Assessing Consistency of Scenarios Across Scales

Developing globally linked internally consistent scenarios under the Shared Socioeconomic Pathways framework

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 this 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

A version of the first manuscript included in this dissertation has been accepted for publication. I, Jude Herijadi Kurniawan, was the main contributor and lead author of the work that has been published and the manuscript in preparation for publication.

The first manuscript included in this dissertation is a version of a final draft journal article entitled "Using Network Analysis to Identify Key Scenario Elements Across Multiple Energy Scenario Studies." This article was co-authored by Dr. Vanessa Jine Schweizer. Following the guidelines set forth by the University of Waterloo, this work is predominantly comprised of my intellectual contribution.

The contribution of each author was: conceptualization (JHK 80%; VJS 20%); research (JHK 95%; VJS 5%); analysis (JHK 95%; VJS 5%); writing (JHK 85%; VJS 15%).

ABSTRACT

In global environmental change research, anticipating the implications of large-scale environmental changes on local development is an important endeavour for mitigating and adapting to difficult challenges. Researchers have used multi-scale scenario analysis to anticipate future changes. Simply put, multi-scale scenario analysis is used to model cross influences between factors or drivers operating at different scales, for example, global, regional, and national levels. To ensure that scenarios are plausible, which is important for policy decisions, scenarios must be consistent across scales. However, there is confusion to what cross-scale consistency means. Consistent scenarios across scales refers to how lower level (e.g., national) scenarios should be developed considering various development pathways at the global scale that can potentially influence domestic developments. Scenario studies often use the term 'consistent' as defined by Zurek and Henrichs' (2007) linking strategies. Zurek and Henrichs (2007) categorize different strategies for linking scenarios across scales. The categorization is based on the process by which scenarios developed by different modelling teams are linked. The degree to which these scenarios are linked is characterized as *equivalent*, *consistent*, *coherent*, *comparable*, and *complimentary*—with equivalent as the strongest link, whereas complimentary as a weak or no link. Link strength is defined by how similar (or different) the scenario elements (logics, drivers, assumptions) are. Linking scenarios across scales (e.g., global and regional) should aim to be *equivalent* or *consistent* across scales; this can be achieved by quantitative downscaling. For scenarios developed in parallel, the degree to which these scenarios can be viewed as consistent depends on whether the elements in these scenarios are the same, if not similar. However, adhering to this criterion is challenging because lower level scenarios may require different scenario elements to be incorporated in the scenario development process—these elements are factors or drivers that are operating at a more localized scale. Therefore, constraining the selection of scenario elements for developing regional or national level scenarios may be impractical.

There are varying degrees of consistency of scenarios across scales much like the concept proposed by Zurek and Henrichs (2007) that spans from equivalent to complimentary. However, there is a missing 'threshold' in their framework—at what point should scenario studies be considered inconsistent. This thesis offers a re-interpretation on the concept of linking strategies by identifying the threshold for which scenarios can be considered inconsistent. In so doing, I

would argue for the need to reinterpret Zurek and Henrichs (2007) concept of linking strategies to advance scholarship in multi-scale scenario research.

This dissertation presents original research by developing an extension study on Canada's energy futures under the Shared Socioeconomic Pathway (SSP) scenario framework. The SSP framework is intended to support more detailed analyses of societal change at a more localized scale; this framework is described in thematic special issues in Climatic Change and Global Environmental Change in 2014 and 2017 respectively. The SSPs described in these special issues are the 'basic' global version; from them, 'extended' SSPs could be elaborated further for detailed regional and national analyses (O'Neill et al., 2017, 2014). The basic SSPs provide a global framing for different socioeconomic and climate change policy developments up to 2100 (O'Neill et al., 2014). The Canadian oil and gas sector interacts directly with global energy markets and is already playing a key role in driving climate change, both as a high carbon emitter and as a major exporter of fossil fuels. Given this context, a multi-scale study provides an understanding of the broader implications of global influences on Canada's low-carbon energy transition and vice-versa. According to the requirement set out in the SSP guidance note (van Ruijven et al., 2014), extension studies must be linked (or 'hooked') to the global SSPs in order to be consistent. The scientific community has developed multiple approaches for extending basic SSPs. One of the approaches is to re-specify the SSP elements. This extension study links to the SSP elements by adding elements necessary for more detailed national and sectoral analyses. Prior to developing scenarios for Canada, there is a need to identify relevant scenario elements. Identifying and prioritizing scenario elements are usually left to scenario developers' subjective interpretation of experts or stakeholder opinions. How one expresses which scenario elements are important resides in individuals' mental models, which are not accessible to others. In contrast, here candidate scenario elements are gleaned from the existing Canadian energy futures studies published in 2015 to 2016, which are then subjected to a network analysis. Network statistics can be used to more objectively identify which scenario elements are key since the method is transparent and data is accessible for public inspection (Lloyd and Schweizer, 2014). Elements identified as important by network analysis are then incorporated for multi-scale scenario analysis. Cross-impact balance (CIB) analysis (Weimer-Jehle, 2006) is used to search for scenario configurations that are consistent across scales. The result of multi-scale scenario analysis suggests that pathways to decarbonization in Canada are likely promoted by domestic effort regardless of which global development pathways (either carbonized or decarbonized) unfold. Scenarios in which the world remains carbonized and Canada decarbonizes and vice-versa are internally consistent.

In relation to Zurek and Henrichs' (2007) linking strategies, a conventional belief or assumption that global and local scenario outcomes must match across scales to be "consistent" has emerged in the scenario research community—though not everyone agrees with this assumption (e.g., van Ruijven et al., 2014; Wiek et al., 2013). This assumption was tested in this research. The result also tells us that internal consistency does not require that the outcomes across scales should be the same. Due to confusion about what cross-scale consistency means, there is the need to perform internal consistency checks in multi-scale scenario analysis. There is also the need to revise the operational definition of consistency across scales. The term scenario consistency across scales should not be confused with their degree of linkages (i.e., more or fewer links). Instead, we can use the consistency definition provided by CIB: internally logically consistent. Nonetheless, what may be more useful is to define the term "inconsistent". This should be reserved for scenarios that are found to have internal logic problems—scenarios that, for good reasons, would be dismissed as implausible.

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To my mom and my sisters, your love is the greatest. Thank you for being there for me even when you are thousand miles away.

DEDICATION

For my two lovely daughters, Isabella and Anabella.

