-0.06* (-0.02)	-0.02 (-0.02)	-0.10* (-0.02)	-0.01 (-0.02)	-0.08* (-0.03)
C	Heating 4,4	0.08 (-0.05)	0.09 (-0.05)	0.08 (-0.05)	0.09 (-0.06)	0.07* (-0.04)	0.11 (-0.06)
D	Heating 1,1	-0.10* (-0.05)	-0.11* (-0.05)	-0.06 (-0.05)	-0.17* (-0.04)	-0.06 (-0.05)	-0.11* (-0.06)
E	Heating 1,6	-0.08 (-0.06)	-0.09 (-0.06)	-0.06 (-0.06)	0.07 (-0.07)	-0.10 (-0.07)	-0.20* (-0.07)
F	Cooling 1,1	0.21* (-0.01)	0.20* (-0.01)	0.24* (-0.01)	0.35* (-0.01)	0.20* (-0.01)	0.09* (-0.01)
G	Heating 3,3	0.13* (-0.05)	0.12* (-0.05)	0.14* (-0.05)	0.23* (-0.05)	0.11* (-0.05)	0.06 (-0.08)
H	Cooling 4,1	-0.19* (-0.01)	-0.26* (-0.01)	-0.01 (-0.01)	-0.46* (-0.01)	-0.08* (-0.01)	-0.20* (-0.01)
I	Cooling 2,2	-0.06 (-0.04)	-0.07 (-0.05)	-0.04* (-0.01)	-0.19* (-0.02)	0.00 (-0.05)	-0.09* (-0.03)
J	Cooling 3,2	-0.49 (-0.26)	-0.47 (-0.27)	-0.54* (-0.25)	-0.45* (-0.22)	-0.45 (-0.27)	-0.64* (-0.3)

$R^2 = 0.669$
p values and complete thermo-behavioural results are additionally reported in Appendix G

6.5 Discussion

This study recognizes the challenges of utilizing standard feedback devices to influence smart grid consumer behaviour. Specifically, while the IHD was not influential at the general population level, the IHD had significant impacts for particular types of consumers. Following segmentation, highly sensitive heating households with evening peak consumption experienced notable influences from the IHD. Consequently, these outcomes present four critical areas for discussion: TOU pricing and the role of real-time feedback, effective feedback program design, applying segmentation for holistic smart grid research, and unlocking pathways for smart grid consumer engagement.

6.5.1 TOU Pricing and real-time IHD feedback

In this study, IHDs provided financial feedback (TOU period and $/kWh) to drive TOU shifts; however, this resulted in limited favourable population-wide changes. Previous studies in Ontario have shown that IHDs with TOU pricing can increase conservation (-7.6%) compared to savings from TOU prices alone (-3.3%) (Hydro One, 2008). However, other studies have found no significant influence of IHDs on Ontario household consumption years following TOU establishment (George, Churchwell, Oh, & Thompson, 2015). Similarly, in California, Schultz et al. (2015), identified no significant reductions from financial and consumption IHD feedback. Buchanan et al. (2015) raise concerns for relying on financial feedback for population shifts, especially when a disconnect between IHD feedback and billing cycles is present, resulting in long periods between the financial savings and the related action. Real-time savings from behavioural changes may also be minimal compared to convenience and other costs (K. Buchanan et al., 2015), which could also be contributing factors within this study.

The outcomes of this paper further articulate the difficulty of engaging consumers with real-time feedback and TOU prices, with only 12% of IHD recipients showcasing significant favourable peak shifts after segmentation consumption analysis. However, these particularly favourable household segments bring insights into which types of consumers may positively respond to this type of real-time pricing feedback facilitated by an IHD. Even though the majority of households exhibited peak consumption patterns, favourable for load-shifting through Ontario's TOU tariffs, this real-time TOU feedback from the IHD resulted in minimal influences on these types of ideal consumer load shapes. Although the capability of smart meter-enabled real-time financial feedback through IHDs is considered valuable for TOU pricing, it may not be the most strategic mechanism for certain consumer types to motivate significant consumption changes.

6.5.2 Designing effective feedback programs

Smart meter-enabled feedback programs provide promising CDM opportunities; however, careful consideration of program design also needs to occur (Cheng, Woon, & Lynes, 2011; Schultz et al., 2015). The delivery and installation of smart grid tools is a crucial part of program engagement (Anda & Temmen, 2014; Darby et al., 2018). In this study, the IHD was delivered by mail; however, research has identified the importance of education and communication strategies during the installation phase of feedback programs (Darby et al., 2018). Although this was a limitation, it highlights an opportunity to compare installation procedures and its impact on smart grid engagement and consumption influences.

A crucial challenge to smart grid adoption is technological acceptance. Designing appropriate devices that are easy to use, and guide users to desired behaviours, is crucial for smart metering engagement (Darby, 2006; Ford et al., 2014; Gangale et al., 2013; Park et al., 2014). The literature defines important dimensions of feedback design (Darby, 2006; Froehlich, 2009; Froehlich et al., 2010; Karlin et al., 2015). The type of feedback is also essential. Strengers (2011b) emphasizes that eco-feedback technology design needs to be designed to influence daily activities, routines and household consumption dynamics. Feedback Intervention Theory (FIT) highlights the importance of meaningful goals (personal or normative) alongside feedback for effective engagement (Abrahamse et al., 2005, 2007; Karlin et al., 2013, 2015; McKenzie-Mohr & Schultz, 2014). Opportunities to align FIT objectives with the design of the study's IHD are evident (e.g., consumption goals, push/pull notifications, normative feedback) (Table 36). Building social tools and feedback has the potential to drive change (Sintov & Schultz, 2015); however, response variability and challenges associated with feedback engagement can be evident, as seen in this study. Therefore, product design and information provision can influence the adoption and use of IHD feedback, which could have been a factor in engaging particular users in this study. Although this cannot be confirmed since user experience data were not obtained, it presents a key consideration for future studies.

6.5.3 Combining segmentation and holistic frameworks for smart grid research development

Types of consumers differ in response to IHDs, and our study aligns with the existing literature (Karjalainen, 2011; van Dam et al., 2010). In this study, certain segments responded favourably to the IHD; however, limited outcomes were evident, where only 12% of the population were favourably influenced following segmentation. Although consumer insights are crucial for CDM program development (K. Buchanan et al., 2015), as experienced in this program, information on consumers' experience may not be available. For instance, the largest notable segment (cluster B, n= 294) could have provided additional insights (Table 40). This particular cluster had evening peak consumption and low-level sensitive heating characteristics.

Existing IHD research highlights limited consumer-centred design, with gaps between environmental phycology and human-computer-interaction in eco-feedback studies (K. Buchanan et al., 2015; Froehlich et al., 2010; Jain et al., 2012). Proven strategies, such as Community Based

Social Marketing (CBSM), can incorporate social and behavioural elements (e.g., motivations and barriers to CDM) into program design, for targeting key behaviours and piloting effective strategies (McKenzie-Mohr, 2000, 2011; McKenzie-Mohr & Schultz, 2014). Effective program design goes beyond technology and incorporates the needs of the target audience before implementation (Goulden et al., 2014). In this IHD program, key CDM barriers were not articulated before engagement and could have influenced engagement levels.

As utilities move towards consumer-centred approaches to product development (SGCC, 2016b), integrating details beyond consumption data can reduce the anonymity among utilities and consumers for grid benefits (Strengers, 2013; Summerton, 2004). For instance, combining load shape profiles with socio-economic data provides policy and program insights and can be applied in interdisciplinary research (Viegas, Vieira, Melicio, Mendes, & Sousa, 2016). Holistic frameworks, such as the energy cultures framework, can deliver understandings for smart grid participant segmentation incorporating comprehensive data types (e.g., socio-demographics, load-shape profiles, thermal characteristics, household profile, CDM awareness) (Lawson & Williams, 2012; Lazowski et al., 2018; M. G. Scott et al., 2016; Stephenson et al., 2010). Research design considerations are essential to collect sufficient data for holistic understanding. Designing an efficient smart grid where residential engagement is concerned, involves synergy between technology and behaviour; thus, the integration of technical and social disciplines can develop a thorough understanding for consumer engagement in future IHD research.

6.5.4 Unlocking pathways to consumer adoption

Segmenting consumers and gathering this detailed information can unlock knowledge on ideal consumers for smart grid advancements beyond IHDs. Load shape profiles and advanced analytics deliver insights into consumer behaviours (Frades, 2016; Ge et al., 2016; Jang et al., 2016; SGCC, 2016a). Certain load shapes exhibited patterns complementary to specific DSR policies (e.g., load shifting, peak clipping, valley filling, strategic conservation) (Alagoz et al., 2012; Ellegård & Palm, 2011; Gellings, 1985; Macedo et al., 2015; Palensky et al., 2011; Patterson, 1996). Similarly, identifying patterns of household consumption can provide understandings for implementing programs for vehicle-to-grid storage, renewable capabilities, and off-grid energy management. For example, households who consume energy On-Peak for heating and cooling (Midday heating or cooling consumers) could benefit from storage programs for peak shifting. As smart technologies are introduced for low-carbon heating transitions, such as in the United Kingdom (Darby et al., 2018), applying segmentation on thermal characteristics can bring additional information for program design to improve demand and related comfort. Therefore, segmented approaches to understanding consumer preferences can be applied beyond smart grid-enabled feedback, and into the uptake of additional smart grid elements.

6.6 Conclusions

Key outcomes from this analysis highlight the insufficiency of this smart meter-enabled IHD feedback to drive favourable consumption changes in the general population, and the importance of investigating IHD responses within specific consumer segments. Distinct thermo-behavioural clusters were evident in the study group. The analysis identified different IHD responses in the consumer segments, underlining key points for future research and policy development. This study aligns with existing studies stressing the challenges of feedback to facilitate population-level shifts in energy consumption. Additionally, though participant segmentation, this study investigated certain types of consumers, based on thermo-behavioural characteristics, were more receptive to smart meter-enabled IHD feedback.

Particular trends in the consumer segments were notable, but with limited IHD impacts on consumption. No significant impact occurred at the population level. Although 34 thermo-behavioural segments were significantly influenced, only five clusters were particularly noteworthy due to size and significant changes. Of these segments, the IHD had the most prominent influences on Heating clusters with high levels of evening and night-time consumption, where these segments changed overall or TOU consumption. However, a limited percentage (12%) of the population households were favourably influenced by the IHD following segmentation analysis, signalling for opportunities to develop useful engagement strategies (Table 42).

Table 42 Summary of five notable energy culture segments

Cluster	Thermo-behavioural Cluster	Characteristic	n	Influence
A	Heating/ Cooling 2, 2	Midday consumers with Non-sensitive high-level thermals	22	Largest reductions
B	Heating 3, 1	Evening peakers with High-level sensitive heating	294	Peak reductions
C	Heating 4, 4	Twin peakers with Low-level non-sensitive heating	97	Off-Peak increases
D	Heating 1, 1	Evening peakers with Low-level sensitive heating	126	Peak reductions
E	Heating 1, 6	Night-owls with Low-level sensitive heating	82	Peak reductions

Critical points for smart grid feedback, participant targeting, and consumer engagement can be emphasized as a result of this study. In particular, the importance of market targeting and segmentation for policy and program implementation. Although the overall population did not demonstrate significant changes, certain types of consumers are potentially more receptive to smart meter-enabled IHD feedback. Therefore, signalling the importance of consumer targeting for large-scale engagement programs. These results also emphasize the importance of 'user-centred' targeting for policy implementation and programming. Consumer surveys, economic analysis, and other targeting approaches can provide additional benefits to initial project implementation alongside advanced consumption data analytics (Viegas et al., 2016).

The outcomes of this analysis also emphasize the importance of going beyond information and feedback in smart grid consumer engagement. As presented in the aggregate results, and identified thoroughly in the literature, feedback alone may not result in favourable outcomes at population-wide levels in smart grid developments (Hargreaves, 2018); however, it may influence particular consumer segments, as articulated in this study. Consequently, this study emphasizes the importance of user-centred strategies to identify, develop, and implement additional engagement mechanisms to harness the capabilities of feedback.

The results of this segmented analysis highlight that specific behavioural and thermal preferences are indicative of intervention effectiveness, where certain notable average group effects were identified in this particular sample group. As a result, emphasizing the importance of consumption profiles for understanding CDM adoption, as articulated by energy analytics organizations, such as Oracle (Frades, 2016), which can bring insights for program targeting, especially as smart grid developments incorporate low-carbon heating, vehicle-to-grid, storage and renewables integration at the consumer-level.

Lastly, this study highlights the potential for utilizing consumption data and behavioural modelling to understand consumers in the absence of socio-demographic data. However, it is ideal to have qualitative and socio-demographic data alongside smart metering data for a detailed understanding of the potential opportunities and influences (Stephenson et al., 2017; Viegas et al., 2016). Opportunities exist to combine load shape profiles with socio-economic data to increase the insights for policy and program development, which has been proven useful in existing research (Viegas et al., 2016). Overall, providing a more comprehensive approach to studying segments of energy cultures, can provide significant insights to policymakers and developers within the smart grid in multiple jurisdictions. At the time of this study, this is a novel application of IHD response segmentation in the literature and brings opportunities for cross-comparisons with other regional contexts.

7. Chapter 7 – ENGAAGGE: Towards an integrated model for collective change

Purpose: This paper presents a novel approach for intervention design for collective sustainability shifts. This new model harnesses the strengths of social marketing (SM), community based social marketing (CBSM), social practice theory (SPT), and design thinking (DT) approaches for societal change.

Design/methodology/approach: This paper reviews SM, CBSM, SPT, and DT and compares their respective approaches to intervention design. Key elements of intervention design are identified. Strengths and limitations of existing approaches are recognized. The strengths of each approach are integrated into a novel approach to intervention design: the ENGAAGGE model. This model incorporates elements drawn from existing approaches to create a comprehensive model for intervention design. This is a conceptual paper involving a review and model proposal.

Findings: The ENGAAGGE model provides a user-centred approach for detailed understanding which integrates the marketing tactics from SM, the proven and successful strategies of CBSM, the societal focus of SPT and the iterative methodology of DT to propose a novel approach for sustainability intervention design, applicable to multiple sectors.

Research limitations/implications: This paper is conceptual and proposes an integrated approach to apply and test in future research.

Practical implications: The proposed ENGAAGGE model could act as a new approach for intervention development and program design. Opportunities exist to identify specific evaluation strategies.

Originality/value: This is a novel, and comprehensive review of SM, CBSM, SPT, and DT applied to develop an integrated model utilizing the strengths of each approach.

Keywords: behaviour change, community based social marketing, design thinking, engagement, intervention design, social marketing, social practice theory, sustainability.

Paper type: Conceptual

7.1 Introduction

A social marketer, community-based social marketer, a social practice theorist, and a design thinker walk into a café. In conversation with the café manager, they learn that the café is having trouble getting customers accustomed to utilizing reusable cups instead of single-use ones. The social marketer proposes a situation analysis to determine a targeted promotion for the café's audience. The community-based social marketer focuses on developing a solution addressing the barriers and benefits influencing social norms. Meanwhile, the social practice theorist feels they need a deeper understanding of customers' practices around coffee drinking and proposes to apply ethnographic methods to identify potential solutions. The design thinker says, "We should begin with user-centred research to design a new product and test prototypes with focus groups." Although striving to achieve the same outcome, the mechanisms, theoretical lenses, and overall approaches used in each case are different.

The above example of reusable versus single-use coffee cups represents one of many hundreds of incremental ways in which we can begin to shift to a more sustainable society. We presently tackle these challenges from distinct disciplinary frameworks, each individually representing a valid approach. What are the possibilities if we adopted a multidisciplinary approach to address the problem?

The last 30 years have seen exponential growth and tension in the development of effective sustainability strategies. Political mechanisms for achieving these shifts involve building capacities, developing coalitions, and also achieving normalization (Bernstein & Hoffmann, 2018; Tozer, 2016). Under the guise of societal shifts, several different theoretical lenses can be applied to develop effective interventions[61] for achieving these changes (T. Brown & Wyatt, 2010; Greene, 2019; N. R. Lee & Kotler, 2008; McKenzie-Mohr, 2011; Shove, 2010; Stern, 2000).

The issue of societal change has been addressed using different lenses from a variety of disciplinary origins in research, in policy, and in practice. These lenses provide different insights into human actions across time (Greene, 2019), including sociology, psychology, marketing, and design. Nestled within these disciplinary silos are approaches such as social marketing (marketing), community-based social marketing (psychology), social practice theory (sociology), and design thinking (design). Discourses on these approaches largely remain in silos; however, there is evidence that multidisciplinary approaches are considered critical for successful transitions (Creutzig et al., 2018; Sovacool & Hess, 2017; Steg et al., 2015; Vlek & Steg, 2007). Consequently, opportunities exist to bring these approaches together. This opportunity forms the foundation for this paper: by

[61] Across disciplines, different terminology is used for change mechanisms. For this paper, the authors decided to use the term intervention to refer to a policy, program, product or alternative mechanism for the achievement of societal shifts towards the desired outcome (Wilson & Dowlatabadi, 2007).

harnessing the strengths of current frameworks, there is potential to make the process of engagement and program design more efficient and, ultimately, yield greater results.

Existing research has investigated and compared social practice theory and design thinking (Ingram, Shove, & Watson, 2007; Pettersen, 2015; Shove, 2006; Shove, Watson, Hand, & Ingram, 2007), social practice theory and behavioural strategies (Shove, 2003b; Spurling, Mcmeekin, Shove, Southerton, & Welch, 2013; Walker & Shove, 2007), and more recently, social practice theory and social marketing (Spotswood et al., 2017); however, social marketing (SM), community-based social marketing (CBSM), social practice theory (SPT), and design thinking (DT) have not yet been compared *together*. Consequently, this paper aims to fulfill multiple objectives: firstly, to provide an overview of existing intervention design elements for sustainability; secondly, to examine the approaches of SM, CBSM, SPT, and DT, to identify their key intervention design elements, and to highlight respective strengths and limitations. Lastly, this paper advances the theory on societal sustainability shifts by proposing the ENGAAGGE model. This new model provides an empathy-based[62] approach and integrates the marketing principles of social marketing (SM), the clear and proven techniques of community-based social marketing (CBSM), the whole-system and societal focus of social practice theory (SPT), and the iterative prototype methodology of design thinking (DT). The outcome is a novel approach to sustainability intervention design, which can be used in diverse scenarios. This paper is conceptual in nature and has not been used empirically; therefore, opportunities exist to develop and test evaluation strategies to provide policymakers, practitioners, and business operators, such as our café manager, with opportunities to tackle their sustainability problems.

7.2 A review of intervention approaches for societal sustainability shifts

Developing interventions that engage society in the uptake of aspirational societal practices is a pivotal aspect of sustainability shifts; however, the forces influencing related societal actions (e.g., the uptake of technology/products, change in actions, utilization of infrastructure and shift in societal standards) remain complex. For example, many personal contextual factors influence residential energy behaviours (e.g., habitual, technical, external) (Kowsari & Zerriffi, 2011). Consequently, multiple disciplinary perspectives addressing this range of factors are required to design effective

[62] An empathy-based approach stems from design thinking, which emphasizes a user-centred approach. An empathy-based approach, therefore, applies and develops an analytical lens from the perspective of the target audience for thorough solutioning and intervention development (T. Brown, 2009a; T. Brown & Rowe, 2008; T. Brown & Wyatt, 2010).

interventions. Existing approaches for designing sustainability interventions have been primarily dominated by behavioural approaches (Chatterton, 2016; Welch, 2016), including SM and CBSM. SM has been applied in public health (e.g., smoking cessation, disease control), and environmental conservation (e.g., water reduction) (Andreason, 2006; Kolter & Lee, 2008; Stinchcombe et al., 2005) and CBSM has been used to target sustainability behaviours (Anda & Temmen, 2014; Lynes, Whitney, & Murray, 2014; McKenzie-Mohr, 2001, 2000, 2011; Schultz, 2014). In this section, an overview of intervention strategies for behavioural and technological strategies is provided, followed by an in-depth investigation into each of the four approaches (SM, CBSM, SPT, and DT) summarized in Table 43.