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LIST OF ABBREVIATIONS

AR4	Fourth Assessment Report
AR5	Fifth Assessment Report
BAU	Business-as-usual
BC	Betweenness Centrality
CI	Cross-impact
CIA	Cross-impact Analysis
CIB	Cross-impact Balance
DDPC	Deep Decarbonization Pathways for Canada
EC	Eigenvector Centrality
FCM	Fuzzy Cognitive Mapping
GHG	Greenhouse Gas
IAM	Integrated Assessment Modelling
IAV	Impact, adaptation, and vulnerability
ICONICS	International Committee on New Integrated Climate change assessment Scenarios
IPCC	Intergovernmental Panel on Climate Change
MA	Millennium Ecosystem Assessment
NEB	National Energy Board (Canada)
NET	Negative emission technology
OSPs	Oceanic System Pathways
PMT	Probabilistic Modified Trends
RAPs	Representative Agricultural Pathways
RCPs	Representative Concentration Pathways
REC	Re-Energizing Canada
SAS	Story and Simulation
SFM	Sustainable Forest Management
SMA	Scenario Matrix Architecture
SNM	Scenario Network Mapping
SPAs	Shared Policy Assumptions
SRES	Special Report on Emissions Scenarios
SSPs	Shared Socioeconomic Pathways
TCL	Tiger Conservation Landscape
TEFP	Trottier Energy Futures Project
WEC	World Energy Council

Chapter 1: Introduction

1.1 Introduction

Holistic understanding of global environmental change and its profound influences on socioeconomic and socio-technical systems at multiple scales (i.e., global, regional, national, and sub-national) will be key in addressing international and domestic energy policy questions (Geels et al., 2016). Decisionmakers (e.g., policymakers, stakeholders) will require information about how such a multi-scale system could unfold in the future—what the anticipated impacts would be due to global climate change, what preventive measures could be adopted domestically, and how much influence global developments would have on the national energy system. One of the useful tools to answer these questions is multi-scale scenario analysis (Alcamo, 2008; Metzger et al., 2005; Scholes et al., 2013). Multi-scale scenarios are the portrayals of future conditions at different scales (e.g. global, regional, national) that are interacting (Alcamo, 2008). However, scenarios should depict *plausible* futures in order to support decision making as well as obtaining stakeholder buy-in (Bishop et al., 2007; Wiek et al., 2013). One way to produce plausible scenarios is to ensure that scenarios across scales (e.g., global, regional, national) are not conflicting or contradicting, meaning that these scenarios must be *consistent* across scales. However, in scenario research, the definition of *consistency* is confusing since there are multiple interpretations that currently exist (Mayerhofer et al., 2002; van Ruijven et al., 2014; Zurek and Henrichs, 2007). Further, there are multiple ways for how consistency can be assessed (Alcamo, 2008; Tietje, 2005; Weimer-Jehle, 2006; Wiek et al., 2013). This problem arises because there is rarely an operational definition of *consistency*. This dissertation builds on and contributes towards multi-scale scenario literature, with a specific aim at clarifying the definition of (scenario) *consistency*. To do this, I develop internally consistent national energy scenarios that are linked to global socioeconomic developments specified in the Shared Socioeconomic Pathway (SSP) framework.

Cebon and Ribsey (2000) described the interrelationships in a multi-scale system (e.g., global-national) as convergent, divergent, and ambivergent. Convergent describes a national or regional model that is ‘downscaled’ from the global model. For instance, global environmental change can influence regional/local and sectoral developments (e.g., impacts of global climate change could have negative implications on local communities) (Genovese and Green, 2015; Hallegatte, 2009; Hunt and Watkiss, 2011; McCubbin et al., 2015; Smit and Wandel, 2006; Vervoort et al., 2014). Divergent describes influences from the regional model to the global model, which may or may not exert significant influence on the global model. Some regional/local and sectoral developments can have significant impacts at the global level (e.g., national greenhouse gas emissions would contribute to global climate change) (Donald and Gray, 2018; Nemet et al., 2018; Peters et al., 2017; Rogelj et al., 2015). Ambivergent describes a situation in which convergent and divergent relationships are present, meaning that regional and global models are co-determined. As Cebon and Ribsey (2000) put it, such framing is important for researchers to think about regional/local issues in relation to global problems. To model the interactions between global and regional/local scales, scenario studies have adopted multi-scale scenario analyses. Alcamo (2008) describes a multi-scale scenario analysis as a scenario framework with two or more levels (e.g., global/regional), whereby global scenarios paint a comprehensive picture of implications of large-scale environmental change, whereas regional scenarios allow more detailed representations of causes and impacts. However, modelling the interrelationship of a multi-scale system requires scenarios across scales (i.e., global, regional, national scenarios) to be consistent. That means consistency is a pre-requisite in multi-scale scenario studies.

To some extent, people seem to think that ‘consistency’ is a straightforward concept; consequently, they use the term without defining it. In this respect, people assume consistent scenarios are ‘realistic’ scenarios (Lekavičius et al., 2019; Reimann et al., 2018). At times, the term ‘consistent’ is also used to describe regional/national scenarios that are developed based on (or extended from) global scenarios (Gollnow et al., 2018; van Ruijven et al., 2014). In this case, consistent means that the scenarios are produced by incorporating widely held assumptions of the global development (Houet et al., 2016; Mayerhofer et al., 2002). However, consistent is more than just incorporating assumptions, it may require a formalized process for evaluating scenarios’ consistency. As argued by Wiek et al. (2013), multi-scale[1] scenario development processes should also include a more empirically grounded consistency analysis (Tietje, 2005)[2]. There is no

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[1] Wiek et al. (2013) used the term ‘integrated’ to describe scenarios developed for different sectors.

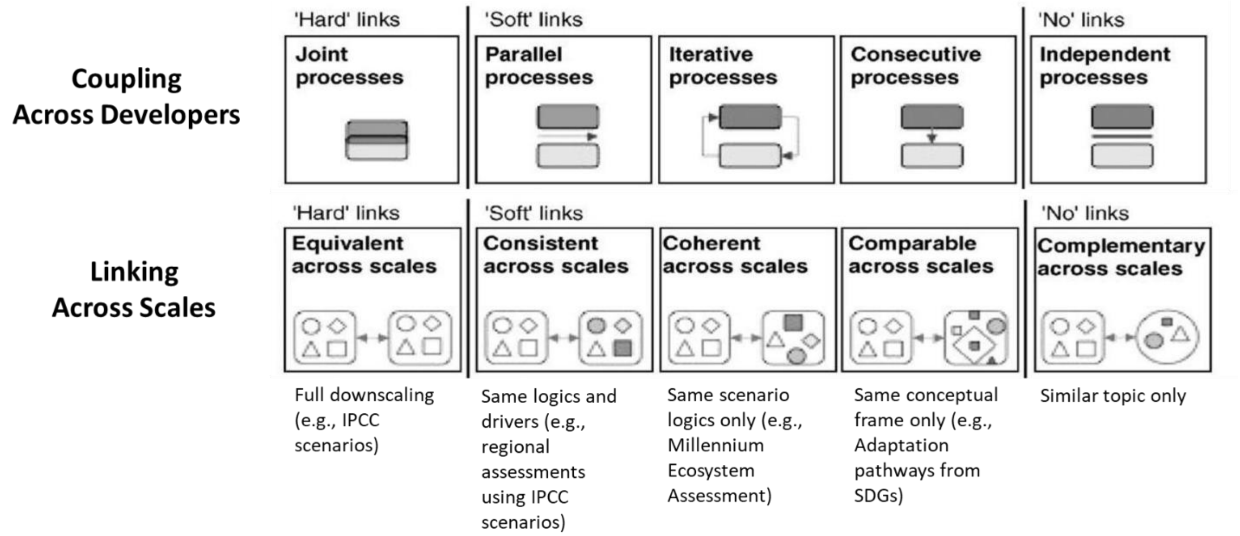
[2] Simply put, the consistency analysis proposed by Tietje (2005) uses a matrix, which documents expert-based qualitative judgments on impact factors between two scenario elements; the algorithm will compute consistency scores for each combinatorial scenario configuration.

consensus on the definition *consistent* scenarios among researchers, but they all agree that "…*inconsistent* scenarios draw no realistic image of the future" (Tietje, 2005, p. 419).