Other approaches have addressed and studied the factors enabling and preventing change. More recently, SPT has brought promise as a theoretical approach for societal sustainability shifts, particularly energy conservation (Shove et al., 2012; Shove & Walker, 2014). The recent uptake of DT in innovation and technology sectors highlights opportunities to utilize this approach for intervention design (T. Brown, 2009b; Ceschin & Gaziulusoy, 2016; Jones, 2013; Taylor, Pollard, Angus, & Rocks, 2013). However, these approaches remain in silos, focusing on either behavioural, social, or technical elements; thus, opportunities for effective sustainability shifts may be overlooked (Spotswood et al., 2017). Behavioural approaches of SM and CBSM remain at the individual-level, SPT approaches focus on the societal level, and lastly, DT approaches concentrate on generating an innovation (physical or otherwise) to facilitate desired shifts. Consequently, a substantial opportunity exists to bring together the strengths of these strategies to enable change.

Similar to the coffee cup example we introduced at the beginning of this paper, the promotion of residential energy conservation can be used as an example to highlight the differences between the aforementioned approaches. The SM approach utilizes extensive market research and applies a marketing mix to encourage a promotional strategy for conservation and demand management behaviours (N. R. Lee & Kotler, 2016). A CBSM method investigates the barriers and benefits of a specific conservation behaviour and develops strategies to reduce barriers (McKenzie-Mohr, 2011). The SPT approach is not linked to one particular methodology; therefore, researchers utilize a wide range of methods (e.g., network analysis, ethnographic methods, energy journaling) to gain more in-depth understanding of the particular energy practice in question (e.g., cooking, cleaning, commuting) (Shove, 2017; Shove et al., 2012). Then strategies are implemented to re-craft practices (e.g., improving appliance/device efficiency), substitute practices (e.g., opening windows instead of using the air conditioner), and/or change how practices interlock (e.g., implementing time-of-use pricing to change consumption patterns) (Spurling & McMeekin, 2015; Spurling et al., 2013). A DT approach applies a user-centred method for investigating the issue and creating an innovative solution vigorously prototyped and tested (Berger & Mau, 2009; T. Brown & Wyatt, 2010; Gibbons, 2016; Jones, 2013; Plattner, 2013). In this case, the focus is on identifying and addressing the underlying problem. An example is the U.S. Department of Energy's Shift Focus program, which identified the need to shift from engineered solutions for presumed energy efficiency needs to consumers' actual desires (e.g., comfort, style and community) (T. Brown, 2009b). Therefore, each approach utilizes specific stages to address particular elements of societal change.

Intervention design and delivery is a crucial component in societal sustainability shifts, involving many elements to enable change (e.g., technology, infrastructure, policy, societal standards, and individual actions). Identifying techniques that change individual behaviours without requiring repetitive involvement is the primary objective of intervention design (De Young, 1993). A range of intervention methods is possible, including informational strategies (e.g., information, social support, and public participation) and structural strategies (e.g., products and services, financial strategies, and regulatory measures) (Steg and Vlek; 2009). Behavioural interventions have been classified in a variety of ways (Michie, Stralen, & West, 2011).

Developing 'sustainable' behaviours through intervention design is a significant area of research. There are components for encouraging pro-environmental behaviour (Froehlich et al., 2010). For effective intervention design, Gardner and Stern (1996) developed eight principles to promote pro-environmental behaviour, creating a foundation for intervention studies. Darnton (2008) further presented principles based on a review of behaviour change theories. Additionally, Steg and Vlek (2009) highlighted four stages for intervention design, including identifying: which behaviours to change, which factors determine the behaviour, which interventions could be best applied, and the intervention effects. These developments in fostering environmental behaviour extend beyond the individual intervention and extend into the development of a behaviour change strategy. Similar stages, such as problem identification, information search, solution development and evaluation, can also be identified in technical design approaches (Hamad, 2014). Although each set of principles may have common aspects for stimulating change and designing interventions, it is essential to investigate specific intervention design approaches further to identify key elements for an integrated model. Each of the four approaches introduced in this paper (i.e., SM, CBSM, SPT, and DT) is explored in more detail in the following sections and summarized in Table 43.

7.2.1 Social marketing (SM)

As an applied approach to behaviour change, SM strategies integrate stakeholder engagement to shape consumer behaviours. Introduced by Kotler and Zaltman (1971), SM uses marketing principles to transform public behaviour towards social goals (N. R. Lee & Kotler, 2008; Lefebvre, 1996). Whereas traditional marketing involves the promotion of goods and services, SM focuses on values to achieve social improvement and desired behaviours (N. R. Lee et al., 2008). Most notably, Kotler and Lee (2008) established ten stages for SM, setting the foundation for SM strategies. The public health literature has developed SM processes, specifically in the Total Process Planning framework, which integrates principles from SM, program planning, and behavioural intervention approaches (Ong & Blair-Stevens, 2010).

In the SM approach to intervention design, the 'problem' is first defined through extensive market research. Several useful strategies for intervention design are incorporated, in particular: targeting, utilizing the marketing mix (i.e., price, product, place, promotion), as well as monitoring and evaluation. However, neither technology nor infrastructure is central in this approach, and the focus remains on individual behaviours. Consequently, the literature has critiqued SM for being individualistic, resulting in potential ineffectiveness at societal scales (Fry, 2014; Spotswood et al., 2017). SM has also been criticized for focusing on short-term change while being costly (Tapp & Rundle-Thiele, 2016). Additionally, the embedded standards and routines of society might be overlooked in the research stages and might potentially result in improperly identifying the root cause. Overall, there are opportunities to further integrate user-specific findings as well as technology and infrastructure into SM.

7.2.2 Community-based social marketing (CBSM)

At the community-level, CBSM is an approach focused on 'fostering sustainable behaviour' and moves beyond traditional attitude-behaviour and economic self-interest models (McKenzie-Mohr, 2011). CBSM outlines five elements for successful behaviour change programs: selecting individuals' behaviours; identifying barriers and benefits; developing strategies; piloting, and; broad-scale implementation (McKenzie-Mohr, 2011). Although this targets individuals and their behaviours, the aim is for community-level shifts. When selecting the behaviour, it is important to differentiate between divisible behaviours (which can be divided further) and non-divisible behaviours (singular behaviours at the root of an action) (McKenzie-Mohr, 2011). Ensuring the target behaviours are non-divisible (e.g. ‘taking a shorter shower’ versus ‘conserving water’) results in effective program development since the strategies focus on the root behaviour (McKenzie-Mohr, 2011).

Identifying barriers and benefits for participation is crucial in this approach and builds on Gardner and Stern (1996), highlighting the importance of interacting with target audiences before program implementation. Successful programs have used CBSM strategies for a wide range of pro-environmental behaviours, including: anti-idling campaigns (McKenzie-Mohr, 2001); residential energy conservation (Kassirer et al., 2014); university energy conservation (Chan et al., 2012), and; residential water conservation (Stinchcombe et al., 2005). As a result, CBSM specifies appropriate strategies for community-level intervention design for sustainability shifts.

In the CBSM intervention design approach, the target behaviour is the main focus and is selected at the initial stage. CBSM is widely adopted for sustainability solutions, and its five stages are easily modified for a variety of scenarios, making it a promising approach for practitioners (McKenzie-Mohr, 2000; Schultz, 2014). By investigating the barriers and benefits at the start of the process, user-centred feedback and problem details are incorporated. Additionally, a variety of well-proven strategies have been implemented and developed utilizing CBSM (Chan et al., 2012; Kassirer et al., 2014; McKenzie-Mohr, 2001, 2011; Stinchcombe et al., 2005). However, by not explicitly integrating technical, infrastructural, and societal-level influences, the root cause might be overlooked. Specifically, where behaviours may only address the ‘tip of the iceberg,’ (Strengers & Maller, 2015b). Furthermore, empathy-based methods, discussed later, can identify additional factors influencing sustainability-oriented behaviours.

7.2.3 Social practice theory (SPT)

A contrast to behaviour-based models is SPT, an emerging theoretical lens in sustainability studies, particularly in energy research. SPT emphasizes going beyond performance or behaviours and identifying the underlying societal factors (Spurling et al., 2013). Schatzki defines practice as, “A temporally and spatially dispersed nexus of doings and sayings,” (1996, p. 89). Practices develop as a conjunction of elements that exist as performances by individuals, who act as the ‘carriers’ of practice and are linked to one another at societal scales (Shove et al., 2012). Shove et al.’s (2012) theoretical description of practice involves three elements: competencies, or the knowledge and ability associated with the practice; materials or the tangible components, and; the meanings, or connotations and significance behind the practice. A practice actively links these three components, which can: shape each other, change over time, link to other practices, and shift from one practice to another (Shove, 2014; Shove et al., 2012). Spotswood et al. (2017) identify fundamental principles for a practice-theoretical approach: interdisciplinary; focusing on the practice, not the individual; utilizing ethnographic methods, and; changing societal conventions. Therefore, SPT investigates societal change as shifts of compounded practices over time.

The SPT approach to intervention design extends beyond individuals and their actions. For example, Strengers (2012) outlines a practice approach to address peak electricity demand, involving: reframing the problem to practice; changing wants and needs (e.g., lifestyle shift); and, redefining the role of end-users. Spurling et al. (2013) outline three types of SPT approaches to policy: first, re-crafting practices, by changing or substituting elements to reduce impact(s) (e.g., electric vehicle instead of diesel vehicle); second, substituting practice, by changing to a more sustainable practice (e.g., walking instead of driving), and; third, changing how practices interlock, by rearranging related practices to reduce impact(s) (e.g., changing schedule for more sustainable commuting) (Spurling et al., 2013).

The SPT approach to intervention design integrates the underlying factors associated with shifts to sustainability; thus, providing a comprehensive lens for developing solutions and investigating issues, extending beyond behaviour-specific strategies, and more recently resulting in a cross-fertilization of approaches due to the SPT analysis and solution framing (McKenzie-Mohr, 2017; Shove et al., 2012; Spotswood et al., 2017; Welch, 2016). However, there is an absence of an applied SPT intervention design methodology (Sahakian & Wilhite, 2014; Spotswood et al., 2017). Additionally, limited empirical research has been conducted on the changes across socio-historical timescales to assess the dynamics of practices over time (Greene, 2019; Greene & Rau, 2018). Difficulties to 'shift' the intervention design mindset from behaviours to practices are barriers for implementation, consequently creating difficulties to test how interventions formed by theories of practice differ from theories of behaviour (Strengers et al., 2015). Unlike SM and CBSM, there is not a set of defined stages for SPT intervention design, resulting in difficulties for practitioner use and engagement; therefore, opportunities remain to develop SPT's application to extend the cross-fertilization of this comprehensive approach.

Recently, Spotswood et al. (2017) integrated SPT with SM by developing the practice-theoretical intervention planning process (P-TIPP). This approach utilized French et al.'s (2010) four stages (scope, develop, implement, evaluate). However, this P-TIPP approach does not necessarily incorporate the interlocking of practices, which is a critical element for changing practice (Spurling et al., 2013). Consequently, processes to address more detailed aspects of interconnectivity, such as technological and infrastructural change, are needed. Although the P-TIPP approach brings value by applying existing principles to SPT, opportunities remain for further development. Specifically, detailed stages and clarity for applying the strengths of SPT for shifts in collective conventions.

7.2.4 Design Thinking (DT)

The implementation of new programs, products or services for sustainability shifts requires effective planning, preparation, and design. Design was generated to solve wicked problems through radical innovations by utilizing knowledge from multiple disciplines (R. Buchanan, 1992; Jones, 2013). In the field of sustainability, design has been used for: green design and eco-design, emotionally durable design, nature-inspired design, and design for sustainable behaviour (Ceschin & Gaziulusoy, 2016). Specific design strategies for sustainability make related behaviours easier and more desirable to perform (e.g., scripting, behavioural steering, forced functionality and eco-feedback) (Ceschin & Gaziulusoy, 2016; Tromp et al., 2011; Wever et al., 2008).

Design thinking, however, goes beyond designing materials and looks at how to approach a problem. Successful design utilizes a human-centred approach and extends beyond technology, and understands how technology interacts with actions, individuals and their routines within society (Goulden et al., 2014). This process generates meaningful knowledge for seamless integration. Consequently, designers play a key role among engineers, policymakers, and product/service providers (Geelen et al., 2013).

DT is a cyclical and iterative process flowing from inspiration to ideation to implementation. DT creates new value by integrating empathy, integrative thinking, collaboration, and experimentalism (Berger & Mau, 2009; Both & Baggereor, 2015; T. Brown, 2008; Gibbons, 2016). A key element of human-centred design is empathy, which develops a detailed understanding of the problem from the users' perspective. This empathy-centred approach helps to identify key elements influencing solution development (Both & Baggereor, 2015; T. Brown & Wyatt, 2010; Karjalainen, 2011; Shapira, Ketchie, & Nehe, 2017). By gaining users' perspectives, this contextualizes the problem to fully articulate how a solution might be developed. At the core of DT is fast innovation by learning through failure and user feedback (Berger & Mau, 2009). Defining and redefining the problem through iterative testing and evaluation is central to this process. Overall, DT implements a user-centred process for generating solutions applicable for intervention design strategy incorporation.

Design thinking brings a unique approach and new tools revolving around iterative feedback and testing. This approach is contrary to typical ‘waterfall’ methods, where feedback only takes place at the final implementation. Design thinking offers three particular methods relevant to intervention design. Firstly, prototyping,[63] transforms ideas into any medium that can be tested before piloting (e.g., post-its, whiteboard drawings, mock-ups, or rough model development) and facilitates immediate feedback (e.g., focus groups, interviews) (Both & Baggereor, 2015; Furr & Dyer, 2014). Secondly, the agile method involves quick test ‘sprints’ of development for immediate feedback and failure; thus, optimizing development stages (Alqudah & Razali, 2017; Beyer, 2010; Ross, Wardell, Wheeler, & Algarra, 2017). Thirdly, the lean method emphasizes efficiency where multiple concept versions are released and developed in small stages (Poppendieck, 2015). These dynamic elements are relevant to non-software environments (Ahlback, Fahrback, Murarka, & Salo, 2017; Bossert, Kretzberg, & Laartz, 2018; Shapira et al., 2017). These strategies can provide benefits to intervention design for sustainability shifts.

From the SPT approach, the concept of design has received some criticism. In particular, Shove et al. (2006) argue for a practice-oriented approach for product design through innovation in practice, while involving user-centric perspectives through user studies, anthropology, and mixed-method approaches. Design can shape practice through multiple methods (e.g., acquisition, appropriation, scripting, assembly, normalization and diffusion of goods, innovations and actions) (Ingram et al., 2007; Shove, 2006; Shove & Watson, 2006). Ingram et al. (2007) argue that design lacks theoretical depth for seamless shifts in practice adoption. At the time of Ingram et al.’s (2007) article, however, DT concepts and methodologies from IDEO[64] and the Stanford Design School had not yet been adopted in a wide range of sectors; however, within the last decade, DT has been adopted several public service processes and management styles (e.g., education, healthcare, public policy) (Ceschin & Gaziulusoy, 2016). Furthermore, utilizing empathy develops a critical point of view from the audience’s perspective, for thorough understanding and development (T. Brown, 2009a; T. Brown & Rowe, 2008; T. Brown & Wyatt, 2010). Iterative prototyping further addresses this issue, by quick cycles of refinement (Plattner, 2013). As a result, the newly adopted notion of DT

[63] For example, the first Google Glass prototype was constructed out of a coat hanger, sheet protector, Pico projector and a netbook in 45 minutes (Furr & Dyer, 2014). In this paper, we emphasize that prototyping extends beyond products and can be related to any medium.
[64] IDEO is a global design and innovation company that specializes in design thinking approaches to solution and product development, management consulting, and organizational design. Tim Brown, the founder, is an international leader in design thinking approaches to innovation who has authored seminal literature on these concepts.

moves beyond the conventional association of design being focused on 'stuff' and, instead, focuses on the user's perspectives to create meaningful solutions related to societal standards and practice. Therefore, the DT stages incorporate approaches that complement SPT.

DT brings an innovative approach and tools to intervention design, which can complement existing approaches and address their limitations. However, DT is often applied in innovation and technology-focused fields, therefore, not necessarily as widely adopted, due to the lack of knowledge and experience with this approach. By integrating this approach into a comprehensive model for intervention design, and by dividing the process into understandable stages, valuable strategies for sustainability-oriented intervention design can be achieved.

7.2.5 Tying it all together

In reviewing and comparing the four approaches (Table 43), opportunities for development across these approaches become evident. As outlined below, the targeting and clear strategies of SM and CBSM, the holistic view of SPT, and the empathy-centred approach and prototyping methodologies from DT, together bring opportunities for a more integrated approach for intervention design.

Table 43 Summary of intervention design approaches[65]

	SM	CBSM	SPT	DT
Elements	Marketing strategies and elements for societal changes	Community and individual behaviour	Materials, meanings, and competencies	The design of everyday life and related factors
Approach process	– Background and purpose function – Situation analysis – Target market – Marketing objectives and goals – Barriers, benefits, competition – Position statement – Strategic marketing mix (4Ps) – Evaluate plan – Budget – Implement plan	– Define target behaviours – Identify barriers and benefits – Develop strategies – Pilot – Implement and evaluate	– Re-crafting practices; substituting practices; changing how practices interlock – Re-framing problem; changing wants and needs; redefining roles	– Empathize – Define – Ideate – Prototype – Test
Unit of analysis	Individuals and their influence on society	Community; Individuals and their action	Dynamics of practice. Behaviours are the 'tip of the iceberg'	The impact of the item or underlying factors related to an issue, topic, product
Policy approach	Incentives, rewards, information, feedback, commitments, communication	Incentives, rewards, information, feedback, commitments, social norms, social diffusion, prompts, communication	Embedded in the system it is attempting to change	Designing a policy, program, or product as an outcome of design-based research
Role of technology	Technology is separate from supply systems and people	Technology is separate from supply systems and people	Technology and supply systems form practice	Technology can play a central role and be embodied in the problem and the solution
Strengths	Application of effective and clear approaches using well-tested marketing principles	Development of specific strategies for target group by identifying barriers and benefits; clear and adaptable five-step approach	Includes technology, infrastructure, and underlying societal factors; Utilizes a variety of research approaches	Applies empathy, prototyping, and new design strategies; Iterative testing and development
Limitations	Emphasis on behaviour and society can overlook underlying factors. Technology and infrastructure are secondary	Emphasis on behaviour-based changes as opposed to user-technology interactions. 'Tip of the iceberg' might overlook underlying factors	Approach might not clear for practitioners resulting in difficulties for application	Approach may be unfamiliar to fields beyond technology and software

[65] Table sources: (N. R. Lee & Kotler, 2016; Lynes et al., 2014; McKenzie-Mohr, 2011; Shove, 2010; Shove et al., 2012; Spotswood et al., 2017; Spurling & McMeekin, 2015; Spurling et al., 2013; Stern, 2000; Strengers, 2012; Strengers et al., 2015).

Opportunities for further development	Inclusivity of technology, infrastructure, and underlying factors. Strategies for empathy as well as technology and infrastructure design	Inclusivity of technology, infrastructure, and underlying societal factors. Strategies for empathy	Proven and clear marketing strategies. Applying empathy and new strategies for social, technical, and infrastructural design	Clear marketing strategies and targeting. Clarity and successful techniques of CBSM

7.2.6 Opportunities for integration

We return to the café manager, as they have reviewed the propositions from each practitioner, they ask, "each approach has its strengths – but can they be brought together?" As we have identified in the review of the SM, CBSM, SPT, and DT intervention approaches, key elements for intervention design, can be brought together, including empathy, issue identification, target audience selection, solution development, prototype development, implementation and evaluation, and reconsideration of the problem. Although each approach on its own does not equally provide a thorough solution to the disposable cup problem, each approach can be integrated into a more holistic approach, to harness the respective strengths. When brought together, this can deliver a new and more comprehensive approach to designing interventions for collective change.

7.3 Towards an integrated model of intervention design

Building on the review of the four approaches, we developed the ENGAAGGE model, which utilizes best practices from SM, CBSM, SPT, and DT. The purpose of ENGAAGGE is to bring together technological, societal, and individual cognitive elements for collective sustainability shifts through intervention design. Through an evaluation of the existing approaches and key elements of intervention design, it is clear that an integrated model can bridge the identified limitations in current 'silos' of approaches to provide a more comprehensive approach to solve wicked sustainability problems. The elements previously identified have been refined and integrated into the eight elements of ENGAAGGE (Table 44). The ENGAAGGE model incorporates eight elements to emphasize an empathy-centred approach while incorporating the aforementioned essential elements in more detail. The resulting model utilizes elements to target the root of the issue to develop successful strategies.

Table 44 The ENGAAGGE model for intervention design[66]

E	N	G	A	A	G	G	E
Empathize and understand the problem throughout the process	**N**orm evaluation: existing and aspirational	**G**ather detailed background information	**A**rticulate the problem and the audience	**A**ctively ideate the potential solution(s)	**G**auge, test, and re-test through prototyping	(re)**G**roup – Redefine and evaluate the norms, barriers, motivations, and prototypes	**E**valuate and implement refined intervention and continue monitoring for success

The ENGAAGGE model provides several unique features for sustainability-focused intervention design. In particular, this model includes behavioural, technical, and societal elements in the intervention design process, while integrating a DT approach. This model emphasizes the importance of market segmentation and target market definition for focused intervention design and applies prototyping methods. Furthermore, ENGAAGGE assesses the initial and idealized societal norms while taking an iterative approach for solution development. The ENGAAGGE model is not linear, it is iterative and feedback loops can occur between elements (e.g., between (re)Grouping and Actively ideating). Empathy is a critical component and utilized throughout the model (Table 44). The following sections articulate the ENGAAGGE model process. Each stage of the model is compared to existing approaches in the discussion.

"E" - Empathize and understand the problem throughout the process

A key element of human-centred design is empathy, which involves observing and deeply understanding the situation from the users' perspective to identify key elements for intervention development (Spurling et al., 2013). In the ENGAAGGE model, empathy occurs throughout the entire process and involves continual problem identification and re-evaluation. The importance of utilizing a mixed-methods approach is a key consideration. The initial process includes brainstorming and evaluation of secondary and/or primary data. The data are revisited to ensure the problem is being adequately addressed. Consequently, a detailed understanding developed to define and understand the problem being addressed. Empathy has been derived from DT and is not explicitly found in CBSM, SM, or SPT approaches.

[66] The ENGAAGGE model proposes an iterative process, where one stage is not more important than the other, and the process flows iteratively between stages. Previous stages can also be returned to, should further development be needed. Empathy is utilized throughout the model.

"N" - Norm evaluation: existing and aspirational

The norm evaluation component defines the existing societal scenario and idealized outcomes. This aligns with societal approaches for studying change and incorporates a beyond-behaviour lens to incorporate conventions influencing collective patterns and change (e.g., visioning and scenario building) (Ford, Walton, et al., 2017; Seyfang & Haxeltine, 2012; Shaw et al., 2009; Shove, 2010; Stephenson et al., 2010; Vergragt & Brown, 2007). Both brainstorming and evaluation of secondary data and existing research are utilized to provide a thorough understanding of the normative standards (existing and aspirational) that may influence the change. Additionally, idealized future outcomes are identified and goals are established. Norm evaluation is partially utilized in existing approaches; however, by explicitly incorporating this element, norms can be more effectively identified and examined. Therefore, in this stage both the existing scenario and the potential idealized scenario(s) are determined.

"G" - Gather detailed background information

In this stage, a detailed background is collected. In particular, the benefits and barriers (e.g., technology, skills, behaviours, norms) associated with idealized shifts are defined. Highlighting the different market segments and associated 'nudges' required for minimizing barriers and maximizing benefits are also crucial. Both primary and secondary data analysis are involved (e.g., market research, focus groups, interviews, workshops, and census data) and the focus can be shaped around the particular issue at hand. This element incorporates the effective strategies identified in SM with the beyond-behaviour approach of SPT. Overall this provides detailed understanding of the socio-technical, societal, and behavioural influences at multiple scales.

"A" - Articulate the problem and the audience

Defining the issue and its components helps to create a focused solution directly addressing the problem. Appropriately scoping the issue (e.g., not too broad or too narrow), ensuring it is 'solvable,' and revisiting the defined problem are critical considerations (T. Brown, 2009a; N. R. Lee et al., 2008). This stage incorporates two objectives: first, to define the problem by clearly articulating a problem statement and categorizing the issue as either: technical, behavioural, or associated with related meanings, skills, and norms; and second, to identify the target audience through market segmentation and target market selection. By targeting and establishing segments of the audience, the empathy element utilized throughout the ENGAAGGE model can be delivered effectively for the correct audience. This stage evaluates the data collected in previous stages. Segmenting results brings clarity on which audience(s) to target and which solutions will work best for specific audiences

(Reynolds & Merritt, 2010). This process incorporates effective strategies from SM to those not met, or partially met, in other approaches. Overall, this stage directs the design process towards a focused solution and a relevant audience.

"A" – Actively ideate the potential solution(s)

Once the audience and problem are defined, generating ideas for solution development becomes prominent. In this stage, the objective is to 'ideate' all of the potential solutions and to identify potential pathways for success (T. Brown, 2008; Shapira et al., 2017). First, potential solutions (e.g., product, policy, or program) are generated through ideation. Second, a select number of ideated solutions are chosen for prototyping. Ideation involves different types of rapid brainstorming techniques, literature reviews and case study analyses. Focus groups and interviews can identify additional solution(s). The aim is to generate the maximum number of ideas and to identify the most pivotal design directions. Overall, this stage harnesses the proven strengths of the ideation method from DT, which is rarely utilized in the other approaches.

"G"- Gauge, test, and re-test through prototyping[67]

At this stage, key ideated interventions are prototyped and tested. Prototyping the developed solution(s) in quick iterations allows for immediate feedback thereby optimizing the design process to gain fast cycles of improvement and can take place in multiple forms (e.g., focus groups, interviews, and workshops) (Both & Baggereor, 2015; T. Brown & Wyatt, 2010). Once the prototypes have generated initial feedback, methods like agile development can be used to test multiple versions. These multi-stage pilots provide critical feedback on initial versions of the intervention (Beyer, 2010). The prototyping strategies from DT align with the strengths of CBSM and SM for further refinement in this model. Overall, this stage aims to identify successful intervention pathways through evaluation and feedback of the prototyped solutions at the early stages of development.

"G"- (re) Group – Redefine and evaluate the norms, barriers, motivations, and prototypes

Following prototyping and iterative testing, feedback is reviewed, and it is determined whether further prototype refinement is required. This element extends beyond existing approaches to highlight a critical element of intervention design: revisiting the problem and knowledge learned. At this stage, feedback and market research is reviewed. Should the intervention(s) have addressed the defined audience(s) and issue(s), it can be finalized utilizing the insights from the iterative prototyping and testing. Alternatively, earlier development stages can be revisited to identify

[67] The term prototype refers to drafted iterations of interventions that can be any medium and are not necessarily product-based.

alternative strategies (e.g., ideation, gauge, and test). Overall, this component is critical to identify whether the prototyped interventions would be successful and to identify additional underlying factors.

"E" - Evaluate and implement refined intervention and continue monitoring for success

Following the intervention testing, the refined intervention is implemented and continually monitored and evaluated. Although the implementation is at a larger scale than prototyping, measuring performance is still critical (N. R. Lee & Kotler, 2016; McVey, Crosier, & Christopoulos, 2010). The objective is to determine whether the refined intervention influenced the target audience to achieve the desired outcome(s), and to identify further areas of improvement through continual feedback and performance measurement (e.g., surveys, interviews, metrics reporting). Should the intervention require further refinement, earlier stages can be revisited. Overall, this provides a specific stage for feedback and refinement alongside evaluation.

7.3.1 Summarizing the ENGAAGGE model

The ENGAAGGE model provides an empathy-centred approach to intervention design (Table 45). As a result, the problem can be clearly defined to develop effective solutions that directly address the problem, rather than addressing the 'tip of the iceberg.' Consequently, this approach can transcend beyond singularly addressing technology, behaviours, or infrastructure, and develop a holistic understanding and solution(s) for facing wicked problems related to collective sustainability shifts. The detailed elements of this model bring insights for practitioner application for sustainability shifts related to capacity development, normative change and coalition building (Bernstein & Hoffmann, 2018; Tozer, 2016). This unique model is applicable across different theoretical domains, since it extends beyond individual behaviours to assess externalities; integrates clarity and proven successful techniques from CBSM and SM models; incorporates socio-technical and societal considerations from SPT, and; enhances traditional intervention design techniques by weaving empathy into the design process. As a result of harnessing the strengths of these approaches, the ENGAAGGE model can thoroughly address societal sustainability problems by integrating societal, technological, and behavioural factors.

Table 45 Explanation of ENGAAGGE model stages

Stage	Questions asked and answered	Methods	Objectives
E - ***Empathize and understand the problem throughout the process***	What is it we are trying to fix? Whom are we trying to approach? What is everything we know about this issue, idea, problem? What is everything we know about the users/consumers/market segment?	Evaluation of secondary data and existing research; re-evaluate problem statement throughout cycle through review of primary data collected	To gain and maintain a detailed understanding of the users' perspective(s) while establishing a focused solution directed at the problem
N – ***Norm evaluation: existing and aspirational***	What is the current societal practice, and what is the idealized future practice?	Evaluation of secondary data and existing research/ information; visioning future outcomes and establishing goals	To gain a thorough understanding of the societal and individual standards (existing and aspirational), that may influence the shift and intervention uptake; to identify idealized future scenarios and related goals
G – ***Gather detailed background information***	What is benefiting/blocking a shift towards this idealized state? What are the motivations and barriers associated with technology, behaviours, skills, normative 'culture,' associated meanings and images, associated 'nudges' required for each barrier/benefit, participant clusters and market segments	Review of primary and secondary data (literature, research, focus groups, interviews, workshops)	To have a detailed understanding of the socio-technical, societal, and behavioural influences at multiple scales that influence both the problem and the potential solution(s)
A – ***Articulate the problem and the audience***	What exactly is our problem? (e.g., technical, behavioural, or associated with related meanings, skills, norms) What is our target audience?	Evaluation of data collected in focus groups, interviews, workshops, and secondary data/existing research. Market research, market segmentation, and targeting. Definition of the problem statement and target audience.	To define the problem and target audience in order to generate a focused solution towards a receptive and relevant audience
A – ***Actively ideate the potential solution(s)***	How might we address this problem and the target audience? What is the technique required for addressing the issue? Is it a product, policy, or program? (e. g., incentive, commitment, feedback, education, and training, the design of a new product) What are the key solutions to test and target?	Brainstorming and evaluation of existing strategies. Ideas are tested or gathered from focus groups, interviews, workshops	To generate the maximum ideas possible in order to develop a solution and to identify select intervention pathways for success

G – ***Gauge, test, and re-test through prototyping***	Of our solutions, what works well and how might we develop them further? Do the solutions address the problem(s)?	Prototyping; Piloting interventions through focus groups, interviews, workshops, or small-scale releases; Agile or lean methodology	To generate quick responses to ideated solutions; to optimize the process by gaining feedback quickly for iterative development cycles
G – ***(re)Group – Redefine and evaluate the norms, barriers, motivations, and prototypes***	How might we improve our prototyped solutions to achieve the aspired norm? Is the prototyped solution effective for addressing the target audience, barriers, and overall defined problem, to achieve the aspired norm?	Evaluation of feedback provided from focus groups, interviews, workshops. Assess alongside market research	To identify whether the prototyped interventions addressed the problem and to further identify the underlying factors associated with the issue
E – ***Evaluate and implement refined intervention and continue monitoring for success***	How has the intervention influenced the audience? Has the intervention reached the desired outcome/aspirational norms? How might we improve the implemented solution?	Consistent measuring of performance and solution feedback via surveys, interviews, reporting	To further improve the solution and to ensure it is meeting the desired outcome(s)

7.4 Discussion

We return to our café manager who has pledged to reduce single-use coffee cups. Utilizing the ENGAAGGE model approach, the manager identifies the current status of disposable coffee cups and establishes a goal for reusable options. The manager then works to collect both primary and secondary data to understand motivations for selecting disposable cups, and barriers preventing reusable cup adoption (e.g., reading market research and conducting a customer survey). The manager further determines the problem and the target audience and works with their staff to ideate potential solutions. Through research and workshops three key options are identified. The manager offers a customer focus group to walk-through the three solutions and receives critical feedback on the strategies' design and implementation.

The solutions are refined and tested at the store. Following testing, the manager incorporates the feedback for strategy refinement and to establish an implementation plan. The manager decides to release only two options, and they are evaluated extensively after their introduction, while continuing to understand what prevents/motivates their customers from using reusable cups. They decide to revisit the problem in six-months' time to further refine their solutions. During the entirety of the process, the owner ensures the understanding of the audience and the problem is fully articulated, to ensure the target issue is addressed.

As seen in this example, the ENGAAGGE model utilizes an empathy-centred approach to help our café manager effectively target the problem, identify solutions, and iteratively test proposed interventions. To further articulate how each stage of this new model enables an innovative approach to intervention design, Table 46 highlights ENGAAGGE model stages in comparison to the existing approaches. As identified in Table 46, when comparing these approaches, it is evident the ENGAAGGE brings together a comprehensive set of elements not yet met by existing approaches. With five stages met, DT remains the closest approach to the ENGAAGGE model, whereas SPT has five stages not met, highlighting opportunities to bring strengths from the existing approaches to improve clarity and application for practitioners. Although all of the stages are partially met in CBSM, the integration of DT methods and beyond behaviour focus of SPT, strengthens this approach for holistic understanding and intervention development. SM delivers strengths for two particular stages of the ENGAAGGE model: emphasizing the importance of identifying background information and establishing targeted strategies. Bringing these elements together, the ENGAAGGE model elicits a new and more comprehensive approach to develop effective strategies to accelerate shifts.

Table 46 Existing approaches in comparison to the ENGAAGGE model[68]

	Social Marketing	Community Based Social Marketing	Social Practice Theory	Design Thinking
Empathize and understand the problem throughout the process	Not met	Partially met in identifying barriers and benefits	Partially met. Variety of methods used allow for deeper understanding. Empathy not explicitly applied	Met in the empathize stage
Norm evaluation: existing and aspirational	Partially met – 'ideal norm' is not established	Partially met in identifying the behaviour – 'ideal norm' is not established	Partially met – 'ideal norm' is not established	Partially met in the empathize stage – 'ideal norm' is not established. Norms are not explicitly considered
Gather detailed background information	Met by segmentation and in multiple stages: background; barriers, benefits; situation analysis	Partially met in identify behaviours, barriers and benefits. Segmenting audience not explicitly mentioned	Partially met through methodologies used but not explicitly stated. Segmenting audience is not mentioned	Partially met in the define stage. Segmenting audience not explicitly mentioned
Articulate the problem and the audience	Met in multiple stages: purpose, function Target market Marketing objectives, goals	Partially met because behaviour based. Target market not explicitly mentioned	Not met – Although implied, the approach does not outline this stage specifically	Partially met in the define stage. Target market not explicitly mentioned
Actively ideate the potential solution(s)	Partially met in: position statement, 4 P's, and budget stages. Does not include 'ideation' method	Partially met in develop stage. The ideation method of rapid brainstorming is not necessarily used	Not met	Met[69] in the ideate stage
Gauge, test, and re-test through prototyping	Partially met in piloting – but prototyping method not utilized as a preliminary stage before piloting	Partially met in piloting – prototyping method not emphasized	Not met	Met[69] in the prototype & retest stage
(re)Group – Redefine and evaluate the norms, barriers, motivations, and prototypes	Partially met in the evaluate plan and implement plan stages but prototyping method not utilized	Partially met in the implement and evaluate stage	Not met	Met[69] in the prototype & retest stage
Evaluate and implement refined intervention and continue monitoring for success	Partially met in the implement and evaluate plan stages – The redefinition of the solution can be added	Partially met in the implement and evaluate stage	Not met	Met[69] in the test stage

The ENGAAGGE model harnesses the strengths of the four existing approaches and incorporates the key elements for intervention design. In particular, this approach provides a clearer and more articulated method for utilizing a SPT perspective for intervention design. Additionally, this

[68] Legend: Whether the ENGAAGGE element is fully met (white), partially met (light grey) or not met (dark grey) within the existing approaches of SM, CBSM, SPT, or DT.
[69] Opportunities to clearly identify and breakdown stages.

model emphasizes the importance of empathy, problem definition, and evaluation throughout the entire design process. Consequently, this model goes beyond behaviours to determine the underlying factors influencing change. This model develops a more thorough approach to addressing the materials, competencies, and norms associated with sustainability-oriented practices. This approach delivers new opportunities for political de-carbonization shifts of capacity building, normative change and coalition development (Bernstein & Hoffmann, 2018; Tozer, 2016). As a result, the strengths from each approach can be harnessed in the ENGAAGGE model to provide a comprehensive approach for intervention design.

7.4.1 Opportunities for applying and evaluating the ENGAAGGE model

The ENGAAGGE model provides a comprehensive approach for designing interventions related to sustainability shifts. Consequently, it allows for a variety of interventions to be designed to influence the behavioural, technical, and societal factors at multiple scales (e.g., individual, household, community-level). Therefore, resulting in opportunities to develop a suite of interventions for collective change. Although this process has opportunities for large-scale use, user experience and empathy are critical components to the ENGAAGGE model. Thus, targeting and utilizing audience segments are necessary to ensure that segments and users' perspectives are considered.

Additionally, this approach can be utilized within a variety of sectors (e.g., private, public, non-profit) and can be scaled-up or scaled-down to adequately address the targeted problem (e.g., household energy, office waste, community-level emissions). Since ENGAAGGE utilizes concepts from technical, societal, and behavioural lenses, this approach can address a variety of sustainability issues (e.g., transportation, waste, energy, water). Consequently, this delivers substantial opportunities for developing strategies for collective change related to climate change commitments (UNFCC, 2018). Overall, the ENGAAGGE model represents a comprehensive approach that can address shifts in action(s), adoption of technology, and change(s) in mindset involved in societal sustainability shifts.

The ENGAAGGE model is not linear; instead, it is iterative and facilitates ongoing knowledge development and solution testing. This aspect is fully incorporated in the central focus of the model, empathy. Derived from DT, this emphasizes the importance of fully understanding and re-visiting the problem during the entire design process. As a result, evaluating intervention success and effectiveness is vital throughout the process, not just in the final stages. The literature has widely identified the necessity of evaluating intervention campaigns and models (Frederiks, Stenner, Hobman, & Fischle, 2016; Strengers, 2012; Strengers et al., 2015); however, a methodology to evaluate the application of this proposed model is beyond the scope of this paper, which warrants a supplementary paper to propose a detailed procedure.

7.5 Conclusion

The ENGAAGGE model proposed in this paper presents a novel comprehensive and integrated approach to intervention design for addressing the wicked problems associated with societal sustainability shifts. This model can be applied at multiple levels and can be scaled to effectively target the fundamental problem accordingly (e.g., households, office buildings, schools, or community). The existing approaches utilized in policy, program, and product development (i.e., SM, CBSM, SPT, and DT) have seen success in the literature, yet they remain in silos of their respective fields. Consequently, an opportunity existed to bring together and review these approaches. By bringing these approaches together in an integrated model to address sustainability problems, the ENGAAGGE model harnesses these elements for the holistic incorporation of social, technical, and behavioural factors. Although this paper is conceptual, and ENGAAGGE has not been tested, this model delivers opportunities to comprehensively address societal sustainability issues. Additionally, opportunities exist to apply ENGAAGGE and to develop an evaluation framework.