1.2 Consistent Scenarios Across Scales

The Millennium Ecosystem Assessment (MA) is an example of a multi-scale scenario study (Carpenter et al., 2005). Although global scenarios were developed first, the MA framework allows the 'downscaling' of global scenarios to a regional level and regional scenarios to a local level. At each level, qualitative scenarios (storylines) were produced incorporating regional/local dynamics, which were subsequently used as input parameterization of the regional/local integrated ecosystem models (Alcamo, 2008; van Vuuren et al., 2011). An important consideration for such a multi-scale scenario approach is the 'linking strategies,' i.e. the mechanisms that guide the development of lower level scenarios (e.g., regional/local) to reflect the development at the global level so that scenarios are consistent across scales.

The dominant definition of consistency for multi-scale scenarios is rooted in the concept of scenario linking categories that arise from the MA scenario framework (Zurek and Henrichs, 2007). The authors categorized the linking of scenarios as *equivalent*, *consistent*, *coherent*, *comparable*, and *complementary* across scales (Figure 1). The linking category touches on analytical processes (or coupling) between different scenario developers as well as the degree to which different modelling efforts could have their scenario elements and outcomes linked. For instance, *consistent* can mean that scenarios across scales would have the same or similar scenario elements (i.e., logics, drivers, assumptions). An example of this is a regional assessment based on quantitative downscaling of emission scenarios developed by the Intergovernmental Panel on Climate Change (IPCC). For the regional and local scenarios under the MA framework, they would be categorized as *coherent* for having the same scenario logics only (Alcamo, 2008). For *comparable* scenarios, scenario drivers and logics may not be identical, but these scenarios would retain only the same conceptual framework. An example of a comparable multi-scale scenario is a scenario study that addresses general issues of Sustainable Development Goals (i.e., poverty, hunger) but covers different aspects of livelihood drivers for rice and tobacco farming communities in Indonesia (e.g., tobacco quality) (Butler et al., 2016). According to Zurek and Hernichs (2007), multi-scale scenarios should aim to occupy the left side of the continuum (Figure 1), meaning that scenarios should be equivalent or at least be consistent across scales, which can be achieved through model coupling and downscaling.



Adapted from Zurek and Henrichs (2007)

Figure 1 Coupling and linking of scenarios across scales

Biggs et al. (2007) suggested that the consistency of scenarios across scales could be evaluated by how loosely or tightly multi-scale scenarios are linked or coupled. Tightly coupled scenarios have a high level of consistency, and they are developed explicitly by downscaling or upscaling routines, where drivers and constraints (a.k.a. elements) of the global scenarios would be ‘transferred’ to the process of developing regional/national scenarios. Loosely linked scenarios have low level of consistency (Biggs et al., 2007). These scenarios are developed by engaging the participation of local stakeholders to frame the issue in the scenario development thereby incorporating more detailed localized drivers and constraints, which may not be within the scope of the global scenarios. However, Biggs et al. (2007) defined loosely linked scenarios to be *inconsistent* across scales because regional/national scenarios would have used different scenario elements. According to the definition by Zurek and Henrichs (2007), these loosely linked scenarios are what they called scenarios that are connected by ‘soft’ links. Soft links would categorize scenarios based on the degree of consistency (i.e. *consistent*, *coherent*, and *comparable*). The “consistent” verbiage used by Zurek and Henrichs (2007) linking strategies can be problematic for scenario users; it is possible that one can misinterpret *coherent* and *comparable* as ‘inconsistent.’ That means scenarios that are neither *equivalent* nor *consistent* across scales, even if these scenarios are *coherent*, *comparable*, and *complementary* across scales, can be misinterpreted as not *consistent*, and, therefore, *inconsistent*.

Being consistent is one of the requirements for multi-scale scenario studies; however, without the operational definition of consistency, it will be challenging to assess whether regional/national scenarios are consistent with global scenarios. This issue is also inherent in multi-scale scenario frameworks, including the current scenario framework for climate change research called Shared Socioeconomic Pathways (SSPs). The SSP framework supports more in-depth investigations of the linkages between climate change, economic development, adaptive capacity, and socio-cultural aspects of energy use and technological change (O'Neill et al., 2014). Although scenarios produced for climate impact assessments include empirical and theoretical information from computational models, they also embody qualitative assumptions that cannot be determined scientifically, namely possible qualitative socioeconomic trends such as shifts in cultural values and social acceptance of emerging technologies. But many qualitative socioeconomic trends are better understood at a regionalized or localized scale. For instance, social acceptance of electric vehicles in the United States took a bumpy ride in the early 2000s because of certain social actors' refusal to change (e.g., automakers, policymakers, regulators) (Paine, 2006). This notion is addressed by the SSP framework by allowing basic or global SSPs (O'Neill et al., 2014) to be extended for more detailed regional/national and sectoral analyses. Nonetheless, the SSP extension studies must be linked to the global SSPs so that scenarios for the extended SSPs are consistent with the global SSPs (Ebi et al., 2014; van Ruijven et al., 2014).

An influential paper for extending the SSPs suggests two approaches (van Ruijven et al., 2014). Extension studies can utilize the SSP qualitative components (O'Neill et al., 2017) using narrative downscaling and the SSP quantitative components (Riahi et al., 2017) using quantitative downscaling. At times, the scope of the SSP qualitative and quantitative components may not be sufficiently broad to be extended usefully for studies with a different context; therefore, studies on extending the SSPs might have incorporated new elements (Frame et al., 2018; Kemp-Benedict et al., 2014; Maury et al., 2017; Palazzo et al., 2017; Valdivia et al., 2015). According to the definition of consistency by Zurek and Henrichs (2007), extension studies that have used new elements (different from the global SSPs) would be considered as either *coherent* or *comparable* or *complementary*. According to Biggs et al. (2007), such extension studies are loosely linked with the global scenarios; therefore, they are inconsistent with the global SSPs. Under the SSPs framework, if studies on extending the SSPs were to be linked to the global SSPs, the extended study will be considered consistent (van Ruijven et al., 2014). The issue of consistency is particularly inherent in downscaling the SSP qualitative narratives (Kok et al., 2019). According to Zurek and Henrichs (2007), in theory, the process of developing extended SSPs through narrative downscaling tends to introduce new elements, which will make these extension studies only *coherent* or *comparable* or *complementary* with the global SSPs. Certain scenario processes, which incorporate different elements, will produce lower level scenarios that will not be consistent but rather *coherent*, *comparable* or *complementary*. In other words, scenario processes employed in developing multi-scale scenarios will indicate whether these scenarios are consistent. However, Kok et al. (2019) suggest the need to evaluate scenario products (rather than scenario processes) and assess whether the content (e.g., qualitative narratives) of different scenarios are consistent or equivalent across scales. That means the scenario consistency should be assessed beyond the process of how different scenario studies are linked or coupled. In scenario research, a small but growing body of research has contributed to developing novel tools, methods, and concepts in multi-scale scenario analyses (Absar and Preston, 2015; Kok et al., 2019; Nilsson et al., 2017; Rohat et al., 2018; Schweizer and Kurniawan, 2016); nonetheless, confusion remains in interpreting the meaning of ‘consistency.’