As seen with our café manager, this approach facilitates iterative solution-development that is focused on understanding the foundation of the problem (e.g., behavioural, technical, knowledge). In conclusion, the benefits this paper brings to the literature are threefold as it: (1) provides a comprehensive and comparative overview of SM, CBSM, SPT, and DT; (2) articulates key elements for intervention design from reviewing the approaches of SM, CBSM, SPT, and DT, and; (3) proposes a novel model for sustainability intervention design by integrating behavioural, practice and technological aspects from existing approaches: the eight-stage ENGAAGGE model. By bringing together the strengths of existing approaches, we can work towards an integrated model for societal change to thoroughly approach, understand and advance shifts towards sustainability. This new model can not only help business managers, such as our café manager, but also assist policymakers, and practitioners fully understand fundamental factors influencing the uptake of aspirational sustainability actions. Like our café manager, this integrated approach allows for sustainability challenges to be addressed with holistic solutions.

8. Chapter 8 – Conclusion

8.1 Introduction

This chapter presents a summary of the conclusions from the dissertation entitled *'Engaging beyond the meter: Encouraging residential energy management using smart grid tools.'* The following sections highlight the significant findings for each chapter, the related contributions, study limitations, and a discussion of the key outcomes of the research. Following is a presentation of areas for future research.

8.2 Main findings

Ontario's early and advanced adoption of smart metering infrastructure delivered a substantial opportunity to study household engagement with, and energy culture influences from, the introduction of smart grid technologies at the residential scale. Therefore, this dissertation applied a mixed-methods approach to study the influence of residential smart grid technologies on Ontario residential energy cultures through four research manuscripts. These four manuscripts incorporate two Ontario residential smart grid case studies as well as a conceptual review of consumer engagement approaches.

The introduction to this dissertation (Chapter 1), introduced five primary research objectives centred around the main dissertation research question: *How can Ontario residential consumers be engaged and re-engaged in the smart grid for the shift towards a smart and sustainable energy culture?* Chapter 4 defined the smart and sustainable energy culture and delivered the conceptual foundation applied within the remaining research chapters. The research presented in Chapters 4 - 7 delivered conclusions for each of the five research objectives (Table 47).

The research presented in Chapters 4-6 addressed Research Objective 1 through the qualitative and mixed-methods assessment of the engagement mechanisms in the EHMS case study (Chapters 4 and 5) as well as the assessment of consumption influences in the IHD case study (Chapter 6). Chapter 4 delivered Research Objective 2 through the qualitative analysis of participants' nuances surrounding long-term smart grid engagement. The mixed-method analysis of EHMS re-engagement in Chapter 5 addressed Research Objective 3. Chapter 6 focused on Research Objective 4 through the quantitative analysis and segmentation of households in conjunction with an IHD introduction in Chapter 6. Lastly, Chapter 7 addressed Research Objective 5 through the comprehensive review of intervention approaches and the design of a novel intervention approach.

Each chapter delivers insights to address the overarching research question. In Chapter 4, EHMS participants' engagement preferences and underlying factors influencing energy management were identified through qualitative analysis. Specifically, participants identified preferences for mobile applications utilizing nudges for engaging with 'smart' household energy management. Additionally, designing programs to align with the motivations (e.g., financial cost savings) and barriers (e.g., lifestyle, convenience, and varieties of household preferences) can deliver strong engagement capabilities. In particular, participants highlighted the preference for financial and comparative data in digestible 'snapshots' for feedback, and the confusion with carbon footprint values. Methods to engage children and teens were also desired. Therefore, this chapter delivers insights on engagement mechanisms for favourably influencing residential 'smart' energy cultures.

In Chapter 5, mixed-methods analysis highlighted the impact of re-engagement in a long-term smart grid study alongside participant feedback. Energy reports were preferred over mobile tablets, where participants valued feedback providing targeted, normative information alongside calls to action. However, since the preferences for peak shifting were not equal across appliance groups, laundry practices were the only significantly impacted consumption in conservation and peak shifting during the autumn re-engagement period. Therefore, this chapter provides insights for re-engaging households over the long-term, and the importance of targeted approaches for shifting energy practices.

In Chapter 6, the detailed analysis of a large-scale implementation of IHDs assessed influences of smart meter-enabled feedback on consumption practices. The outcomes identified no significant influences at the general population level; however, some thermo-behavioural segments experienced significant favourable changes in consumption through conservation and peak shifting. The insights delivered from this manuscript highlight the influence of behavioural and thermal consumption profiles on household energy management, indicating that audience segmentation and target market analysis can provide key insights for producing effective programs to certain consumers. Additionally, Chapter 6 highlights the value of using consumption data for understanding energy consumers in the absence of socio-demographic data. Overall, the outcomes of this Chapter emphasize the importance of extending smart grid engagement strategies beyond feedback for the ideal targeted consumers.

In Chapter 7, the comprehensive conceptual review delivered details regarding the distinct disciplinary approaches to consumer engagement. The outcomes identified the particular benefits and limitations for the engagement strategies delivered by SM, CBSM, SPT, and DT, and highlighted the opportunity for a holistic integrated approach for intervention design. The eight-stage ENGAAGGE model identified in Chapter 7 delivers a comprehensive approach to design and deliver interventions and is considered applicable to the smart grid. Therefore, following the challenges for smart grid consumer engagement identified in Chapters 4-6, Chapter 7 highlights techniques for designing consumer-centered smart grid interventions

In conclusion, the outcomes from these four manuscripts identify: (1) the importance of designing intervention mechanisms strategically balancing participants' barriers and motivations towards energy management, specifically through effective feedback and mechanisms provision (Chapter 4); (2) key insights for engagement and re-engagement in long-term participation in the residential smart grid, including targeted feedback, utilizing normative feedback and calls to action (Chapter 5); (3) the importance of applying consumer targeting through smart metering data to target, and design appropriate mechanisms, and; (4) an integrated approach for designing comprehensive mechanisms within the smart grid (Chapter 7). Overall, this research emphasizes the importance of extending engagement beyond the meter, and the sole provision of smart meter data, for residential smart grid engagement for home energy management. The utilization of multidisciplinary research, incorporating social science and mixed methods approaches, alongside the facilitation of integrated intervention approaches, can deliver advantages for research and practice in developing strategic mechanisms. The five research objectives addressed in the dissertation manuscripts (Chapters 4–7) delivered several research findings. Table 47 and the following sections summarize the main research outcomes from each research chapter.

Table 47 Research question and objectives applied in the dissertation

Main RQ: *How can Ontario residential consumers be engaged and re-engaged in the smart grid for the shift towards a smart and sustainable energy culture?*			
Research objective	**CH**	**Approach**	**Outcomes**
O1: To determine whether smart grid engagement mechanisms influenced household energy cultures within two distinct residential smart grid projects	4	- Assessment of participant interviews and survey responses - Overview of households' changes in material culture, practices and skills, and norms and aspirations surrounding energy use	- Increased awareness and actions towards HEM - Despite newer homes, changes in material culture were evident and motivated by cost savings and increased consumption awareness
	5	- Assessment of household energy consumption levels - Analysis of interview responses	- Limited significant changes from re-engagement from a tablet and reports - Laundry conservation and peak-shifting from autumn re-engagement - Difficulties making long-term changes
	6	- Assessment of participants' whole-house energy consumption changes	- No significant influence at general population level - Limited segments with significant favourable shifts (e.g., conservation and peak shifting)
O2: To gain a detailed understanding of underlying factors influencing household energy management	4	- Qualitative participant interviews - Assessment of survey responses - Overview of households' changes in energy culture - Assessment of barriers and motivations surrounding household energy management	- Households classified as economists (8) and compromisers (7),[70] which influenced their HEM motivations and barriers - Barriers: Lifestyle, convenience, competing household values for HEM - Motivation: financial cost savings - Increased awareness and practices due to web portal and electricity report - Changes in material culture evident

[70] By Gaye and Wallenborn's (2015) smart grid consumer typology

Research objective	CH	Approach	Outcomes
O3: To determine whether, and if so the extent to which, consumers re-engaged within a multi-year smart grid project	5	- Introduction of two feedback mechanisms for re-engagement in a residential smart grid study - Quantitative assessment of household energy consumption at whole-house and appliance levels - Assessment of two phases of participant interviews for insights on re-engagement mechanisms	- Limited significant changes in overall consumption; however, notable reductions and peak-shifting in autumn laundry practices - Peak shifting preferences were not equal across appliance groups - Preferences for report over tablet for re-engagement - Self-reported actions aligned with laundry and total consumption patterns - Feedback preferences: targeted and normative feedback with calls to action
O4: To assess consumer segments in a large-scale smart grid project and to identify types of consumers that may positively react to smart grid feedback at the residential scale	6	- Household segmentation - Consumption analysis of both the general population and segments	- No significant change in general population - Certain thermal and behavioural clusters evident in the households - Creation of 78 thermo-behavioural clusters to incorporate thermal and behavioural consumption characteristics - Limited significant favourable influences on household segments - Of notable segments, households with prevalent evening and heating consumption patterns exhibited peak reductions
O5: To review the disciplinary approaches for consumer engagement and to identify an integrated model for intervention design applicable to multiple sectors, including the energy system	7	- Conceptual review - Intervention approach assessment and comparison - Engagement model proposal	- Diverse approaches with clear differences for targeting change - SM, CBSM, SPT, and DT have distinct strengths and limitations - Evident opportunity to integrate strengths provided through the eight-stage ENGAAGGE model - The ENGAAGGE model delivers integrated strengths of each approach

8.2.1 Chapter 4 – EHMS case study paper 1

The paper entitled '***Towards a smart and sustainable residential energy culture: assessing participant feedback from a long-term smart grid pilot project***' provides three key outcomes related to household energy management and smart grid technologies. First, this chapter highlights increases in self-reported awareness and energy management practices as a result of long-term engagement in a residential smart grid program. In particular, participants identified the web portal and weekly newsletter feedback as the most helpful for influencing change. Second, this paper presents participants' preferences for additional guidance to make substantial changes within the home, although participants increased their energy consumption awareness. Third, this chapter identifies challenges for long-term household energy management created by the complexities of household-level factors, as well as lifestyle standards and expectations of convenience. Overall, this study emphasizes the challenges of engaging homeowners with home energy management technologies due to competing interests and a desire for more catered guidance. The outcomes of this study call for implementing user-centred approaches in the design of smart grid engagement mechanisms and respective technologies.

8.2.2 Chapter 5 – EHMS case study paper 2

The paper entitled ***'Re-engagement in a long-term smart grid study: Influences on household energy management practices'*** provides three key outcomes related to household energy management and smart grid technologies. First, this chapter highlights changes in laundry practices related to re-engagement through a tablet and electricity report in a long-term case study. In particular, participants significantly conserved and shifted their laundry consumption. Second, this research presents users' experiences for re-engagement and highlights participants' preferences for 'slower' feedback in the form of an electricity report through interviews, combined with Google analytics data. Third, this chapter identifies the correlation between participants' perceived changes in overall energy reductions and levels of On-Peak share during the monitoring period. Overall, this study presents opportunities for future studies to integrate mixed-methods approaches for studying temporalities of energy practices and testing mechanisms for re-engagement that go 'beyond feedback' for stimulating shifts in energy management.

8.2.3 Chapter 6 – IHD case study paper

The paper entitled **'*Who's responding anyway? Assessing segment-specific responses to real-time energy displays*'** provides three key outcomes related to energy feedback for household energy management. First, this paper presents quantitative insights that feedback alone, in the form of an IHD, was insufficient to drive favourable consumption changes (e.g., conservation and peak shifting) within the general population. Second, this chapter highlights different energy culture segments within the participant households and identifies that different segments responded differently to the IHD. Third, this research identifies that only a small proportion of participating households presented significant favourable changes in consumption (e.g., peak shifting or conservation), in conjunction with the IHD following segmented analysis. Therefore, although limited households presented favourable changes, their profile similarities were indicative of favourable responses. Overall, this study presents a strong rationale for designing smart grid engagement programs with targeted consumer approaches and applying user-centered methods. Clustering methodologies, such as the one utilized in the study, can provide a more detailed understanding of consumer trends beyond the general population. Future studies applying clustering methodologies catered towards holistic research frameworks (e.g., the energy cultures framework) can integrate socio-demographic data and participants' smart grid preferences and experiences for detailed understandings related to program development.

8.2.4 Chapter 7 – Engagement model paper

The paper entitled **'*ENGAAGGE: Towards an integrated model for collective change*'** provides three central outcomes related to consumer engagement for collective sustainability shifts. First, this paper delivers a comparative overview of social marketing (SM), community based social marketing (CBSM), social practice theory (SPT), and design thinking (DT) intervention design approaches. Second, this chapter articulates key elements for intervention design from reviewing the SM, CBSM, SPT, and DT approaches. Third, this chapter develops and presents a novel model for sustainability intervention design integrating behavioural, practice and technological aspects from existing approaches: the eight-stage ENGAAGGE model. Overall, this chapter identifies key elements for intervention design focused on sustainability and presents a novel model for intervention development. Opportunities for applying this model in future research are also presented.

8.3 Research reflections: Thinking ‘big and small’ in smart grid research

This dissertation research applied both small-and large-scale case studies to understand smart grid consumer engagement, thereby delivering interesting reflections for future research. Although widespread changes are needed for sustainable energy developments, as seen within these two case studies, designing, and delivering the appropriate mechanisms for stimulating this change is crucial for achieving intended CDM targets. Both large-and small-scale studies deliver their benefits and limitations for research, as articulated in the respective manuscripts. For instance, large-scale studies can provide robust validation of smart grid mechanisms applicable across different consumer groups; however, the computing power and resource allocation required for detailed analysis at large-scales can bring limitations for certain researchers. Additionally, focusing on consumption patterns, at large scales can focus on the ‘tip of the iceberg’ and miss underlying factors contributing to, or preventing changes.

Similarly, small-scale studies allow for delving into detailed nuances surrounding engagement and discovering insights to test with larger audiences. Particularly with smart grid studies, small-scale studies have been identified as beneficial in both social and technical studies studying residential energy consumption (Esmaeilimoakher, Urmee, Pryor, & Baverstock, 2016; Hargreaves et al., 2010, 2013; Jack, Suomalainen, Dew, & Eyers, 2018; Jenkins, Patidar, & Simpson, 2014; Khan, Jack, & Stephenson, 2019; Knowles, Hostetler, & Liebovitch, 2018; Peacock & Newborough, 2005; Wood & Newborough, 2003). In particular, these studies have identified that, despite small sample sizes, crucial findings can be derived, which can support and give direction for future research, thereby allowing progress in research. However, with small sample sizes, data constraints resulting from technical issues and participant involvement can become prohibitive, as identified in the research limitations in this dissertation. Therefore, both small-and large-scale studies deliver distinct and valuable insights for smart grid research, allowing for ‘thinking big and small’ to understand smart grid engagement. As seen in this dissertation research, both large and small-scale studies resulted in limited favourable influences as a result of increased feedback from smart meters and additional home energy management and feedback devices. Future research can deliver additional paired studies for understanding consumer engagement within the smart grid for the design and delivery of effective engagement beyond the meter.

8.4 Contributions

This dissertation research brings multiple contributions to academic and practice fields. The application of this dissertation research delivers contributions as a result of its combination of methodological, conceptual, and integrated approaches. This research provides contributions to the five areas of literature for development, as indicated in the introduction and literature review: (1) facilitating social science approaches in residential smart grid engagement research; (2) understanding smart grid consumer segments; (3) utilizing long-term analysis to study occupant behaviour and engagement in the residential smart grid; (4) applying the energy cultures framework to residential smart grid research, and; (5) investigating integrated approaches to intervention design.

8.4.1 Academic contributions

The outcomes of this dissertation research present five main academic contributions. First, this dissertation research integrates social sciences approaches to smart grid energy research at the residential scale. This is achieved both conceptually and methodologically. The energy cultures framing and development, as well as the mixed-methods, and clustering approaches applies social-science framing to conceptual and methodological techniques for studying smart grid engagement. Chapter 4 delivers a qualitative methodology by applying a holistic framework for understanding consumer engagement in the EHMS study. Chapter 5 applies mixed-methods research to deliver detailed understanding of re-engagement in a long-term smart grid study. This mixed-methodology applied in the EHMS case study, is also novel in the literature, particularly within long-term smart grid contexts. Chapter 6 applies thermal and behavioural archetype clustering methodology for comprehensive consumer understanding. Chapter 7 develops a new integrated model for intervention development, delivering opportunities for future social science research in the field of energy.

Second, this research applies segmentation and consumer typologies for thorough understanding of consumer segments within the smart grid. In Chapter 4, Gaye and Wallenborn's (2014, 2015) typology of smart grid consumers is applied to gain additional understanding of households' motivations and barriers surrounding home energy management in the smart grid. Chapter 5 applies thermo-behavioural clustering of 5274 central Ontario homes to develop understanding of consumption impacts on particular consumer segments from smart meter-enabled feedback.

Third, this dissertation research utilizes long-term analysis to study occupant behaviour and reactions to smart grid engagement. At the time of this dissertation, the EHMS case study (Chapters 4 and 5) delivers a novel application of long-term residential smart grid engagement, where limited approaches to studying long-term engagement and re-engagement within the smart grid are present in the literature. These two papers develop the holistic understanding of long-term engagement and re-engagement within the residential smart grid. Therefore, this research presents long-term insights for consumer engagement with smart meter-enabled feedback.

Fourth, this dissertation provides the first application of the energy cultures framework to the residential smart grid, where Chapter 4 presents the conceptual overview of a smart and sustainable energy culture, Chapter 5 further applies this framework into mixed-methods research and Chapter 6 proposes opportunities for quantitative clustering techniques to further apply this research framing in residential segmented research. Specifically, these research elements provide important directions for future studies to integrate a holistic approach to studying consumer engagement and energy management in the residential smart grid.

Fifth, at the time of this dissertation, the conceptual paper presented in Chapter 7 provides a novel and comprehensive comparative overview of SM, CBSM, SPT, and DT. As an outcome, this chapter presents a comprehensive review of key elements for intervention design from collectively reviewing the SM, CBSM, SPT, and DT intervention design approaches. Additionally, this chapter presents an innovative model for sustainability intervention design integrating behavioural, practice and technological aspects from existing approaches: the eight-stage ENGAAGGE model. Overall, the outcome of this research presents an essential contribution for developing engagement research through its comparative review as well as a proposal of a novel model for future application and research.

8.4.2 Contributions to practice

The outcomes of this dissertation research present three key contributions to practice. First, the holistic methodology applied in the EHMS study (Chapters 4 and 5) delivered insights for designing and testing future residential smart grid pilot projects with larger audiences. In particular, the research results highlight user experiences and insights with technologies, engagement mechanisms, and household energy management. These particular insights in user preferences for engagement and barriers/motivations for household energy management pose strategic lessons applicable for future smart grid project research and development with larger audiences, in different regional contexts.

Second, the clustering methodology applied in the IHD paper (Chapter 6), presents key considerations for designing future smart grid feedback programs. Specifically, this study highlights the importance of targeted approaches, gathering detailed consumer data for effective segmentation, and identifying household preferences for information and feedback during project implementation. As an outcome, this study presents a strong case for the application of user-centred approaches and segmented market analysis to intervention and program design within the smart grid.

Third, as an outcome of the two smart grid case studies, and their challenges presented for smart grid engagement and re-engagement, a substantial opportunity for establishing and presenting engagement strategies is highlighted. Therefore, the ENGAAGGE model presented in Chapter 7 provides a novel intervention approach integrating behavioural and societal intervention design approaches (i.e., SM, CBSM, SPT, and DT). The review of theoretical approaches to intervention design and the proposal of an integrated model brings 'theory into practice' to develop intervention mechanisms for societal sustainability shifts. Specifically, the model delivered in this paper brings unique opportunities for practitioner application and intervention development in policy, industry, and research.

8.5 Research limitations

8.5.1 EHMS study limitations

As previously articulated, limitations related to the EHMS study were identified (Chapters 4 and 5). The primary limitation was the sample size for both qualitative and quantitative analysis. The technological constraints related to the study also reduced the availability of data, and subsequently, the participation of certain households. It should be noted that these constraints are not isolated in the literature and that these limitations present considerations for future studies (e.g., study design, technology selection, long-term participant engagement/recruitment). Despite this limitation, the richness of long-term and disaggregated consumption data alongside detailed participant qualitative insights provided abundant research opportunities for this case study. Notably, the data available presented a substantial opportunity to: (1) apply the energy cultures framework for a holistic understanding of household smart grid engagement; (2) develop a mixed-methods approach for understanding consumer re-engagement with the smart grid, and; (3) generate a detailed understanding of long-term household energy practices at whole-house and appliance-levels through consumption analysis. Small sample sizes are evident in smart grid research in various jurisdictions as a result of intrusive and expensive technology and related technical difficulties (Bager & Mundaca, 2017; Bradley et al., 2016; Hansen & Hauge, 2017). Additionally, small sample sizes provide benefits to research development by identifying novel areas and insights within larger system dynamics that can be further developed and tested with more extensive cohorts (Hargreaves et al., 2013). These benefits were evident within the EHMS study, where nuances in long-term smart grid engagement brought novel insights to test with larger participant cohorts. Therefore, the EHMS project provided a detailed understanding of the nuances related to smart household energy management, despite the small sample size.

8.5.2 IHD Study limitations

As previously articulated, limitations were associated with the IHD study (Chapter 6) and should be noted. The data collected were limited to energy consumption, and therefore, socio-economic data were not available for analysis. Specifically, these limitations were related to the access to only consumption and outdoor temperature data for analysis and segmentation. Additionally, this study did not have access to IHD consumer engagement data, nor participants' socio-demographic data due to participants' anonymity; therefore, information on the location and use of the IHD were not available for analysis. Despite these limitations, the richness and size of the dataset outweigh these limitations and provide novel applications as a result of the research presented in Chapter 6. Specifically, access to consumption data for 5274 households with an IHD allowed for a detailed assessment of IHD influences as well as consumer segmentation analysis. Furthermore, the longevity of the data available (two years) with hourly granularity presented a wealth of consumption data for a thorough understanding of household energy consumption patterns, and in consumer segments. Therefore, despite the study's limitations, the size, and richness of the dataset for the IHD study provided substantial opportunities for studying cluster-based responses to smart meter-enabled IHD feedback.

8.5.3 ENGAAGGE paper limitations

Limitations associated with the ENGAAGGE paper presented in Chapter 7 should also be highlighted. The ENGAAGGE model was not empirically tested within Chapter 7, as it was beyond the scope of the paper. Applications of the ENGAAGGE model, and related empirical testing can bring additional insights for evaluating and applying this model effectively. Furthermore, applications in research can provide a detailed understanding of particular avenues where this approach would be best suited. Despite this limitation, the outcomes of the conceptual paper (Chapter 7) present substantial opportunities to apply the ENGAAGGE model in future research and intervention design and, therefore, bring contributions to both academia and practice.

8.6 Considerations for residential smart grid engagement and research

The outcomes of this dissertation research present three challenges for residential consumer engagement for household energy management. ***The first challenge is the role of habits and preferences***. As discussed thoroughly in this dissertation research, the role of contextual factors and habits surrounding household energy cultures can inhibit or promote the ability of households to make energy culture changes. From a quantitative perspective, energy actions may not change substantially, except within specific target audiences, as seen in the IHD study (Chapter 6); however, upon further investigation, these changes may only be limited to certain energy management practices, as seen in the EHMS study (Chapters 4 and 5). As recognized in the EHMS study, consumption analysis highlighted measured changes in laundry energy management practices, which was further articulated in participants' appliance-specific preferences for peak shifting. In this study, specific habits and consumption preferences prevented peak shifting. Therefore, certain types of consumers may be willing to change, but these could be limited to particular energy practices due to particular barriers, habits, and preferences. These limitations present a challenge for changing household energy management practices and highlight opportunities for future smart grid research to understand these limitations.

The second challenge is residential consumers' capabilities for substantially changing their energy culture. The results of the two smart grid case studies presented limited favourable changes in energy culture (e.g., consumption reductions and peak shifts; appliance upgrades; and changes in energy expectations) in conjunction with the introduction of smart grid tools and smart metering feedback. Although underlying factors influencing participants' energy culture were not available for assessment in the IHD case study, qualitative insights from the EHMS study bring potential insights for the limited influence of feedback on energy management. The challenges of contextual factors, household profiles, and 'backgrounding' of energy feedback overtime were highlighted and reflected outcomes similar to existing research (Hargreaves et al., 2013; Wemyss et al., 2019). EHMS participants also emphasized the importance of skills and targeted advice for engaging with energy goals. However, the new age, and subsequently higher efficiency of the participants' built environment presented a limitation for making substantial upgrades. For project design and delivery, taking the complexity of household energy cultures into account, and moving beyond households as 'black boxes' of energy demand is crucial (Darby, 2008) and can be applied in future research applying holistic frameworks.

The third challenge is overcoming barriers to idealized shifts in energy management. As identified in the literature review (Chapter 2) and the EHMS study (Chapters 4 and 5), barriers to idealized energy patterns and changes are essential to consider. Opportunities to reduce these barriers and to deliver more effective programs could be overlooked until the fundamental barriers and motivating factors are identified. Additional understanding of household energy practices and the association of daily habits influencing energy consumption is required to overcome these obstacles. The outcomes from both the EHMS and IHD case studies align with Hargreaves' (2018) call for going 'beyond feedback' to engage households with home energy management. Applying holistic models for understanding household engagement in the smart grid and opportunities for advancing changes in long-term energy management practices can assist in this development. Overarching policy mechanisms, such as energy pricing, can influence these shifts. However, despite the presence of TOU pricing in both dissertation smart grid case studies, TOU price differences were not enough for substantial energy management changes. As identified in Chapter 7, utilizing integrated approaches for developing intervention approaches brings opportunities for thorough solution development and testing. These three considerations, presented as outcomes of this dissertation research, provide a robust foundation for future research, as identified in detail in the following section.

8.7 Recommendations for future research

As an outcome of this dissertation research, five considerations and suggestions for future research are identified. ***The first research recommendation is applying the energy cultures framework to develop understanding of smart grid consumer engagement and household energy management.*** The energy cultures framework applied to the smart grid, as articulated in Chapter 4, can be applied to larger case studies for developing a holistic understanding of consumer engagement in the residential smart grid. As identified in detail throughout this dissertation, although increased technology brings additional opportunities for household energy control and management, particular attention needs to be paid the role of the consumer and their adoption and utilization of these technologies for energy management. The energy cultures framework brings a comprehensive and scalable framework to study household interactions in the smart grid, as seen in-depth within Chapter

4. Furthermore, as smart home technology advances, this framework can be altered further for a comprehensive understanding of household technological adoption and energy management within the smart home ecosystem.

The second research suggestion is deploying and testing the ENGAAGGE model. Utilizing the ENGAAGGE model in practice for testing intervention development can advance this model through application and evaluation. Additionally, through its application, evaluation methodologies for this intervention design model can be developed. Applying this model in practice and in research, can identify avenues for model evaluation and improvement. Scaling-up the application (e.g., from dormitory-level to campus-level application) throughout the testing and evolution of the model can also determine additional strategies for application at different scales. Furthermore, applying the ENGAAGGE model can bring opportunities for integration with existing holistic frameworks. As highlighted by Stephenson (2018) the energy cultures framework presents abundant opportunities to apply the framework to a broad range of practices beyond energy and into 'sustainability cultures' (e.g., waste, water, transportation). Applying the scalable energy cultures framework to develop understanding of broader sustainability cultures can deliver insights into the interlinking factors influencing the adoption of larger-scale sustainability practices, norms, and materials. Therefore, this presents substantial opportunities for further research to apply the ENGAAGGE model independently or in combination with holistic frameworks, such as the energy cultures framework.

The third research recommendation is testing the outcomes of the EHMS study with larger and more randomized participant samples. Insights gathered from the EHMS study on long-term engagement and re-engagement with the smart grid presents opportunities for applying similar research to larger participant cohorts. As identified by Darby et al. (2018) to make shifts towards idealized energy management, a detailed understanding of consumer engagement with these technologies and demand management programs is necessary and can be facilitated through future research and development. The EHMS case study presents the value of sub-metered electricity data for developing detailed insights into the diversity and complexity of household energy practices. The additional collection of qualitative energy monitoring data (e.g., activity monitoring and energy journaling) can also produce insights into the activities influencing the variability of energy consumption within a home. An example is Grunewald et al.'s (2018) Meter Project, where participating households log their activity, location, and emotion during energy consumption activities. Studies collecting detailed participant data, such as these, can provide comprehensive insights on consumption practices while delivering information on the complex factors surrounding energy consumption (e.g., emotions, motivations, and activities). Opportunities exist to bring similar studies within sub-metered projects to gain additional insights on household energy management, particularly within the smart grid. Additionally, as smart grid infrastructure becomes more thoroughly developed across Canada, this presents substantial opportunities for applying similar sub-metered energy research in larger cohorts and within different Canadian regions for comparisons.

The fourth research suggestion is advancing multidisciplinary approaches to smart grid research. As identified within the EHMS case study, qualitative data alongside consumption data delivers detailed insights on household energy practices. These types of research methodologies can integrate users' perspectives into smart grid research. Holistic frameworks, such as the energy cultures framework, bring opportunities to fuse qualitative and quantitative insights for smart grid consumer engagement. However, to thoroughly apply multidisciplinary approaches to this field of research, collecting the most suitable data is a vital component. As experienced in the IHD study, certain types of data beyond consumption data (e.g., socio-economic status, consumer profile, technology preferences) are essential for developing knowledge of consumer energy cultures and establishing consumer segments. Therefore, integrating multidisciplinary research approaches into the research design process is an essential component for establishing a holistic understanding of household engagement within the smart grid. Furthermore, developing teams of multidisciplinary researchers for the design, implementation and analysis of this research is critical for bridging these gaps, and moving towards a more holistic understanding of household energy management and engagement with smart grid technologies.

The fifth research recommendation is applying these research insights into energy management research with smart home technologies. The literature points to the questionable and unknown benefits of smart *home* technology for household energy management (e.g., smart plugs, smart light bulbs, smart thermostats, smart appliances, smart speakers, etc.,) (Darby, 2018a; Hargreaves et al., 2018; Tirado Herrero et al., 2018). The knowledge developed from research in user experience and consumer engagement with smart grid technology is applicable to consumer-facing smart home technology research related to home energy management. The techniques and methodologies utilized and suggested as an outcome of this research provide crucial opportunities for future research focused on studying users' applications of smart home technologies for home energy management. Additionally, these techniques pose opportunities to quantify the specific impact(s) of these technologies on energy consumption. Furthermore, extending this area of research into the smart home ecosystem would benefit from the application and use of holistic frameworks, the integration of mixed-methods approaches for studying intervention design, and the application of integrated intervention design approaches for developing effective consumer engagement.

8.8 Conclusions

This dissertation entitled *'Engaging beyond the meter: Encouraging residential energy management using smart grid tools'* applied two Ontario residential case studies to gain additional understanding of the opportunities for smart grid technologies to engage residential consumers for energy management. These two case studies highlighted challenges for engaging households for home energy management. Additionally, a novel integrated intervention approach was developed as an outcome of a comprehensive review of sustainability-based intervention design approaches. Overall, the energy cultures framework was applied as an organizing framework for this dissertation research (Figure 55).

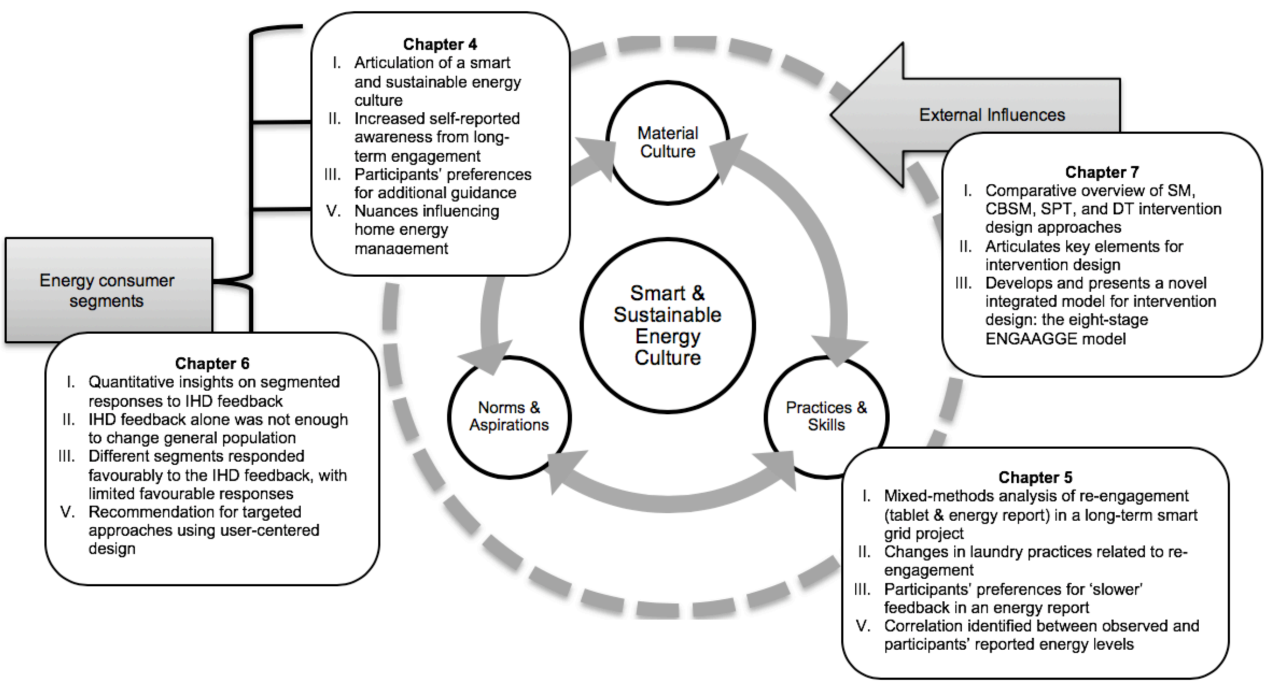

Figure 55 Dissertation research overview and related outcomes

This research brings contributions to academia and practice related to household energy management and engagement in the smart grid. Specifically, in Chapter 4, this dissertation brings a novel application of the energy cultures framework to the residential smart grid and presents the conceptual framing of a smart and sustainable energy culture. The research in the EHMS study in Chapters 4 and 5 presents insights into long-term engagement and re-engagement with residential smart grid technologies from both qualitative and appliance-level data, delivering insights on consumer engagement, user preferences, and nuances influencing household energy management practices. In Chapter 6, this dissertation research delivers a quantitative application of consumer segmentation in the residential smart grid with 5274 IHD recipient households in central Ontario. The outcomes of this chapter present novel insights for segment-based research on smart grid consumer engagement. Furthermore, this study emphasizes the importance of going beyond the provision of feedback and establishing targeted audience segments for program design. Following the presentation of challenges related to smart grid engagement, as mentioned within Chapters 4-6, Chapter 7 delivers a review of the existing approaches for intervention design and, following, proposes an innovative and integrated approach for intervention design. The eight-stage ENGAAGGE model harnesses the strengths of the existing approaches and delivers an integrated approach for intervention design for collective sustainability shifts. Overall, this dissertation brings together a multidisciplinary approach for investigating consumer engagement with smart grid technologies for home energy management and highlights prospects to advance future research in these areas. Bringing together these chapters presents key results for engaging residential smart grid consumers *beyond the meter* for household energy management.

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10. Appendix A: EHMS Interview 1 Questions

1. What are your current motivations for energy management decisions in your home? What are your current motivations for participating in the EHMS project? Please rate your motivations from 1 – 7:

   1 → strongly disagree

   2 → disagree

   3 → somewhat disagree

   4 → neither agree nor disagree

   5 → somewhat agree

   6 → agree

   7 → strongly agree

If the rationale is not applicable, please circle n/a.

Rationale	**Rating – Home Energy**								**Rating – Participation in EHMS**							
To save money	1	2	3	4	5	6	7	n/a	1	2	3	4	5	6	7	n/a
To respond better to time-of-use electricity prices	1	2	3	4	5	6	7	n/a	1	2	3	4	5	6	7	n/a
To reduce the amount of energy consumed in your household	1	2	3	4	5	6	7	n/a	1	2	3	4	5	6	7	n/a
To reduce the carbon footprint associated with your household energy usage	1	2	3	4	5	6	7	n/a	1	2	3	4	5	6	7	n/a
To increase your personal comfort in your home	1	2	3	4	5	6	7	n/a	1	2	3	4	5	6	7	n/a
To learn more about your behaviours to help you plan your home energy usage	1	2	3	4	5	6	7	n/a	1	2	3	4	5	6	7	n/a
You purchased energy efficient appliances and want to lower your energy usage even more	1	2	3	4	5	6	7	n/a	1	2	3	4	5	6	7	n/a
You made home renovations to conserve energy and want to lower your energy usage even more	1	2	3	4	5	6	7	n/a	1	2	3	4	5	6	7	n/a
You like trying a new web-based energy management technology	1	2	3	4	5	6	7	n/a	1	2	3	4	5	6	7	n/a

2. During the project were there any major changes in your household that would have impacted your energy consumption? *If so, please provide details and note when they took place.* Examples (prompts):
    a. More or less people in the household.
    b. Number of people home during peak hours or during the day (e.g. changes in job hours)
    c. Added/removed major appliances
    d. Increased/decreased activities in the home (e.g. home business, etc.)
3. Compared to similar houses in your neighbourhood, how would you rate your consumption, before the project, and now from very low to very high?

Before Project	Very Low	Low	Average	High	Very High
Current	Very Low	Low	Average	High	Very High

4. In terms of general forms of communication, what type(s) do you prefer when participating in voluntary projects, such as this? Please rate on a scale from 1 (not preferable) to 5 (preferable).

Verbal	1	2	3	4	5
Written	1	2	3	4	5
Visual	1	2	3	4	5
Other (please specify)	1	2	3	4	5

5. Keeping your preference(s) in mind, did the methods of communication throughout this project meet your needs? (E.g. emails, web portal, weekly reports, surveys…)
    a. Verbally - were things clear? Were there any reasons why verbal information was ineffective?
    b. Written - were there any barriers or reasons why written information was ineffective?
    c. Visual - were the graphics, images, and visuals used in the web portal and reports clear and understandable?
        i. Would you have preferred less or more?
        ii. Would you have preferred more descriptions to understand the graphics?
6. Throughout the EHMS project various types of project-led interactions occurred. We would like to know which types were the most effective. In looking at the following list, please indicate their effectiveness on a scale from 1 (not effective) to 5 (very effective). Effective meaning it provided you with any necessary knowledge of a project aspect and motivated you to actively participate in the EHMS project.

Interaction	Rating					
Recruitment email & signing up for the project	1	2	3	4	5	n/a
Home profile and analysis survey	1	2	3	4	5	n/a
Welcome survey	1	2	3	4	5	n/a
Electricity budget allocation	1	2	3	4	5	n/a
Activation and use of the web portal	1	2	3	4	5	n/a
Fixing outstanding data/ equipment problems & the electrical circuit diagram	1	2	3	4	5	n/a
Reminder email	1	2	3	4	5	n/a
Responses to queries by phone	1	2	3	4	5	n/a
Responses to queries by email	1	2	3	4	5	n/a
Webinars	1	2	3	4	5	n/a
Post monitoring survey	1	2	3	4	5	n/a
The incentivized control program	1	2	3	4	5	n/a
Weekly electricity report	1	2	3	4	5	n/a

7. Can you please explain why you found certain interactions more effective than others?
8. During the project, describe your experience with the email reminders.
    a. Are there changes that would make it more suitable? Examples:
        i. Frequency
        ii. Delivery method
        iii. Information provided
        iv. Reminder by other communication
9. Did you participate in the incentivized control portion of the EHMS project? Prompt: This took place in July and August 2013 and provided a $100 incentive for using the scheduling function to control the A/C in the homes of those who participated.
    a. If no:
        i. Why did you not participate?
        ii. On the following scale please indicate the minimum financial incentive would have motivated you to participate in this past portion of the project (specify amount if over $500).

Greater than 100, less than $200	$200	$300	$400	$500	Greater than $500	No incentive would have been sufficient for my participation

b. If yes:
    i. Please describe your experience with the incentivized portion of the project.
    ii. Do you use the control option? Why or why not?
    iii. Would you participate again in the future? Why/Why not?