One method that can be deployed to analyse scenario consistency across scales is cross-impact balance analysis (CIB) (Weimer-Jehle, 2009, 2006) or linked CIB, which is a multi-scale variant of CIB (Schweizer and Kurniawan, 2016). CIB is a tool for systematic exploration of how alternative developments of different scenario elements (e.g., driving factors) would influence one another in a multi-scale system (e.g., global and regional energy system). In CIB terms, scenario elements are variables that can act as a source of influence affecting other variables or as a sink of influence exerted by other variables. CIB uses a matrix structure to collate these influence judgments[3]. By having access to these influence judgements in a matrix, the CIB algorithm solves the cross-impact (CI) matrix by searching those scenario elements that are self-reinforcing—a.k.a. internally consistent in CIB parlance. In a multi-scale system, there are many elements from multiple levels, sectors, and scales; together, these elements are subjected to a CIB analysis. With that many elements, the CI matrix will be large and potentially computationally intractable. In a situation where the large CI matrix cannot be solved computationally (i.e., using CIB analysis software, ScenarioWizard), solving the CI matrix can be separated using linked CIB. Linked CIB

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[3] In CIB analysis, influence judgments can be obtained through expert elicitations (Schmid et al., 2017; Schweizer and O’Neill, 2014), participatory stakeholder workshops (Kemp-Benedict et al., 2014), and/or literature reviews (Schweizer and Kriegler, 2012).

partitions a large multi-scale CI matrix into smaller sub-matrices which can be solved by traditional CIB; the results of CIB analysis on individual sub-matrices can be linked to produce a complete solution.

To produce extended SSPs that are consistent with the global SSPs, it is, therefore, necessary for SSP extension studies be linked to the global SSPs. The extension studies can be linked to the global SSP via two approaches as proposed by van Ruijven et al. (2014), namely quantitative downscaling and narrative downscaling. These two approaches, nonetheless, are not prescriptive. Researchers have innovated new ways for linking their studies to the global SSPs. For instance, studies can adopt the SSP fundamental scenario logic to produce alternative but compatible frameworks such as Representative Agricultural Pathways (Palazzo et al., 2017; Valdivia et al., 2015) and Oceanic System Pathways (Maury et al., 2017). Alternatively, studies can utilize key elements of the global SSPs; however, extended studies can include not only key elements of the global SSPs but also re-specify the scenario elements that are relevant in the context of the study such as an extension study on New Zealand’s socioeconomic futures (Frame et al., 2018). The latter approach is employed in this thesis. Studies employing this mode (re-specification of the SSP elements) may incorporate some of the key elements of the SSPs (e.g., population, income growth, carbon intensity) as well as introducing new elements necessary for developing scenarios for the extended SSPs. During the development of the SSP framework, Schweizer and O’Neill (2014) constructed a CI matrix comprising of 13 elements of the global SSPs. The existing CI matrix for the global SSPs can be expanded to include new scenario elements relevant to the study context. This study will link to the global SSPs using the CI matrix as the interface. This expanded CI matrix models the interaction of a multi-scale system (i.e. the global socioeconomic system and national energy system) and can be subjected to CIB analysis to search for internally consistent scenarios across scales.

The research community has hands-on experience with developing multi-scale scenarios, more specifically downscaling global scenarios such as the IPCC SRES and the MA scenarios. Yet a puzzle remains: would extended SSP studies be consistent when they are linked to the global SSPs? Yes, they would be consistent according to van Ruijven et al. (2014). But according to Zurek and Henrichs (2007) and Biggs et al. (2007), potentially, these scenarios would not be consistent depending on the scenario development process employed. Zurek and Henrichs (2007) linking strategies may categorize such SSP extension studies (that are linked to the global SSPs) as *coherent* or *comparable*. But it is also possible that one may interpret *coherent* or *comparable* scenarios as ‘inconsistent’ since these scenarios are neither considered *equivalent* or *consistent* across scales. In this dissertation, I would argue for the need to establish the operational definition of consistency and inconsistency. The term ‘inconsistent’ should be reserved to describe ‘junk’ or conflicting scenarios (Wiek et al., 2013). As Tietje (2005) puts it, inconsistent scenarios are ‘unrealistic’ scenarios, meaning that regional/national (or extension) scenarios portray development pathways that would not otherwise be feasible from the global perspective. Further, there are varying degrees of consistency of scenarios across scales much like the concept proposed by Zurek and Henrichs (2007) that spans from *equivalent* to *complementary* across scales. However, there is a missing ‘threshold’ in their framework—at what point should scenario studies be considered inconsistent. This dissertation offers a re-interpretation on the concept of linking strategies by identifying the threshold for which scenarios can be considered inconsistent.

1.3 Study Context: Canada’s Energy Scenarios

Canada has ratified the Paris Agreement in 2016, committing to reduce its GHG emissions by 30% below 2005 levels by 2030 (Environment and Climate Change Canada, 2020). This means that, in order to meet Canada’s emission reduction target, Canada’s economic sectors must reduce their emissions by 199 Mt CO_2 eq with the major reductions expected to come from buildings, oil and gas and electricity sectors. That means Canada must decarbonize as much as possible in many sectors. But one question remains: how would global development pathways influence Canada’s low-carbon energy transition in the future? First, there is a need to explore what plausible situations are in the future domestically and globally. Second, how global developments can influence Canada’s energy development in the future and vice versa must be clarified. Third, given the uncertainties about the future, the assumptions used to envision the future must be sufficiently broad to discover alternative scenarios, especially scenarios that are counterintuitive. One way to envision a plausible future is to ensure that the projected development pathways in Canada must be consistent with the global development. Recent scenario studies such as Re-Energizing Canada (Potvin et al., 2016) and the Trottier Energy Futures Project (TEFP, 2016) have used two different assumptions to depict the future: (1) Canada will decarbonize in a decarbonized world, or (2) Canada remains carbonized in a carbonized world. These assumptions portray that global and Canada’s developments are lockstep; such a portrayal is believed to be feasible and assumed to be consistent. What would happen when global and Canadian development pathways differ? Scenarios for which Canada decarbonizes even though the world remains carbonized and vice versa were analysed and tested for consistency across scales.

1.4 Research Goals and Objectives

The overarching goals of this thesis are to:

1. Assess multiple interpretations and applications of ‘consistency’ in order to clarify the definition of scenario consistency across scales.
2. Reinterpret Zurek and Henrichs (2007) spectrum of linking strategies to identify the missing threshold of inconsistency. In short, wringing our hands about consistency may be misguided; rather, inconsistency is what we should worry about.
3. Demonstrate the flexibility of the SSP framework.

Canadian energy futures are the case used to address the research questions below:

1. How can globally linked, internally consistent multi-scale energy scenarios for Canada be developed under the SSP framework and how the extension study can be linked to the global SSPs? (Chapter 2)
2. How might an extension study that is consistent with the global SSPs be developed using CIB analysis?
    2.1. How can one identify and select elements for developing national / sectoral scenarios under the SSP framework? (Chapter 5)
    2.2. How can one utilize the CI matrix of the SSPs for extending the SSPs for more detailed regional or national analyses? (Chapter 6)
3. What are the implications of global developments on Canada’s decarbonization? (Chapter 6)

The development of the SSP extension study on energy scenarios for Canada is in three phases (Figure 2). The first phase is to identify different ways to extend the global SSPs. The second phase is to choose the elements for scenarios development process. The third phase is to construct multi-scale scenarios using CIB analysis.

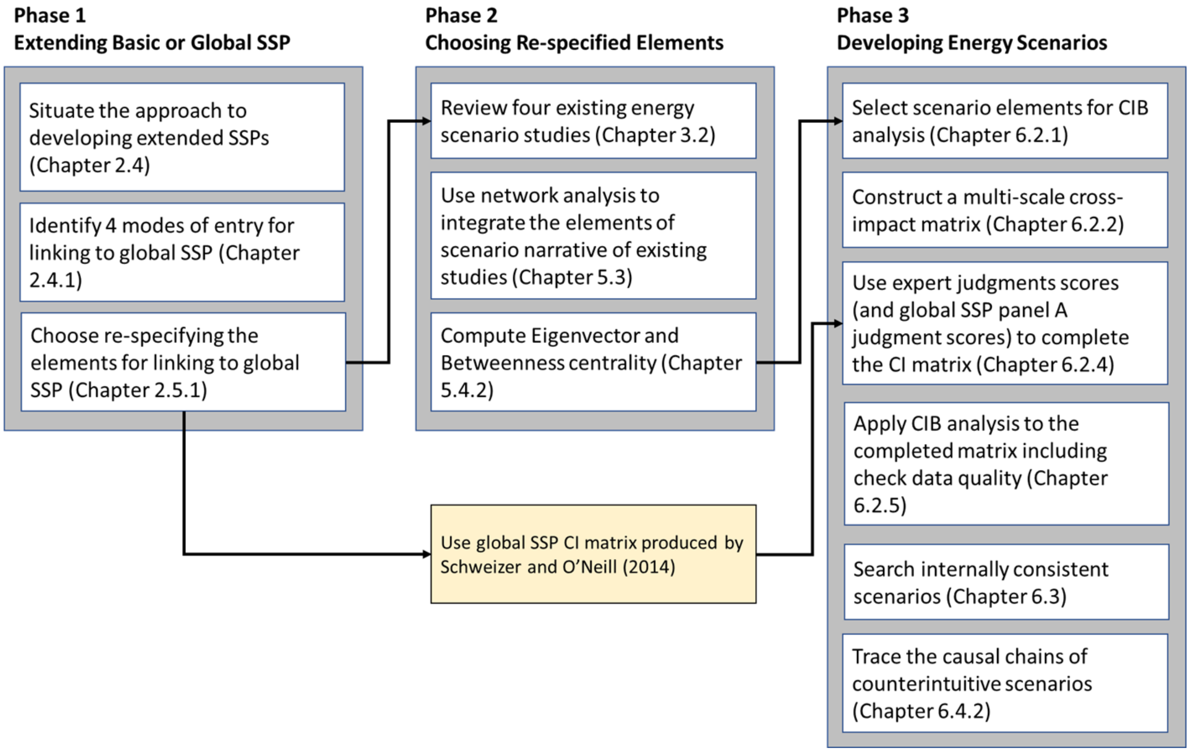

Figure 2 An overview of research design

1.4.1 Phase One (Extending 'basic' or global SSPs)

Phase one involved reviewing SSP extension studies to help identify different modes of entry for extension studies to link to the global SSPs (Chapter 2). Besides linking to the global SSPs by downscaling SSP narratives and SSP quantifications, the review shows that extension studies can also be linked to the global SSPs through two other modes of entry: (1) the SSP archetypes by developing compatible but different framework such as Representative Agricultural Pathways (Palazzo et al., 2017) and Oceanic System Pathways (Maury et al., 2017), and (2) the SSP elements by re-specifying new elements necessary for more detailed regional and sectoral analyses such as socioeconomic futures of New Zealand (Frame et al., 2018). The latter approach was employed in this research on Canada's energy futures. There is an existing CI matrix that documents the interactions of 13 key elements of the global SSPs (e.g., population, carbon intensity, urbanization) (Schweizer and O'Neill, 2014) that can be utilized and extended in the context of the Canadian energy scenario study, meaning that the CI matrix will be the interface. When the global SSP CI matrix is expanded, new scenario elements for Canada's energy scenarios will be re-specified and incorporated into the CI matrix.

1.4.2 Phase Two (Choosing re-specified scenario elements)

In this thesis, network analysis (Wasserman and Faust, 1994) was used to identify and choose scenario elements for the extended SSP for developing energy scenarios for Canada (Chapter 5). Once selected, these elements would become a part of the scenario products (qualitative narratives). Traditionally, a broad range of scenario elements could be identified through expert or stakeholder elicitations; however, only a few elements can be selected to be incorporated in a scenario development process. The selection process is usually conducted in a stakeholder workshop, where the participants discuss and choose elements that they consider important. Eventually, participants would be asked to cast their votes individually; elements would then be selected according to the tallied votes. The selection of elements by voting can help to minimize biases and is intended to be based on consensus. However, from my experience in conducting a scenario planning workshop in Singapore (Zahraei et al., 2019), I found that a participant can influence the voting process by casting all his or her votes on one scenario elements[4]. To overcome this challenge, I used network analysis applied to published documents or reports authored by expert panels and the government. To do this, scenario elements for developing Canada's energy scenarios were identified from four existing reports, namely, the Trottier Energy Futures Project (TEFP, 2016), Deep Decarbonization Pathways in Canada (Bataille et al., 2015), Re-Energizing Canada (Potvin et al., 2016), and Energy Supply and Demand Projections to 2040 (NEB, 2016). Since these elements are already part of the scenario products produced by these studies, scenario elements relevant to the Canadian energy futures can be obtained from these study reports. The process of extracting elements of the scenario narratives is called 'deconstructing scenarios' (Scheele et al., 2018). The deconstructing technique for extracting scenario elements is adapted based on a study by Schweizer and Kriegler (2012). In their study, authors deconstructed scenarios in the Special Report on Emissions Scenarios (SRES) (Nakicenovic et al., 2000) for CIB analysis.

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[4] In this scenario planning workshop, 20 scenario elements were presented to the workshop participants. The participants were asked to identify scenario elements that are highly impactful and highly uncertain. To cast their votes, each participant was given three yellow dot stickers (for highly impactful elements) and three blue dot stickers (for highly uncertain elements). In this workshop, one participant placed all the votes on one scenario element, propelling this element to be selected when the votes were tallied.

Since the scenario elements extracted from the four existing scenario studies on Canada's energy futures also contain information for how different elements interact, these elements and their interrelationship can be analysed as a network. Subsequently, I calculated the node centrality scores for each element to rank them. The approach used in this study is novel because not one, but four scenario studies were deconstructed.