*Please note that there are no plans to offer another version of this incentivized program in the future.

10. During your experience with the project, please identify some positive elements of the web portal and any aspects of the web portal that you would change. Please refer to the print out. Examples: ease of use, accessibility, visuals, presentation of information.
11. Schedule - Did you use the scheduling feature of the web portal?
    a. If so:
        i. How did you use it, or incorporate it into your daily life?
        ii. Did you find it was effective/useful for managing your energy consumption? Why or why not?
    b. If not:
        i. What prevented you from using the scheduling function?
        ii. What method(s) for scheduling would you have preferred?
    c. If you stopped using the scheduling function, what caused you to stop?
12. During the project, various types of feedback were given. Which was your most preferred type and why (e.g. timing/frequency, delivery, type of feedback).
    a. Logging into the web portal
    b. Emails
    c. Weekly electricity report
13. Goal setting - During this project, did you set energy conservation goals?
    a. If so:
        i. Did you set them through the web portal or did you set them on your own?
        ii. Did you find the goal-setting effective?
    b. If you did not set goals:
        i. What caused you to not set goals?
    c. If you stopped setting goals, what caused you to stop?

14. Please indicate how you perceive your current level of awareness with regards to energy management in your home. Please rate the following statements using the previous scale of 1-7 (1=strongly disagree, 7=strongly agree) or not applicable.

Statement	**Rating**							
Currently, I am aware of how much electricity is used by each of my electric appliances	1	2	3	4	5	6	7	n/a
Currently, I am aware of how much money it costs to use each of my electric appliances.	1	2	3	4	5	6	7	n/a
Currently, I am aware of the carbon footprint associated with using each of my electric appliances	1	2	3	4	5	6	7	n/a

15. How did your awareness of energy conservation differ from before the project to now? Please rate your beginning and current level from 1-5, where 1 is no awareness and 5 is completely aware.

Before Project	1	2	3	4	5
Current	1	2	3	4	5

a. If more awareness:
   i. What caused you to gain more awareness during the project?
   ii. Did the project interactions contribute to this change?

b. If the same level of awareness: Why? What would have provided you with more awareness?

16. To what extent do the following statements describe your current attitudes of energy management in your home? Please rate the following statements from 1-7 using the scale used earlier (1=strongly disagree, 7=strongly agree) or not applicable.

Statement	**Rating**							
I believe that it is important to conserve as much energy in my home as possible	1	2	3	4	5	6	7	n/a
I believe that it is important to reduce my electricity usage during On-Peak times as much as possible	1	2	3	4	5	6	7	n/a

17. How have your attitudes of energy conservation differed from before the project to now? Please rate your beginning and current level from 1-5, where 1 is having strongly negative attitudes, 5 is having strongly positive attitudes about energy conservation, and 3 is neutral.

Before Project	1	2	3	4	5
Current	1	2	3	4	5

a. If change in attitudes occurred:
   i. What caused you to change your attitudes?
   ii. Did the project interactions contribute to this change?

18. To what extent do the following statements describe your current actions of energy management in your home? Please rate your motivations from 1 – 7 using the scale used earlier (1= strongly disagree, 7 = strongly agree) or not applicable.

Statement	**Rating**							
I try to conserve as much energy in my home as possible	1	2	3	4	5	6	7	n/a
I try to reduce my electricity usage during On-Peak times as much as possible	1	2	3	4	5	6	7	n/a

19. How did your actions towards energy conservation differed from before the project to now? Please rate your beginning and current level from 1-5, with 1 being taking no actions towards energy conservation and 5 being continual actions towards energy conservation.

Before Project	1	2	3	4	5
Current	1	2	3	4	5

b. If more action:
   i. How did you change your actions?
   ii. Did the project interactions contribute to this change?

c. If the same/less level of action – Why?

21. Are there barriers that prevented you from shifting your energy consumption during the EHMS project?
22. What motivated you to shift your energy consumption during the EHMS project?
23. When this project ends, do you intend to continue energy reduction efforts?
   a. If yes: Why? What challenges do you anticipate for reducing your energy consumption?
   b. If no: Why not? What would motivate you to continue or improve your energy conservation efforts?
24. Do you think your attitudes reflect those of others in the household?
25. Do you think your actions are similar to those of others in your household

11. Appendix B: EHMS Interview 2 Questions

1. How many days a week is someone typically home during the day? ________
2. Has this pattern changed in recent years? If yes, what was the previous pattern? When did it change?
3. At this time in the project, how many people occupy your home? What are their approximate ages?
4. Within the Energy Hub Management System, you had the opportunity to set monthly goals regarding your home's electricity consumption. Did you use this feature? If yes, did you:
   - Set goals to DECREASE your home's electricity consumption
   - Set goals to MAINTAIN THE SAME LEVEL of electricity consumption
   - Set goals to MINIMIZE AN INCREASE of your home's electricity consumption
   - Other, Please specify: _____________

   If no, why did you not use this feature?
5. Have you made any changes that have impacted your energy consumption over the past 4 years (Refer to the list below for examples)? Did the project influence your decision(s) on completing these retrofits/installations?
   To complete a full analysis of your energy consumption changes throughout the program, could you provide us with how much natural gas you have consumed each year?

Examples of energy-saving retrofits and installations:

- Replacing bulbs with high efficiency ones
- Increasing insulation
- Replacing windows
- Replacing major appliances with more efficient ones
- Installing a more efficient HVAC system
- Completing a home energy audit
- Installing weather stripping
- Installing light and appliance timers
- Installing hot water pipes
- Installing motion sensors for lights
- Installing a solar hot water heat

6. For viewing your household electricity consumption, would you have preferred a dedicated in-home energy display to the tablet? Please elaborate on your response.
   (In-home display description: A dedicated in-home display is a simple electronic device similar to a thermostat; it is often located at one central point in the house, and the sole purpose of the device is to present visual real-time electricity consumption feedback).
   a. Yes No

7. When the tablet was introduced, how did it impact your interactions with this program? Please elaborate. Examples of discussion points:
    c. Presentation of information
    d. Awareness of progress
    e. Goal-setting
    f. Use of scheduling and optimization
    g. Engaging others in home

8. In your household, who was the primary user of the tablet for the mobile web application? Why? What is the approximate age of this individual?

9. Please rate the effectiveness of the tablet for energy management in your home on the scale of 1-5 (1 = not very effective, 5 = very effective), with the term effective meaning it provided you with information and motivated you to actively participate.
    1 2 3 4 5

    Please elaborate and describe your experience with the tablet and use of the web application

10. Did you access the mobile web application?

If response to question 11 is no, please answer the following, then move to question 15:

- If no, could you explain why?
- What would make it easier for you to use? What would you have preferred?
- Do you have any additional feedback for the development of a web application for home electricity monitoring and feedback?
-

If response to question 11 is yes, please answer the following questions:

11. How did you access the new mobile web application? Was it through the tablet or mobile devices?
12. What were the purpose(s) for using the mobile web application? (Select all that apply).
    a. Check consumption
    b. Access optimization functions
    c. Check and change goals
    d. Discuss or share energy use with others in your home
    e. Other (please specify): ____

13. How did the tablet & mobile web application impact your:
    a. Awareness towards energy management
        i. On a scale of 1 – 5 (low to high) what would you rate your current level of awareness towards energy management in your home. Did the introduction of the tablet impact this rating? If so, how and what is your new rating?
    b. Attitudes towards energy management

ii. On a scale of 1 – 5 (low to high) what would you rate your current level of attitudes towards energy management in your home. Did the introduction of the tablet impact this rating? If so, how and what is your new rating?

c. Actions towards energy management in your home

iii. On a scale of 1 – 5 (low to high) what would you rate your current level of actions towards energy management in your home. Did the introduction of the tablet impact this rating? If so, how and what is your new rating?

14. Please provide any additional feedback you might have for web applications and mobile devices for home energy monitoring.

15. What percentage reduction in your monthly electricity bill would motivate you commit to load shifts of major appliances in your home? Please elaborate.

16. How much higher would the price of On-Peak electricity need to be compared to Off-Peak electricity to cause you to shift your consumption from On-Peak to Off-Peak usage for the following appliances?
Current Off-Peak cost: 7.5 ¢/kWh

Current On-Peak cost: 13.5 ¢/kWh

Appliance Use	**If On-Peak is 2x Off-Peak (15¢/kWh)**	**If On-Peak is 3x Off-Peak (22.5¢/kWh)**	**If On-Peak is 4x Off-Peak (30¢/kWh)**	**If On-Peak is 5x Off-Peak (37.5¢/kWh)**	**If On-Peak is 6x Off-Peak or greater (45¢/kWh)**	**N/A**
Washing Machine						
Clothes Dryer						
Air Conditioner						
Dishwasher						
Entertainment System						
Home Office						
Oven & Stove						
Other: _______						
Other: _______						

17. What percentage reduction in your monthly electricity bill would motivate you to use the optimization feature for your air conditioner? Please elaborate.

18. On a scale of 1-5 (not very willing to very willing) how willing are you to use control features to manage the electricity consumption of your appliances and HVAC system? Please elaborate on your rating.
1 2 3 4 5

Has your opinion on control features changed since the beginning of the program? Please elaborate.

The final questions of the interview allow for a reflection on this conversation and the overall EHMS project.

19. At the end of this project, what are your views of household smart grid and home electricity monitoring technologies?
    a. Are you satisfied with these technologies? Why/Why not?
        i. What are the challenges of using this technology in your home?
        ii. What are the benefits for using this technology in your home?
    b. Without involvement in a project, would you pursue installing this technology in your home? Why/why not?
    c. Would you recommend this type of technology to your neighbours, friends or family? Why/why not?

20. *I would now like to explore 3 related questions regarding your household conservation actions.* How often do you complete the following conservation actions? Has the frequency of the actions changed since the beginning of the program? Did the project contribute to this change? Please indicate how often the actions were performed at the beginning of the program and currently, using the following options:

    - At least once per day
    - Every 2 or 3 days
    - Once per week
    - Every 2 or 3 weeks
    - Once per season
    - Once per year
    - Never
    - Not applicable

	Action	How Often Completed (Before & After)	Did project interaction(s) contribute?	If so, Which one(s)?
Year -Round	Use less hot water		Yes/No	
	Turn off lights when no one is in the room		Yes/No	
	Hang clothes instead of using the clothes dryer		Yes/No	
	Adjust heating/cooling vents in rooms that are not in use		Yes/No	
	Run electric appliances at Off-Peak times		Yes/No	
	Do you use a power bar to turn-off phantom load when appliances are not in use (e.g., printers, speakers, TV's)		Yes/No	
Colder Seasons	Adjust/set the thermostat (manually or programmable) to lower heat when no one is home		Yes/No	
	Adjust/set thermostat to lower heat when my family is asleep		Yes/No	
	Wear warmer clothes, so the thermostat can be kept lower		Yes/No	
Warmer Seasons	Use fans/open windows instead of air conditioner		Yes/No	
	Adjust/set the indoor temperature to use less air conditioning		Yes/No	
	Close drapes during hot summer days		Yes/No	
	Other (please specify)		Yes/No	
	Other (please specify)		Yes/No	

21. What would cause you to use the system more? What elements should future projects use to encourage more use of the system?

22. Any further project feedback or comments?

12. Appendix C: Chapter 5 - Results tables for 12-week summer

Table 48 Whole-house consumption paired t-test outcomes, 12-week summer period, average weekly kWh

Pair	Time Period						Mean Difference	95% CI for Mean Difference					
	Base Period			Monitoring Period									
	M	SD	n	M	SD	n					t	df	*p*
Total	293.2	113.9	7	273.5	104.1	7	-19.7	-44.4	,	4.9	-2.0	6	0.098
On-Peak	50.1	22.2	7	45.0	21.8	7	-5.1	-10.5	,	0.4	-2.3	6	0.064
Off-Peak	193.4	83.7	7	181.4	72.2	7	-12.0	-34.2	,	10.2	-1.3	6	0.234
Mid-Peak	49.7	17.6	7	47.0	17.3	7	-2.7	-9.7	,	4.3	-0.9	6	0.384

Table 49 Air conditioning consumption paired t-test outcomes, 12-week summer period, average weekly kWh

Pair	Time Period						Mean Difference	95% CI for Mean Difference						
	Base Period			Monitoring Period										
	M	SD	n	M	SD	n					t		df	*p*
Total	107.0	30.7	6	74.1	27.2	6	-33.0	-48.7	,	-17.2	-5.4	*	5	0.003

*p<0.05

Table 50 Cooking consumption paired t-test outcomes, 12-week summer period, average weekly kWh

Pair	Time Period						Mean Difference	95% CI for Mean Difference					
	Base Period			Monitoring Period									
	M	SD	n	M	SD	n					t	df	*p*
Total	4.1	3.1	7	4.5	2.9	7	0.5	-0.9	,	1.8	0.8	6	0.460
On-Peak	0.6	0.7	7	0.5	0.6	7	0.0	-0.4	,	0.3	-0.3	6	0.778
Off-Peak	2.0	1.7	7	2.6	2.1	7	0.6	-0.3	,	1.5	1.7	6	0.138
Mid-Peak	1.5	1.2	7	1.4	1.1	7	-0.1	-0.5	,	0.3	-0.7	6	0.524

Table 51 Entertainment consumption paired t-test outcomes, 12-week summer period, average weekly kWh

Pair	Base Period M	Base Period SD	Base Period n	Monitoring Period M	Monitoring Period SD	Monitoring Period n	Mean Difference	95% CI for Mean Difference			t	df	*p*
Total	28.7	28.0	6	21.6	18.4	6	-7.1	-0.9	,	1.8	-1.6	5	0.167
On-Peak	5.1	5.4	6	3.4	2.8	6	-1.7	-0.4	,	0.3	-1.5	5	0.206
Off-Peak	18.1	17.3	6	14.5	12.9	6	-3.5	-0.3	,	1.5	-1.6	5	0.162
Mid-Peak	5.6	5.4	6	3.7	2.8	6	-1.9	-0.5	,	0.3	-1.6	5	0.170

Time Period

Table 52 Laundry consumption paired t-test outcomes, 12-week summer period, average weekly kWh

Pair	Base Period M	Base Period SD	Base Period n	Monitoring Period M	Monitoring Period SD	Monitoring Period n	Mean Difference	95% CI for Mean Difference			t	df	*p*
Total	21.4	12.8	7	22.2	13.1	7	0.8	-1.5	,	3.1	0.9	6	0.410
On-Peak	3.7	5.0	7	1.7	1.8	7	-2.0	-5.0	,	1.1	-1.6	6	0.168
Off-Peak	14.8	8.5	7	18.2	10.6	7	3.4	-1.0	,	7.8	1.9	6	0.105
Mid-Peak	3.0	2.7	7	2.3	1.8	7	-0.6	-2.1	,	0.8	-1.1	6	0.325

Time Period

Table 53 Dishwasher consumption paired t-test outcomes, 12-week summer period, average weekly kWh

Pair	Base Period M	Base Period SD	Base Period n	Monitoring Period M	Monitoring Period SD	Monitoring Period n	Mean Difference	95% CI for Mean Difference			t	df	*p*
Total	3.4	3.8	6	3.5	4.2	6	0.1	-0.7	,	0.8	0.2	5	0.827
On-Peak	0.3	0.5	6	0.5	1.0	6	0.2	-0.5	,	0.8	0.7	5	0.525
Off-Peak	2.7	2.9	6	2.4	2.4	6	-0.3	-1.0	,	0.4	-1.2	5	0.296
Mid-Peak	0.4	0.5	6	0.6	0.9	6	0.2	-0.2	,	0.6	1.4	5	0.234

Time Period

13. Appendix D: Chapter 5 - Household total and Air Conditioning consumption in comparison to CDDs

Table 54 Household total and air conditioning (AC) consumption in comparison to CDDs, base and monitoring period, source: (Environment, 2015)

Year	Number of CDDs in the study period	Total Average consumption	Average AC consumption	Average Total / CDDs	Average AC/CDDs
2013	274	543.87	182.29	1.98	0.67
2014	214.9	526.76	128.94	2.45	0.60

14. Appendix E: Chapter 5 - Results tables for 10-week autumn

Table 55 Whole-house consumption paired t-test outcomes, 10-week autumn period, average weekly kWh

Pair	Time Period						Mean Difference	95% CI for Mean Difference			t	df	*p*
	Base Period			Monitoring Period									
	M	SD	n	M	SD	n							
Total	181.7	62.8	14	166.8	57.0	14	-14.9	-35.9	,	6.0	-1.5	13	0.148
On-Peak	28.7	10.9	14	26.3	9.4	14	-2.5	-6.0	,	1.1	-1.5	13	0.157
Off-Peak	124.0	44.5	14	114.3	39.5	14	-9.7	-25.0	,	5.5	-1.4	13	0.191
Mid-Peak	29.0	10.1	14	26.2	8.7	14	-2.7	-6.5	,	1.1	-1.6	13	0.143

Table 56 Cooking consumption paired t-test outcomes, 10-week autumn period, average weekly kWh

Pair	Time Period						Mean Difference	95% CI for Mean Difference			t	df	*p*
	Base Period			Monitoring Period									
	M	SD	n	M	SD	n							
Total	4.6	3.6	13	4.8	3.0	13	0.1	-1.8	,	2.1	0.2	12	0.870
On-Peak	0.9	0.9	13	1.0	0.9	13	0.0	-0.3	,	0.4	0.3	12	0.806
Off-Peak	2.5	2.1	13	2.7	1.7	13	0.2	-1.0	,	1.4	0.4	12	0.687
Mid-Peak	1.2	1.2	13	1.1	0.8	13	-0.1	-0.6	,	0.4	-0.5	12	0.608

Table 57 Entertainment consumption paired t-test outcomes, 10-week autumn period, average weekly kWh

Pair	Time Period						Mean Difference	95% CI for Mean Difference			t	df	*p*
	Base Period			Monitoring Period									
	M	SD	n	M	SD	n							
Total	27.1	28.5	8	22.1	23.0	8	-5.0	-10.8	,	0.9	-2.0	7	0.085
On-Peak	4.6	5.2	8	3.6	4.0	8	-0.9	-2.1	,	0.2	-1.9	7	0.102
Off-Peak	18.1	18.3	8	14.8	15.0	8	-3.3	-7.0	,	0.5	-2.1	7	0.076
Mid-Peak	4.4	5.0	8	3.7	4.0	8	-0.7	-1.8	,	0.4	-1.5	7	0.174

Table 58 Dishwashing consumption paired t-test outcomes, 10-week autumn period, average weekly kWh

Pair	Time Period						Mean Difference	95% CI for Mean Difference					
	Base Period			Monitoring Period									
	M	SD	n	M	SD	n					t	df	*p*
Total	5.7	9.5	11	5.8	10.1	11	0.1	-0.4	,	0.6	0.44	10	0.673
On-Peak	0.9	1.9	11	1.0	2.5	11	0.2	-0.2	,	0.6	0.98	10	0.351
Off-Peak	3.7	5.1	11	3.9	5.5	11	0.1	-0.3	,	0.5	0.71	10	0.496
Mid-Peak	1.1	2.6	11	0.9	2.2	11	-0.2	-0.5	,	0.1	-1.72	10	0.116