1.4.3 Phase Three (Multi-scale scenario analysis using CIB)

Based on the ranking information produced by node centrality scores in Phase Two, these elements were further deliberated through consultations with two experts: one expert was involved in the development of the SSP framework, and another expert is in the transportation sector. Seven scenario elements related to Canada's energy systems were selected to be incorporated into the CI matrix, and together with the 13 key elements of the global SSPs, a multi-scale CI matrix was constructed. The CI matrix will document pair-wise influence judgments through expert elicitations (i.e., asking the participants questions on how variable X directly influences variable Y) (Chapter 4). The instrument for expert elicitation was developed first. For each element, there will be two or three different end-states (for how elements could develop differently in the future). For developing different end-states (pathways), I utilized trend analysis based on existing literature and data. For instance, income growth in Canada could unfold as a high, medium, or low pathway. These pathways are informed by GDP and population projections for Canada retrieved from the SSPs database hosted by the International Institute of Applied System Analysis (IIASA) (Riahi et al., 2017). The pathways for each element were developed as an elicitation instrument (Appendix B). During the expert elicitation, the participants would use a pathway diagram to 'calibrate' their judgments. The expert elicitation follows a protocol; individual expert participants are asked to provide impact judgments for how variable X would influence variable Y (variables are scenario elements of the global SSPs and Canadian energy futures). For this task, they need to think only about the direct influences (not indirect)—this requirement was made known to the participants at the start of the meeting. Expert participants ($n = 8$) are the lead or contributing authors of the Re-Energizing Canada study (Potvin et al., 2016), the Deep Decarbonization Pathways for Canada report (Bataille et al., 2015), or faculty members of higher learning institutes in Canada. The influence judgments provided by individual experts are directed at one specific element related to their field of expertise, meaning that they will only respond to a portion of the CI matrix.

Subsequently, all influence judgments from different experts were collated to complete the CI matrix for CIB analysis. CIB analysis was performed using software called ScenarioWizard (Weimer-Jehle, 2018). Based on the results of CIB analysis, I analysed the consistent scenarios for Canada when the world decarbonizes and when the world remains carbonized.

1.5 Organization of Dissertation

The formalization of the SSP framework presents important opportunities for more detailed regional/local and sectoral analyses building on the global SSPs, which would be necessary for assessing climate impacts as well as mitigative and adaptive capacities at a localized scale. This chapter has introduced the major research goals and research gaps. A brief outline of the remaining chapters is as follows.

Chapter 2 begins with a review of existing literature on environmental scenario research. Here, I delve deeper into scenario development processes that might be relevant for designing an SSP extension study on national energy. This review is used to introduce the SSP framework as well as to highlight what is meant by ‘consistent’ scenarios across scales. Under the SSP framework, the requirement is that all extension studies must be linked to the global SSPs so that scenarios extended to regional, local or sectoral scales are consistent with the global SSPs. Chapter 2 also notes that the sub-global study would incorporate new scenario elements relevant to the study context because the global SSPs components are meant to be ‘generic’, hence, many scenario elements have local dynamics, and these elements fall outside the scope of the global SSPs. In this dissertation, linking to the global SSPs is done by re-specifying the SSP elements, meaning that the relevant elements for the study on Canada’s energy futures are added along with the existing global SSP elements. To produce an SSP extension study for more detailed national or sectoral analyses, the existing cross-impact matrix of the global SSPs was be extended to incorporate scenario elements relevant in the context of the sub-global study. Chapter 2 addresses research question 1: How can globally linked, internally consistent multi-scale energy scenarios for Canada be developed under the SSP framework and how the extension study can be linked to the global SSPs?

Chapter 3 reviews Canada’s energy systems and studies that explore how it will take shape in the future. The review of four Canada’s energy scenario studies revealed different assumptions of global developments. There is a consensus among these four studies that low-carbon electricity generation could be key in Canada’s energy transition. Additionally, the three major energy consuming sectors identified by these studies are transportation, commercial and residential buildings (built environment), and manufacturing. The objective of examining different national scenario studies produced by different author teams is to better understand what scenario factors, or elements, were included or excluded across studies. Doing so helps to identify what scenario elements (i.e. drivers, trends or events) all studies agree could be significant in shaping Canada’s energy futures. Understanding such scenario elements is important for making headway on national commitments to reduce greenhouse gas emissions.

Chapter 4 provides an overview of the research design. As previously mentioned, there are three phases in this research. This chapter details the steps undertaken for phase two and phase three of the research. In developing national / sectoral extension studies, the requirement is to link them to the global SSPs. Here, linking to the global SSPs was achieved by expanding the existing CI matrix of the global SSPs (Schweizer and O’Neill, 2014). The necessary elements for national energy scenario studies must be ‘re-specified’ first. Phase two identifies candidate elements by consulting four existing energy scenario studies in Canada. These studies were ‘deconstructed’ to extract scenario elements. In phase three, I performed multi-scale scenario analysis using CIB, incorporating the scenario elements of the global SSPs as well as elements of scenario narratives for the four energy scenario studies in Canada. The information for how different scenario elements interact was elicited from a panel of experts. Their judgments were used to perform CIB with the software tool ScenarioWizard.

Chapter 5 presents methodological research on network analysis in scenario research that might be relevant to answering research question 2.1: How can one identify and select elements for developing energy scenarios for Canada under the SSP framework? This chapter has been submitted and accepted for publication in the journal *Society and Natural Resources*. To better situate the coverage of each scenario study and to obtain a more holistic perspective on how the studies together characterize the key elements for Canada’s energy future, this chapter details the use of network analysis to integrate the scenario elements of the different studies. Elements that are characterized by these four studies as important for Canada’s energy sector were selected and incorporated as variables for CIB analysis.

Chapter 6 presents the CIB analysis method step-by-step employed in this dissertation. The results of the CIB analysis address research question 3: What are the implications of global developments on Canada’s decarbonization? The results of CIB analysis identify 88 scenario configurations that are internally consistent across scales. Out of 88 consistent scenarios, 64 scenarios portray either a decarbonized Canada in a decarbonized world (4 scenarios) or a carbonized Canada in a carbonized world (60 scenarios). These 64 scenarios are aligned unsurprisingly with the assumptions that cross-scale developments proceed lockstep. However, 24 scenarios are also found to be consistent when cross-scale developments are not lockstep. There are ten consistent scenarios portraying a decarbonized Canada in a carbonized world and two scenarios portraying a carbonized Canada in a decarbonized world. The remaining twelve scenarios are counter-intuitively off-diagonal, depicting that Canada could be decarbonized even though the world developments are in the ‘middle of the road’ (i.e. the world is neither fully carbonized nor fully decarbonized). In sum, the global developments do not necessarily dictate energy development in Canada, and it is plausible that the world could remain carbonized but Canada decarbonizes and vice versa. The results suggest that whichever energy development pathways is pursued by Canada is ultimately a domestic issue; the global energy market does not set the agenda.

Chapter 7 provides a conclusion to this dissertation by summarizing its contributions. The conventional belief or assumption that global and local outcomes must match across scales to be ‘consistent’ was tested in this research. There is confusion about what cross-scale consistency means. Therefore, there is an urgent need to perform internal consistency checks in multi-scale scenario analysis. Internal consistency does not mean the outcomes across scales must be the same. What may be more useful is to define the term ‘inconsistent’. This term should be reserved for scenarios that are found to have internal logic problems, meaning that inconsistent scenarios, for good reasons, would be dismissed as implausible.

Chapter 2: Extending the Shared Socioeconomic Pathways

How can one extend scenarios to different scales under the Shared Socioeconomic Pathways (SSPs) framework? This chapter begins to address this question by revisiting the historical development of scenario methodology. Over the years, researchers have invented many new methods of scenario development. With these many scenario development methods, this has become 'methodological chaos' in scenario research. However, most scenario researchers agree on a common principle—the developed scenario must be plausible. In multi-scale scenario research, one of the criteria to ensure that scenarios are plausible is consistency, meaning that scenarios must be consistent across scales. Section 2.2 examines how the scenario research community describes the definition of scenario *consistency* across scales. The definition of *consistency* has been influenced by the Millennium Ecosystem Assessment (MA). This analysis is used to differentiate what consistency across scales means; however, there is no consensus among scenario researchers. Section 2.3 examines the SSPs scenario framework, which is multi-scale. The analysis of existing SSP extension studies is used to determine how an extension study can be linked to the global SSPs.

2.1 Introduction: Environmental Scenarios

In foresight research or futures studies, a scenario is defined succinctly as a narrative or story describing plausible causes and effects, bridging the present and the future conditions by illustrating actions and consequences (Glenn and Gordon, 2009). In climate change research, however, the definition of scenario is often used synonymously to describe not only qualitative narratives but also quantitative projections produced by computational models such as climate models or integrated assessment models (see e.g., Sarofim and Reilly, 2011). Future climate projections are called **quantitative scenarios** whereas stories or narratives depicting the future are called **qualitative scenarios** (see e.g., Alcamo, 2008; Rounsevell and Metzger, 2010). Qualitative or quantitative scenarios are usually integrated as a single product. Alcamo (2008) describes such integration as 'Story and Simulation' (SAS), where *story* refers to the qualitative scenario and *simulation* is the quantitative scenario produced by a computational model. This dissertation adopts the convention of using the terminologies defined by Alcamo (2008).

***Key definitions* – Common Scenario Terminology**

A Scenario is a description of how the future may unfold based on “if-then” propositions and typically consists of a representation of an initial situation and a description of the key driving forces and changes that lead to a particular future state (Alcamo, 2008, p. 15).

Scenario development is the discursive procedure by which a scenario or a set of scenarios is conceived, formulated, and elaborated. A synonymous term is “scenario building” (Alcamo, 2008, p. 16).

Scenario analysis is a procedure covering the development of scenarios, comparison of scenario results, and evaluation of their consequences. A key idea is to explore alternative future developments (Alcamo, 2008, p. 16).

Qualitative scenarios describe possible futures in primarily non-numerical forms (Alcamo, 2008, p. 22). This term also refers to scenario ‘narratives’ or ‘storylines.’

Quantitative scenarios describe possible futures in numerical forms such as graphs or tables. They are most commonly produced using a model or models (Alcamo, 2008, p. 22).

Scenario logics are the two variables used to define x- and y-axes, which will create four quadrants where each quadrant represents a distinct development pathway.

Scenario archetypes are the four quadrants defined by scenario logics where each quadrant is represented by one particular end-state of each scenario logic.

2.1.1 Evolution of Scenario Development

Scenarios were popularized by Herman Kahn as a tool for strategic and policy analyses in the public and private sectors. Scenario research originated at the RAND Corporation in the ‘50s with the aim to explore potential military threats to the US (Bradfield et al., 2005). Scenario techniques are used to portray, explore, and imagine alternative futures. Early scholars tended to think in terms of three scenarios: the business-as-usual scenario, worst-case scenario, and best-case scenario (Glenn and Gordon, 2009). Three alternative scenarios are meagre compared to the vast number of scenarios for military strategy. Nonetheless, three scenarios are enough to provide a framing to force one to think more deeply about contrasting alternate possibilities and to devise strategies to adjust to the uncertain futures.

Over the years, research communities have introduced new methods of scenario development to model complex social and environmental processes. The plethora of methods in scenario research is often described as ‘methodological chaos.’ While the objectives of scenario exercises remain the same, which is to explore plausible futures, the methods to develop scenarios are becoming increasingly diverse (Bradfield et al., 2005; Scheele et al., 2018). Broadly, scenario analysis can be classified into two distinct school of thought, namely Intuitive Logics and Probabilistic Modified Trends (Bradfield et al., 2005).

2.1.2 Intuitive Logic and Probabilistic Modified Trend Schools

The Intuitive Logics (IL) school employs creative approaches to develop qualitative scenarios. The IL approach originates at Shell in the Netherlands in the ‘70s; accordingly, such an approach is often referred to as the ‘Shell method.’ For Shell, scenario analysis is fundamental in their corporate planning (Wack, 1985; Wilkinson and Kupers, 2014). Scenario development by intuitive logics requires the company’s top executives to participate in the process of developing scenarios where participants involved in scenario development would learn to navigate extremely complex challenges that could potentially undermine Shell’s business operations. The intuitive logics approaches are easy to implement, as the methods whittle down ‘infinite’ future conditions to manageable sets of 2, 3 or 4 scenarios. While the over-simplification can be viewed as practical, it can also invite criticism for undermining the complexity of the future, more specifically socio-environmental futures (Lloyd and Schweizer, 2014). In environmental change research, there are many interrelated variables (socioeconomic, socio-political, socio-technical) necessary for scenario development that presents a challenge for participants to heuristically conceptualize cascading effects arising from these interrelated variables.

Other approaches to scenario development fall under the Probabilistic Modified Trend (PMT) school (Bradfield et al., 2005). Cross-impact analysis, trend-impact analysis, and computer-based modelling are some examples of PMT that use mixed methods (creative and scientific techniques) for scenario development (Glenn and Gordon, 2009; Gordon and Hayward, 1968). A landmark study under the PMT school is the Club of Rome's (COR) *Limits to Growth* (Meadows et al., 1972), which is based on an integrated assessment model of economy-demography-environment-technology. To some extent, PMT approaches (e.g., trend-impact analysis) may require historical data to produce projections of different variables (socioeconomic, socio-technical) into the future and use probability to account for how certain projections are more plausible than others. While historical data can be useful in providing projections of what the future would be, Anderson (2010) argues that the reliance on historical data to develop scenarios may potentially produce depictions that are too conservative (Anderson, 2010). Instead, the use of imagination, which is typical in IL approaches, can produce a more ambitious depiction of the future that can motivate society to work towards it (Kurniawan and Kundurpi, 2019). Nevertheless, scenarios that are too imaginative are often viewed with skepticism, raising the question of the plausibility of such scenarios.

2.1.3 Exploratory and Normative Scenarios

Because the future cannot be determined with any precision, researchers will develop a set of scenarios, which encompasses a broad span of alternative yet plausible futures, avoiding choosing a single 'most likely' vision of the future. Understanding alternative scenarios is good for decision making for evaluating decisions' robustness in coping with the eventualities of these scenarios (Kurniawan and Kundurpi, 2019). Scenarios can describe a snapshot in time or the conditions of important variables at a particular time in the future. Such scenarios highlight radical changes in the future to solicit strategic decisions for appropriate interventions; these scenarios are called **normative scenarios** (Robinson, 1982).

In addition to having a radical vision of the future, understanding the development pathway that might lead to realizing the envisioned future is another aspect of scenarios useful for decision making. Scenarios are often accompanied by qualitative description of the evolutionary pathways to realizing the portrayal of the future and/or quantitative projections of socioeconomic variables or trends extrapolated to the future. Scenarios that portray only the evolutionary pathways are called **exploratory scenarios**. Exploratory scenarios are useful for policy analysis to understand, for instance, what policies would be needed to maintain or deflect these pathways. Such evolutionary pathways are not only distinct to exploratory scenarios; normative scenarios can also usually be accompanied by the descriptions of evolutionary pathways. This can be done by backcasting (instead of forecasting) the development pathways, starting from the future condition (i.e., normative future) to the present (Robinson, 1982).