15. Appendix F: Chapter 6 - Summary of thermo-behavioural segments

Table 59 Summary of thermo-behavioural segments, IHD recipients, Chapter 6

Cluster	Heating activation threshold (avg °C)	Heating gradient (avg kW/°C)	Cooling activation threshold (avg °C)	Cooling gradient (avg kW/°C)	Cluster Size
Cooling, 1, 1			22.17	0.215	1
Cooling, 1, 2			18.84	0.214	11
Cooling, 1, 3			20.25	0.180	19
Cooling, 1, 4			20.88	0.157	19
Cooling, 1, 5			20.24	0.179	47
Cooling, 1, 6			20.40	0.172	14
Cooling, 2, 1			22.72	0.031	1
Cooling, 2, 2			23.80	0.161	2
Cooling, 2, 3			24.56	0.104	72
Cooling, 2, 4			24.79	0.116	47
Cooling, 2, 5			24.93	0.128	51
Cooling, 2, 6			24.70	0.100	28
Cooling, 3, 2			23.16	0.291	3
Cooling, 3, 3			25.64	0.300	15
Cooling, 3, 4			24.73	0.244	15
Cooling, 3, 5			25.41	0.283	39
Cooling, 3, 6			25.94	0.275	9
Cooling, 4, 1			20.41	0.067	1
Cooling, 4, 2			17.84	0.082	9
Cooling, 4, 3			18.61	0.066	84
Cooling, 4, 4			18.56	0.067	28
Cooling, 4, 5			17.81	0.081	42
Cooling, 4, 6			17.95	0.066	21
Heating, 1, 1	14.24	0.174			93
Heating, 1, 2	9.60	0.179			3
Heating, 1, 3	12.51	0.171			24
Heating, 1, 4	12.84	0.168			28
Heating, 1, 5	12.58	0.173			35
Heating, 1, 6	13.18	0.163			62
Heating, 2, 1	16.24	0.037			77
Heating, 2, 2	15.83	0.027			2

Heating, 2, 3	15.19	0.019			90
Heating, 2, 4	15.64	0.024			109
Heating, 2, 5	15.87	0.025			53
Heating, 2, 6	15.78	0.028			148
Heating, 3, 1	14.79	0.090			205
Heating, 3, 2	14.44	0.087			2
Heating, 3, 3	13.72	0.082			48
Heating, 3, 4	13.94	0.084			100
Heating, 3, 5	14.03	0.090			35
Heating, 3, 6	14.03	0.091			149
Heating, 4, 1	9.58	0.072			42
Heating, 4, 2	7.35	0.055			5
Heating, 4, 3	8.15	0.041			100
Heating, 4, 4	8.35	0.044			66
Heating, 4, 5	8.04	0.062			58
Heating, 4, 6	8.80	0.048			63
Heating/Cooling, 1, 1	14.98	0.131	24.34	0.097	32
Heating/Cooling, 1, 2	9.64	0.155	23.23	0.212	17
Heating/Cooling, 1, 3	11.56	0.151	24.00	0.136	34
Heating/Cooling, 1, 4	12.32	0.138	24.16	0.122	48
Heating/Cooling, 1, 5	10.81	0.143	23.47	0.155	77
Heating/Cooling, 1, 6	12.23	0.128	24.12	0.110	33
Heating/Cooling, 2, 1	14.43	0.042	18.17	0.071	14
Heating/Cooling, 2, 2	11.59	0.040	18.39	0.139	13
Heating/Cooling, 2, 3	12.11	0.025	18.88	0.072	89
Heating/Cooling, 2, 4	12.80	0.020	19.27	0.083	65
Heating/Cooling, 2, 5	12.61	0.026	18.41	0.108	75
Heating/Cooling, 2, 6	12.99	0.019	18.77	0.087	78
Heating/Cooling, 3, 1	15.16	0.042	24.19	0.147	42
Heating/Cooling, 3, 2	12.47	0.035	21.44	0.284	10
Heating/Cooling, 3, 3	14.03	0.024	23.61	0.140	98
Heating/Cooling, 3, 4	13.94	0.026	23.69	0.151	133
Heating/Cooling, 3, 5	13.99	0.028	23.09	0.186	99
Heating/Cooling, 3, 6	14.29	0.025	23.62	0.173	133
Heating/Cooling, 4, 1	9.28	0.041	22.99	0.098	14
Heating/Cooling, 4, 2	5.96	0.036	19.92	0.147	5
Heating/Cooling, 4, 3	7.70	0.037	22.11	0.094	168
Heating/Cooling, 4, 4	8.08	0.035	22.39	0.103	130
Heating/Cooling, 4, 5	7.29	0.040	21.57	0.145	105

Heating/Cooling, 4, 6	7.98	0.036	22.53	0.108	99
NonThermal, 1, 1					16
NonThermal, 1, 2					117
NonThermal, 1, 3					558
NonThermal, 1, 4					208
NonThermal, 1, 5					431
NonThermal, 1, 6					158

16. Appendix G: Chapter 6 - Influence of IHD on all Thermo-behavioural clusters

Table 60 IHD effect on thermo-behavioural clusters, overall consumption, (estimate in hourly kWh). * is significant where *p*<0.05

Cluster	Period	Estimate	Standard Error	*p*
Cooling 1,1	Overall	0.2109	0.0051*	0.0000
Cooling 1,2	Overall	-0.1872	0.1477	0.2050
Cooling 1,3	Overall	0.0545	0.0636	0.3920
Cooling 1,4	Overall	0.0196	0.0236	0.4070
Cooling 1,5	Overall	-0.0261	0.0467	0.5760
Cooling 1,6	Overall	0.0144	0.0328	0.6610
Cooling 2,1	Overall	-0.0150	0.0051*	0.0030
Cooling 2,2	Overall	-0.0635	0.0375	0.0900
Cooling 2,3	Overall	0.0466	0.0209*	0.0260
Cooling 2,4	Overall	-0.0097	0.0181	0.5910
Cooling 2,5	Overall	-0.0551	0.0394	0.1630
Cooling 2,6	Overall	0.0017	0.0370	0.9630
Cooling 3,2	Overall	-0.4915	0.2627	0.0610
Cooling 3,3	Overall	-0.0156	0.0453	0.7300
Cooling 3,4	Overall	-0.0221	0.0613	0.7180
Cooling 3,5	Overall	-0.0450	0.0444	0.3110
Cooling 3,6	Overall	0.0391	0.0277	0.1570
Cooling 4,1	Overall	-0.1889	0.0051*	0.0000
Cooling 4,2	Overall	-0.0591	0.1348	0.6610
Cooling 4,3	Overall	0.0638	0.0238*	0.0070
Cooling 4,4	Overall	0.0852	0.0641	0.1840
Cooling 4,5	Overall	0.1319	0.0342*	0.0000
Cooling 4,6	Overall	0.0662	0.0592	0.2630
Heating 1,1	Overall	-0.0965	0.0473*	0.0410
Heating 1,2	Overall	-0.1144	0.5255	0.8280
Heating 1,3	Overall	0.0106	0.0988	0.9150
Heating 1,4	Overall	-0.0550	0.1086	0.6130
Heating 1,5	Overall	-0.1381	0.0688*	0.0450
Heating 1,6	Overall	-0.0833	0.0628	0.1850
Heating 2,1	Overall	-0.0099	0.0183	0.5870
Heating 2,2	Overall	0.1169	0.1956	0.5500
Heating 2,3	Overall	0.0278	0.0200	0.1650
Heating 2,4	Overall	-0.0064	0.0199	0.7470
Heating 2,5	Overall	-0.0797	0.0319*	0.0130
Heating 2,6	Overall	-0.0242	0.0186	0.1930
Heating 3,1	Overall	-0.0473	0.0215*	0.0280
Heating 3,2	Overall	-0.5484	0.4350	0.2070
Heating 3,3	Overall	0.1256	0.0505*	0.0130
Heating 3,4	Overall	0.0083	0.0286	0.7700
Heating 3,5	Overall	-0.1487	0.0755*	0.0490
Heating 3,6	Overall	0.0415	0.0260	0.1100
Heating 4,1	Overall	0.0596	0.0441	0.1770
Heating 4,2	Overall	0.0763	0.2046	0.7090
Heating 4,3	Overall	0.1449	0.0308*	0.0000
Heating 4,4	Overall	0.0839	0.0466	0.0710
Heating 4,5	Overall	0.0938	0.0518	0.0700
Heating 4,6	Overall	0.1445	0.0365*	0.0000
Heating/Cooling 1,1	Overall	-0.0678	0.0785	0.3880

Heating/Cooling 1,2	Overall	-0.1377	0.1515	0.3640
Heating/Cooling 1,3	Overall	-0.0832	0.0937	0.3740
Heating/Cooling 1,4	Overall	0.0159	0.0290	0.5830
Heating/Cooling 1,5	Overall	-0.1157	0.0584*	0.0480
Heating/Cooling 1,6	Overall	-0.0885	0.0525	0.0920
Heating/Cooling2,1	Overall	-0.0116	0.0335	0.7290
Heating/Cooling2,2	Overall	-0.4722	0.1899*	0.0130
Heating/Cooling2,3	Overall	0.0410	0.0246	0.0960
Heating/Cooling2,4	Overall	0.0165	0.0239	0.4880
Heating/Cooling2,5	Overall	-0.0373	0.0358	0.2980
Heating/Cooling2,6	Overall	0.0265	0.0223	0.2350
Heating/Cooling3,1	Overall	0.0292	0.0428	0.4960
Heating/Cooling3,2	Overall	-0.0885	0.1324	0.5040
Heating/Cooling3,3	Overall	0.0014	0.0201	0.9450
Heating/Cooling3,4	Overall	-0.0257	0.0163	0.1150
Heating/Cooling3,5	Overall	-0.0522	0.0277	0.0600
Heating/Cooling3,6	Overall	0.0171	0.0183	0.3520
Heating/Cooling 4,1	Overall	0.0460	0.0263	0.0800
Heating/Cooling 4,2	Overall	0.1831	0.1421	0.1970
Heating/Cooling 4,3	Overall	0.0716	0.0220*	0.0010
Heating/Cooling 4,4	Overall	0.0149	0.0149	0.3170
Heating/Cooling 4,5	Overall	-0.0045	0.0211	0.8320
Heating/Cooling 4,6	Overall	0.0496	0.0221*	0.0250
NonThermal 1,1	Overall	0.0008	0.0224	0.9730
NonThermal 1,2	Overall	-0.1385	0.0535*	0.0100
NonThermal 1,3	Overall	0.0735	0.0137*	0.0000
NonThermal 1,4	Overall	0.0175	0.0129	0.1740
NonThermal 1,5	Overall	-0.0524	0.0173*	0.0020
NonThermal 1,6	Overall	-0.0007	0.0180	0.9700

$R^2 = 0.669$

Table 61 IHD effect on thermo-behavioural clusters, day type consumption, (estimate in hourly kWh). * is significant where *p*<0.05

Cluster	Period	Estimate	Standard Error	*p*
Cooling 1,1	Weekday	0.2000	0.0052*	0.0000
Cooling 1,2	Weekday	-0.1847	0.1561	0.2370
Cooling 1,3	Weekday	0.0624	0.0636	0.3270
Cooling 1,4	Weekday	0.0221	0.0239	0.3570
Cooling 1,5	Weekday	-0.0197	0.0465	0.6710
Cooling 1,6	Weekday	0.0215	0.0370	0.5610
Cooling 2,1	Weekday	0.0110	0.0052*	0.0330
Cooling 2,2	Weekday	-0.0744	0.0520	0.1530
Cooling 2,3	Weekday	0.0483	0.0210*	0.0210
Cooling 2,4	Weekday	-0.0103	0.0176	0.5590
Cooling 2,5	Weekday	-0.0590	0.0386	0.1270
Cooling 2,6	Weekday	0.0032	0.0374	0.9310
Cooling 3,2	Weekday	-0.4712	0.2672	0.0780
Cooling 3,3	Weekday	-0.0189	0.0481	0.6950
Cooling 3,4	Weekday	-0.0180	0.0597	0.7640
Cooling 3,5	Weekday	-0.0415	0.0451	0.3580
Cooling 3,6	Weekday	0.0394	0.0276	0.1530
Cooling 4,1	Weekday	-0.2623	0.0052*	0.0000
Cooling 4,2	Weekday	-0.0577	0.1383	0.6770
Cooling 4,3	Weekday	0.0700	0.0236*	0.0030
Cooling 4,4	Weekday	0.0836	0.0615	0.1740
Cooling 4,5	Weekday	0.1403	0.0347*	0.0000
Cooling 4,6	Weekday	0.0636	0.0619	0.3050
Heating 1,1	Weekday	-0.1124	0.0468*	0.0160
Heating 1,2	Weekday	-0.1207	0.5156	0.8150
Heating 1,3	Weekday	0.0033	0.0973	0.9730
Heating 1,4	Weekday	-0.0584	0.1093	0.5930
Heating 1,5	Weekday	-0.1436	0.0703*	0.0410
Heating 1,6	Weekday	-0.0930	0.0637	0.1450
Heating 2,1	Weekday	-0.0099	0.0189	0.6000
Heating 2,2	Weekday	0.1617	0.2005	0.4200
Heating 2,3	Weekday	0.0307	0.0207	0.1370
Heating 2,4	Weekday	-0.0108	0.0197	0.5830
Heating 2,5	Weekday	-0.0838	0.0321*	0.0090
Heating 2,6	Weekday	-0.0212	0.0183	0.2490
Heating 3,1	Weekday	-0.0601	0.0215*	0.0050
Heating 3,2	Weekday	-0.5288	0.4395	0.2290
Heating 3,3	Weekday	0.1188	0.0500*	0.0170
Heating 3,4	Weekday	0.0025	0.0288	0.9300
Heating 3,5	Weekday	-0.1499	0.0758*	0.0480
Heating 3,6	Weekday	0.0404	0.0259	0.1190
Heating 4,1	Weekday	0.0599	0.0437	0.1700
Heating 4,2	Weekday	0.1324	0.1935	0.4940
Heating 4,3	Weekday	0.1486	0.0309*	0.0000
Heating 4,4	Weekday	0.0865	0.0470	0.0660
Heating 4,5	Weekday	0.0984	0.0522	0.0590
Heating 4,6	Weekday	0.1456	0.0365*	0.0000
Heating/Cooling 1,1	Weekday	-0.0841	0.0783	0.2820
Heating/Cooling 1,2	Weekday	-0.1444	0.1499	0.3350
Heating/Cooling 1,3	Weekday	-0.0998	0.0939	0.2880
Heating/Cooling 1,4	Weekday	0.0028	0.0302	0.9270
Heating/Cooling 1,5	Weekday	-0.1175	0.0581*	0.0430
Heating/Cooling 1,6	Weekday	-0.0897	0.0514	0.0810

Heating/Cooling2,1	Weekday	-0.0118	0.0364	0.7470
Heating/Cooling2,2	Weekday	-0.4640	0.1906*	0.0150
Heating/Cooling2,3	Weekday	0.0435	0.0245	0.0750
Heating/Cooling2,4	Weekday	0.0142	0.0254	0.5750
Heating/Cooling2,5	Weekday	-0.0396	0.0358	0.2690
Heating/Cooling2,6	Weekday	0.0352	0.0232	0.1300
Heating/Cooling3,1	Weekday	0.0195	0.0433	0.6530
Heating/Cooling3,2	Weekday	-0.0557	0.1393	0.6890
Heating/Cooling3,3	Weekday	0.0040	0.0202	0.8430
Heating/Cooling3,4	Weekday	-0.0245	0.0163	0.1320
Heating/Cooling3,5	Weekday	-0.0490	0.0283	0.0840
Heating/Cooling3,6	Weekday	0.0200	0.0187	0.2860
Heating/Cooling 4,1	Weekday	0.0514	0.0259*	0.0470
Heating/Cooling 4,2	Weekday	0.2025	0.1437	0.1590
Heating/Cooling 4,3	Weekday	0.0740	0.0218*	0.0010
Heating/Cooling 4,4	Weekday	0.0159	0.0148	0.2830
Heating/Cooling 4,5	Weekday	0.0001	0.0209	0.9960
Heating/Cooling 4,6	Weekday	0.0534	0.0220*	0.0150
NonThermal 1,1	Weekday	-0.0024	0.0203	0.9060
NonThermal 1,2	Weekday	-0.1286	0.0547*	0.0190
NonThermal 1,3	Weekday	0.0749	0.0138*	0.0000
NonThermal 1,4	Weekday	0.0157	0.0130	0.2280
NonThermal 1,5	Weekday	-0.0539	0.0174*	0.0020
NonThermal 1,6	Weekday	0.0005	0.0181	0.9770
Cooling 1,1	Weekend	0.2382	0.0051*	0.0000
Cooling 1,2	Weekend	-0.1932	0.1306	0.1390
Cooling 1,3	Weekend	0.0348	0.0648	0.5910
Cooling 1,4	Weekend	0.0134	0.0258	0.6030
Cooling 1,5	Weekend	-0.0421	0.0510	0.4090
Cooling 1,6	Weekend	-0.0034	0.0354	0.9230
Cooling 2,1	Weekend	-0.0798	0.0051*	0.0000
Cooling 2,2	Weekend	-0.0362	0.0052*	0.0000
Cooling 2,3	Weekend	0.0421	0.0216	0.0510
Cooling 2,4	Weekend	-0.0083	0.0228	0.7150
Cooling 2,5	Weekend	-0.0453	0.0437	0.3000
Cooling 2,6	Weekend	-0.0020	0.0378	0.9570
Cooling 3,2	Weekend	-0.5421	0.2521*	0.0310
Cooling 3,3	Weekend	-0.0074	0.0415	0.8570
Cooling 3,4	Weekend	-0.0326	0.0675	0.6300
Cooling 3,5	Weekend	-0.0539	0.0442	0.2230
Cooling 3,6	Weekend	0.0385	0.0290	0.1840
Cooling 4,1	Weekend	-0.0062	0.0051	0.2270
Cooling 4,2	Weekend	-0.0626	0.1331	0.6380
Cooling 4,3	Weekend	0.0482	0.0249	0.0530
Cooling 4,4	Weekend	0.0892	0.0714	0.2120
Cooling 4,5	Weekend	0.1111	0.0366*	0.0020
Cooling 4,6	Weekend	0.0729	0.0571	0.2010
Heating 1,1	Weekend	-0.0568	0.0495	0.2510
Heating 1,2	Weekend	-0.0986	0.5509	0.8580
Heating 1,3	Weekend	0.0286	0.1049	0.7850
Heating 1,4	Weekend	-0.0465	0.1078	0.6670
Heating 1,5	Weekend	-0.1243	0.0688	0.0710
Heating 1,6	Weekend	-0.0592	0.0619	0.3390
Heating 2,1	Weekend	-0.0100	0.0191	0.6020
Heating 2,2	Weekend	0.0057	0.1835	0.9750
Heating 2,3	Weekend	0.0204	0.0195	0.2960
Heating 2,4	Weekend	0.0045	0.0219	0.8380
Heating 2,5	Weekend	-0.0695	0.0344*	0.0430

Heating 2,6	Weekend	-0.0319	0.0205	0.1200
Heating 3,1	Weekend	-0.0156	0.0227	0.4920
Heating 3,2	Weekend	-0.5972	0.4239	0.1590
Heating 3,3	Weekend	0.1425	0.0529*	0.0070
Heating 3,4	Weekend	0.0228	0.0290	0.4320
Heating 3,5	Weekend	-0.1456	0.0763	0.0560
Heating 3,6	Weekend	0.0444	0.0272	0.1020
Heating 4,1	Weekend	0.0589	0.0470	0.2110
Heating 4,2	Weekend	-0.0633	0.2401	0.7920
Heating 4,3	Weekend	0.1355	0.0320*	0.0000
Heating 4,4	Weekend	0.0777	0.0459	0.0910
Heating 4,5	Weekend	0.0823	0.0528	0.1190
Heating 4,6	Weekend	0.1419	0.0381*	0.0000
Heating/Cooling 1,1	Weekend	-0.0271	0.0804	0.7360
Heating/Cooling 1,2	Weekend	-0.1209	0.1581	0.4450
Heating/Cooling 1,3	Weekend	-0.0420	0.0936	0.6530
Heating/Cooling 1,4	Weekend	0.0488	0.0282	0.0840
Heating/Cooling 1,5	Weekend	-0.1113	0.0602	0.0650
Heating/Cooling 1,6	Weekend	-0.0854	0.0600	0.1540
Heating/Cooling 2,1	Weekend	-0.0112	0.0303	0.7100
Heating/Cooling 2,2	Weekend	-0.4928	0.2009*	0.0140
Heating/Cooling 2,3	Weekend	0.0346	0.0259	0.1810
Heating/Cooling 2,4	Weekend	0.0223	0.0246	0.3640
Heating/Cooling 2,5	Weekend	-0.0316	0.0381	0.4080
Heating/Cooling 2,6	Weekend	0.0049	0.0222	0.8260
Heating/Cooling 3,1	Weekend	0.0533	0.0440	0.2250
Heating/Cooling 3,2	Weekend	-0.1699	0.1196	0.1550
Heating/Cooling 3,3	Weekend	-0.0051	0.0208	0.8080
Heating/Cooling 3,4	Weekend	-0.0286	0.0173	0.0970
Heating/Cooling 3,5	Weekend	-0.0603	0.0277*	0.0290
Heating/Cooling 3,6	Weekend	0.0099	0.0188	0.6000
Heating/Cooling 4,1	Weekend	0.0325	0.0298	0.2740
Heating/Cooling 4,2	Weekend	0.1350	0.1389	0.3310
Heating/Cooling 4,3	Weekend	0.0657	0.0229*	0.0040
Heating/Cooling 4,4	Weekend	0.0125	0.0161	0.4370
Heating/Cooling 4,5	Weekend	-0.0158	0.0235	0.5000
Heating/Cooling 4,6	Weekend	0.0399	0.0236	0.0910
NonThermal 1,1	Weekend	0.0086	0.0417	0.8370
NonThermal 1,2	Weekend	-0.1630	0.0531*	0.0020
NonThermal 1,3	Weekend	0.0701	0.0139*	0.0000
NonThermal 1,4	Weekend	0.0222	0.0137	0.1060
NonThermal 1,5	Weekend	-0.0487	0.0178*	0.0060
NonThermal 1,6	Weekend	-0.0036	0.0189	0.8470

$R^2 = 0.669$

Table 62 IHD effect on thermo-behavioural clusters, TOU consumption, (estimate in hourly kWh). * is significant where $p<0.05$

Cluster	Period	Estimate	Standard Error	*p*
Cooling 1,1	Mid-Peak	0.3469	0.0055*	0.0000
Cooling 1,2	Mid-Peak	-0.2529	0.1965	0.1980
Cooling 1,3	Mid-Peak	0.0788	0.0639	0.2170
Cooling 1,4	Mid-Peak	0.0308	0.0309	0.3190
Cooling 1,5	Mid-Peak	-0.0169	0.0488	0.7290
Cooling 1,6	Mid-Peak	0.0578	0.0460	0.2100
Cooling 2,1	Mid-Peak	0.0161	0.0055*	0.0030
Cooling 2,2	Mid-Peak	-0.1859	0.0195*	0.0000
Cooling 2,3	Mid-Peak	0.0515	0.0208*	0.0130
Cooling 2,4	Mid-Peak	-0.0411	0.0225	0.0680
Cooling 2,5	Mid-Peak	-0.0676	0.0396	0.0880
Cooling 2,6	Mid-Peak	0.0072	0.0366	0.8440
Cooling 3,2	Mid-Peak	-0.4498	0.2172*	0.0380
Cooling 3,3	Mid-Peak	0.0083	0.0579	0.8860
Cooling 3,4	Mid-Peak	-0.0559	0.0699	0.4240
Cooling 3,5	Mid-Peak	-0.0661	0.0497	0.1830
Cooling 3,6	Mid-Peak	0.0744	0.0368*	0.0430
Cooling 4,1	Mid-Peak	-0.4563	0.0055*	0.0000
Cooling 4,2	Mid-Peak	-0.1057	0.1575	0.5020
Cooling 4,3	Mid-Peak	0.0914	0.0246*	0.0000
Cooling 4,4	Mid-Peak	0.0886	0.0701	0.2060
Cooling 4,5	Mid-Peak	0.1348	0.0393*	0.0010
Cooling 4,6	Mid-Peak	0.0889	0.0673	0.1870
Heating 1,1	Mid-Peak	-0.1699	0.0444*	0.0000
Heating 1,2	Mid-Peak	-0.1426	0.3462	0.6800
Heating 1,3	Mid-Peak	0.1224	0.0984	0.2130
Heating 1,4	Mid-Peak	-0.0856	0.1068	0.4230
Heating 1,5	Mid-Peak	-0.1436	0.0666*	0.0310
Heating 1,6	Mid-Peak	0.0657	0.0684	0.3370
Heating 2,1	Mid-Peak	-0.0321	0.0224	0.1520
Heating 2,2	Mid-Peak	0.1401	0.2548	0.5820
Heating 2,3	Mid-Peak	0.0550	0.0216*	0.0110
Heating 2,4	Mid-Peak	-0.0418	0.0222	0.0600
Heating 2,5	Mid-Peak	-0.1182	0.0339*	0.0000
Heating 2,6	Mid-Peak	-0.0117	0.0192	0.5410
Heating 3,1	Mid-Peak	-0.1034	0.0224*	0.0000
Heating 3,2	Mid-Peak	-0.4545	0.4163	0.2750
Heating 3,3	Mid-Peak	0.2282	0.0538*	0.0000
Heating 3,4	Mid-Peak	-0.0330	0.0319	0.3010
Heating 3,5	Mid-Peak	-0.1689	0.0728*	0.0200
Heating 3,6	Mid-Peak	0.1323	0.0296*	0.0000
Heating 4,1	Mid-Peak	0.0426	0.0502	0.3960
Heating 4,2	Mid-Peak	0.0948	0.1367	0.4880
Heating 4,3	Mid-Peak	0.1808	0.0306*	0.0000
Heating 4,4	Mid-Peak	0.0865	0.0619	0.1620
Heating 4,5	Mid-Peak	0.0920	0.0550*	0.0940
Heating 4,6	Mid-Peak	0.1591	0.0398*	0.0000
Heating/Cooling 1,1	Mid-Peak	-0.1253	0.0865	0.1470
Heating/Cooling 1,2	Mid-Peak	-0.2014	0.1477	0.1730
Heating/Cooling 1,3	Mid-Peak	-0.0791	0.0803	0.3250
Heating/Cooling 1,4	Mid-Peak	-0.0717	0.0369	0.0520
Heating/Cooling 1,5	Mid-Peak	-0.1092	0.0525*	0.0380
Heating/Cooling 1,6	Mid-Peak	-0.0429	0.0500	0.3920

Heating/Cooling2,1	Mid-Peak	-0.0130	0.0570	0.8190
Heating/Cooling2,2	Mid-Peak	-0.4836	0.2087*	0.0200
Heating/Cooling2,3	Mid-Peak	0.0546	0.0242*	0.0240
Heating/Cooling2,4	Mid-Peak	-0.0093	0.0317	0.7690
Heating/Cooling2,5	Mid-Peak	-0.0518	0.0366	0.1570
Heating/Cooling2,6	Mid-Peak	0.0605	0.0260*	0.0200
Heating/Cooling3,1	Mid-Peak	-0.0159	0.0499	0.7500
Heating/Cooling3,2	Mid-Peak	-0.1105	0.1663	0.5060
Heating/Cooling3,3	Mid-Peak	0.0274	0.0213	0.1990
Heating/Cooling3,4	Mid-Peak	-0.0386	0.0185*	0.0360
Heating/Cooling3,5	Mid-Peak	-0.0450	0.0326	0.1670
Heating/Cooling3,6	Mid-Peak	0.0277	0.0203	0.1740
Heating/Cooling 4,1	Mid-Peak	0.0650	0.0319*	0.0420
Heating/Cooling 4,2	Mid-Peak	0.1780	0.1377	0.1960
Heating/Cooling 4,3	Mid-Peak	0.0869	0.0217*	0.0000
Heating/Cooling 4,4	Mid-Peak	0.0000	0.0161	0.9980
Heating/Cooling 4,5	Mid-Peak	-0.0124	0.0248	0.6160
Heating/Cooling 4,6	Mid-Peak	0.0680	0.0231*	0.0030
NonThermal 1,1	Mid-Peak	-0.0215	0.0322	0.5040
NonThermal 1,2	Mid-Peak	-0.0993	0.0558	0.0750
NonThermal 1,3	Mid-Peak	0.0862	0.0139*	0.0000
NonThermal 1,4	Mid-Peak	-0.0027	0.0152	0.8600
NonThermal 1,5	Mid-Peak	-0.0779	0.0181*	0.0000
NonThermal 1,6	Mid-Peak	0.0074	0.0185	0.6900
Cooling 1,1	Off-Peak	0.2020	0.0050*	0.0000
Cooling 1,2	Off-Peak	-0.1554	0.1201	0.1960
Cooling 1,3	Off-Peak	0.0493	0.0655	0.4520
Cooling 1,4	Off-Peak	0.0185	0.0209	0.3750
Cooling 1,5	Off-Peak	-0.0325	0.0459	0.4780
Cooling 1,6	Off-Peak	-0.0192	0.0279	0.4910
Cooling 2,1	Off-Peak	-0.0496	0.0050*	0.0000
Cooling 2,2	Off-Peak	-0.0048	0.0475	0.9200
Cooling 2,3	Off-Peak	0.0412	0.0206*	0.0460
Cooling 2,4	Off-Peak	-0.0018	0.0182	0.9230
Cooling 2,5	Off-Peak	-0.0615	0.0389	0.1140
Cooling 2,6	Off-Peak	-0.0103	0.0362	0.7750
Cooling 3,2	Off-Peak	-0.4534	0.2710	0.0940
Cooling 3,3	Off-Peak	-0.0202	0.0399	0.6130
Cooling 3,4	Off-Peak	-0.0062	0.0651	0.9240
Cooling 3,5	Off-Peak	-0.0482	0.0423	0.2540
Cooling 3,6	Off-Peak	0.0024	0.0292	0.9350
Cooling 4,1	Off-Peak	-0.0817	0.0050*	0.0000
Cooling 4,2	Off-Peak	-0.0382	0.1326	0.7730
Cooling 4,3	Off-Peak	0.0432	0.0232	0.0630
Cooling 4,4	Off-Peak	0.0835	0.0612	0.1720
Cooling 4,5	Off-Peak	0.1160	0.0327*	0.0000
Cooling 4,6	Off-Peak	0.0463	0.0548	0.3980
Heating 1,1	Off-Peak	-0.0616	0.0482	0.2010
Heating 1,2	Off-Peak	-0.0698	0.6111	0.9090
Heating 1,3	Off-Peak	0.0015	0.1071	0.9890
Heating 1,4	Off-Peak	-0.0295	0.1088	0.7870
Heating 1,5	Off-Peak	-0.1448	0.0697*	0.0380
Heating 1,6	Off-Peak	-0.0989	0.0654	0.1300
Heating 2,1	Off-Peak	-0.0001	0.0180	0.9970
Heating 2,2	Off-Peak	0.0342	0.1517	0.8220
Heating 2,3	Off-Peak	0.0079	0.0191	0.6800
Heating 2,4	Off-Peak	0.0097	0.0204	0.6340
Heating 2,5	Off-Peak	-0.0718	0.0325*	0.0270

Heating 2,6	Off-Peak	-0.0358	0.0188	0.0580
Heating 3,1	Off-Peak	-0.0138	0.0212	0.5170
Heating 3,2	Off-Peak	-0.5626	0.4359	0.1970
Heating 3,3	Off-Peak	0.1085	0.0498*	0.0290
Heating 3,4	Off-Peak	0.0247	0.0274	0.3680
Heating 3,5	Off-Peak	-0.1434	0.0754	0.0570
Heating 3,6	Off-Peak	0.0233	0.0263	0.3770
Heating 4,1	Off-Peak	0.0779	0.0415	0.0610
Heating 4,2	Off-Peak	0.0413	0.2438	0.8650
Heating 4,3	Off-Peak	0.1231	0.0303*	0.0000
Heating 4,4	Off-Peak	0.0731	0.0371*	0.0490
Heating 4,5	Off-Peak	0.0889	0.0509	0.0810
Heating 4,6	Off-Peak	0.1422	0.0362*	0.0000
Heating/Cooling 1,1	Off-Peak	-0.0403	0.0728	0.5790
Heating/Cooling 1,2	Off-Peak	-0.0935	0.1529	0.5410
Heating/Cooling 1,3	Off-Peak	-0.0815	0.0989	0.4100
Heating/Cooling 1,4	Off-Peak	0.0411	0.0296	0.1650
Heating/Cooling 1,5	Off-Peak	-0.1149	0.0605	0.0580
Heating/Cooling 1,6	Off-Peak	-0.1096	0.0567	0.0530
Heating/Cooling2,1	Off-Peak	-0.0125	0.0280	0.6550
Heating/Cooling2,2	Off-Peak	-0.4983	0.1780*	0.0050
Heating/Cooling2,3	Off-Peak	0.0307	0.0260	0.2380
Heating/Cooling2,4	Off-Peak	0.0274	0.0209	0.1910
Heating/Cooling2,5	Off-Peak	-0.0202	0.0379	0.5940
Heating/Cooling2,6	Off-Peak	0.0047	0.0208	0.8200
Heating/Cooling3,1	Off-Peak	0.0418	0.0399	0.2950
Heating/Cooling3,2	Off-Peak	-0.1042	0.1234	0.3980
Heating/Cooling3,3	Off-Peak	-0.0122	0.0200	0.5420
Heating/Cooling3,4	Off-Peak	-0.0207	0.0152	0.1740
Heating/Cooling3,5	Off-Peak	-0.0643	0.0262*	0.0140
Heating/Cooling3,6	Off-Peak	0.0079	0.0176	0.6540
Heating/Cooling 4,1	Off-Peak	0.0277	0.0235	0.2380
Heating/Cooling 4,2	Off-Peak	0.1659	0.1381	0.2300
Heating/Cooling 4,3	Off-Peak	0.0591	0.0215*	0.0060
Heating/Cooling 4,4	Off-Peak	0.0196	0.0144	0.1740
Heating/Cooling 4,5	Off-Peak	-0.0073	0.0220	0.7420
Heating/Cooling 4,6	Off-Peak	0.0340	0.0225	0.1300
NonThermal 1,1	Off-Peak	0.0203	0.0244	0.4060
NonThermal 1,2	Off-Peak	-0.1657	0.0523*	0.0020
NonThermal 1,3	Off-Peak	0.0620	0.0136*	0.0000
NonThermal 1,4	Off-Peak	0.0271	0.0122*	0.0270
NonThermal 1,5	Off-Peak	-0.0459	0.0172*	0.0080
NonThermal 1,6	Off-Peak	-0.0131	0.0181	0.4690
Cooling 1,1	On-Peak	0.0888	0.0062*	0.0000
Cooling 1,2	On-Peak	-0.2041	0.1878	0.2770
Cooling 1,3	On-Peak	0.0430	0.0687	0.5310
Cooling 1,4	On-Peak	0.0107	0.0329	0.7460
Cooling 1,5	On-Peak	-0.0179	0.0554	0.7460
Cooling 1,6	On-Peak	0.0614	0.0449	0.1710
Cooling 2,1	On-Peak	0.0480	0.0062*	0.0000
Cooling 2,2	On-Peak	-0.0940	0.0296*	0.0010
Cooling 2,3	On-Peak	0.0565	0.0251*	0.0250
Cooling 2,4	On-Peak	0.0025	0.0245	0.9200
Cooling 2,5	On-Peak	-0.0233	0.0488	0.6330
Cooling 2,6	On-Peak	0.0299	0.0471	0.5260
Cooling 3,2	On-Peak	-0.6425	0.3010*	0.0330
Cooling 3,3	On-Peak	-0.0287	0.0535	0.5920
Cooling 3,4	On-Peak	-0.0298	0.0534	0.5780

Cooling 3,5	On-Peak	-0.0131	0.0528	0.8050
Cooling 3,6	On-Peak	0.1038	0.0430*	0.0160
Cooling 4,1	On-Peak	-0.1971	0.0062*	0.0000
Cooling 4,2	On-Peak	-0.0665	0.1275	0.6020
Cooling 4,3	On-Peak	0.0915	0.0274*	0.0010
Cooling 4,4	On-Peak	0.0866	0.0702	0.2180
Cooling 4,5	On-Peak	0.1736	0.0446*	0.0000
Cooling 4,6	On-Peak	0.0976	0.0714	0.1720
Heating 1,1	On-Peak	-0.1142	0.0564*	0.0430
Heating 1,2	On-Peak	-0.2076	0.4870	0.6700
Heating 1,3	On-Peak	-0.0844	0.1288	0.5120
Heating 1,4	On-Peak	-0.0925	0.1205	0.4430
Heating 1,5	On-Peak	-0.1129	0.0789	0.1520
Heating 1,6	On-Peak	-0.2010	0.0722*	0.0050
Heating 2,1	On-Peak	-0.0131	0.0244	0.5900
Heating 2,2	On-Peak	0.3206	0.2556	0.2100
Heating 2,3	On-Peak	0.0541	0.0246*	0.0280
Heating 2,4	On-Peak	-0.0129	0.0220	0.5560
Heating 2,5	On-Peak	-0.0598	0.0367	0.1030
Heating 2,6	On-Peak	-0.0052	0.0220	0.8120
Heating 3,1	On-Peak	-0.0801	0.0268*	0.0030
Heating 3,2	On-Peak	-0.6102	0.4527	0.1780
Heating 3,3	On-Peak	0.0627	0.0756	0.4070
Heating 3,4	On-Peak	0.0078	0.0349	0.8240
Heating 3,5	On-Peak	-0.1411	0.0876	0.1070
Heating 3,6	On-Peak	-0.0057	0.0330	0.8640
Heating 4,1	On-Peak	0.0274	0.0546	0.6170
Heating 4,2	On-Peak	0.1542	0.1706	0.3660
Heating 4,3	On-Peak	0.1671	0.0358*	0.0000
Heating 4,4	On-Peak	0.1116	0.0587	0.0570
Heating 4,5	On-Peak	0.1098	0.0603	0.0690
Heating 4,6	On-Peak	0.1355	0.0415*	0.0010
Heating/Cooling 1,1	On-Peak	-0.0818	0.0930	0.3790
Heating/Cooling 1,2	On-Peak	-0.1918	0.1657	0.2470
Heating/Cooling 1,3	On-Peak	-0.0920	0.1023	0.3680
Heating/Cooling 1,4	On-Peak	0.0408	0.0376	0.2770
Heating/Cooling 1,5	On-Peak	-0.1248	0.0641	0.0520
Heating/Cooling 1,6	On-Peak	-0.0785	0.0615	0.2020
Heating/Cooling2,1	On-Peak	-0.0072	0.0494	0.8840
Heating/Cooling2,2	On-Peak	-0.3869	0.2343	0.0990
Heating/Cooling2,3	On-Peak	0.0551	0.0253*	0.0290
Heating/Cooling2,4	On-Peak	0.0147	0.0367	0.6880
Heating/Cooling2,5	On-Peak	-0.0688	0.0385	0.0740
Heating/Cooling2,6	On-Peak	0.0508	0.0278	0.0670
Heating/Cooling3,1	On-Peak	0.0428	0.0536	0.4250
Heating/Cooling3,2	On-Peak	-0.0209	0.1436	0.8840
Heating/Cooling3,3	On-Peak	0.0116	0.0225	0.6070
Heating/Cooling3,4	On-Peak	-0.0253	0.0199	0.2040
Heating/Cooling3,5	On-Peak	-0.0261	0.0337	0.4390
Heating/Cooling3,6	On-Peak	0.0316	0.0229	0.1680
Heating/Cooling 4,1	On-Peak	0.0769	0.0406	0.0580
Heating/Cooling 4,2	On-Peak	0.2367	0.1630	0.1460
Heating/Cooling 4,3	On-Peak	0.0904	0.0261*	0.0010
Heating/Cooling 4,4	On-Peak	0.0185	0.0190	0.3310
Heating/Cooling 4,5	On-Peak	0.0122	0.0235	0.6050
Heating/Cooling 4,6	On-Peak	0.0731	0.0249*	0.0030
NonThermal 1,1	On-Peak	-0.0291	0.0270	0.2800
NonThermal 1,2	On-Peak	-0.1045	0.0640	0.1020

NonThermal 1,3	On-Peak	0.0924	0.0155*	0.0000
NonThermal 1,4	On-Peak	0.0132	0.0164	0.4200
NonThermal 1,5	On-Peak	-0.0425	0.0198*	0.0320
NonThermal 1,6	On-Peak	0.0257	0.0216	0.2350

$R^2 = 0.669$