2.1.4 Scenario-as-a-process and Scenario-as-a-product

An open question within the scenario research community is how scenarios can benefit decisionmakers. The benefits of scenarios can be quite different depending on whether the scenario is viewed as a ‘process’ or as a ‘product.’ The scenario-as-a-process is synonymous with the IL school, whose methods rely mostly on participatory approaches to scenario development. Scenario-as-a-process will engage participants to imagine the future with the discontinuities, which paint radical but plausible futures (Anderson, 2010). During the process of developing the scenarios, participants are often encouraged to step out of their comfort zone and to think out of the box, and they therefore learn. A participatory scenario development process is useful for integrating and mobilizing knowledge as well as internalizing different options (Swart et al., 2004; Wilkinson and Kupers, 2014). However, it should be noted that IL approaches, by convention, do not assign a probability of a scenario, meaning that all scenarios developed are assumed to be equally plausible.

Such a convention, however, may raise issues on the subjectivity of the scenario products (Lloyd and Schweizer, 2014). Evidence-based decision making relying on scenario analyses would require some means to test what-if assumptions. For instance, scenario analysts can test their assumptions by changing or modifying certain variables such as population, income, or education to assess the consequences of a policy decision. In this situation, what is considered important is the scenario product (scenario-as-a-product). The scenario-as-a-product is often viewed as a scientific assessment that can chart the evolution of driving forces (Alcamo, 2008). Information on evolutionary pathways is good for policymaking because decisions can then be tailored to align with desirable development pathways or deflect undesirable ones. However, charting evolutionary pathways often falls back on extrapolating past data to future developments, which may not be on track to achieving desired sustainability outcomes. Through the governance lens, how to translate a scenario-as-a-product or scenario-as-a-process into political interventions remains unclear (Burch et al., 2019). Nonetheless, there is a consensus within the scenario research community that scenarios developed by any methods must be plausible to be useful.

***Key definitions* – Scenario Types**

Exploratory scenarios start in the present (i.e., with an initial situation) and a set of assumptions on policies, measures and key driving forces to explore plausible future developments (Alcamo, 2008, p. 20).

Normative (anticipatory) scenarios start with a prescribed vision of the future (either optimistic, pessimistic, or neutral) and then work backwards in time to visualize how this future could emerge (Alcamo, 2008, p. 20).

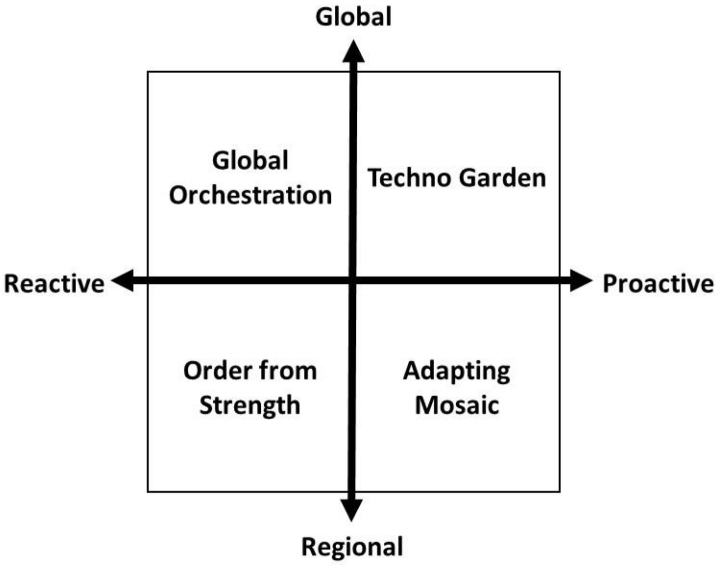
2.2 Multi-scale Scenario Analysis: The Influence of The Millennium Ecosystem Assessment

For complex multi-scalar systems such as global environmental change, identifying which scenarios are plausible can be challenging. This is in part due to the interactions of driving forces at global, regional, and local scales. The developments at different scales are co-determined, meaning that the global development pathways can potentially influence the developments at regional and national levels and vice-versa. For instance, economic developments of individual countries (a local variable) who rely heavily on fossil fuel as an energy source have contributed to global climate change (a global variable) (IPCC, 2014). Additionally, global climate change (a global variable) could have negative ramifications on food production at the regional level (a regional variable), which raises the issue regarding food security in certain local communities (a local variable) (Palazzo et al., 2017; Vermeulen et al., 2013). In multi-scale scenario research, one way to develop plausible scenarios is to ensure that scenarios at different scales are consistent (Alcamo, 2008).

The Millennium Ecosystem Assessment (MA) is a scenario framework for assessing the effects of ecosystem changes on human well-being that takes an approach that is multi-scale

(Carpenter et al., 2005). Providing a comprehensive assessment at the global scale under the MA framework is complex, in part due to earth's diverse ecosystems in different regions (Alcamo et al., 2005; Carpenter et al., 2005). As a result, many assessments were initiated on a specific ecosystem scale (a.k.a. regional or sub-global), which has similar ecological characteristics such as the Caribbean Sea, tropical forest margins, and downstream Mekong.

Initially, the MA framework guides the development of global visions producing four reference qualitative scenarios that represent different development pathways of the ecosystem services and human well-being (Figure 3). Subsequently, more detailed and comprehensive accounts related to individual ecosystems are ascribed to these regional scenarios. The regional scenarios would adopt similar development pathways as the global scenarios, and these development pathways will be tailored to individual ecosystems. Consequently, these regional scenarios could be extended further to assess the impacts on human well-being at a more localized scale (Alcamo et al., 2005). In terms of relationship across scales, these lower-level scenarios are nested under the regional scenarios. Although local scenarios would provide detailed contextual information, the scenario scope is 'restricted' within the boundary conditions as defined by the global scenarios (Alcamo, 2008; Zurek and Henrichs, 2007).



Source: Carpenter et al. (2005)

Figure 3 Four reference scenarios of the Millennium Ecosystem Assessment

Many scenarios under the MA framework were produced using story and simulation (SAS) (Alcamo et al., 2005). As the name implies, SAS is a two-step process of scenario analysis where the researchers will first construct a story and then perform simulation based on the story. The reference scenarios are qualitative scenarios (stories) which will serve as inputs for quantitative models (simulation) to produce quantitative scenarios. The modelling stage used eight different global models to produce an assessment of ecosystem services for different regions (Alcamo et al., 2005).

A critical point at this juncture is how stories (qualitative scenarios) at the regional/local levels are customized so that they reflect more closely the development pathways at the regional or local scales but they do not deviate too much from the global development as expressed by MA's global scenarios. Usually, these qualitative scenarios are produced in intuitive logics exercises through a participatory process. Participatory approaches present opportunities for local participants to contribute to the development of storylines by incorporating local phenomena, which are not captured by global scenarios. One should note that the storylines would incorporate many elements that cannot be determined predictively, namely possible qualitative socioeconomic trends such as shifts in cultural values and social capital. One of the limitations for such scenario developments is that the assumptions and mental models of the storyline contributors tend to be concealed (Potvin et al., 2016). Such a practice can potentially raise the question of scientific credibility because the analysis using intuitive logics approaches may not be reproducible. Although it is not impossible to reproduce the same storylines, it is extremely difficult. The lack of reproducibility has resulted in branding these storylines 'unscientific' (Alcamo, 2008).

2.2.1 Linking Scenarios Across Scales

Scenarios under the MA framework were developed at multiple scales (e.g., global, regional, local); consequently, these scenarios must be linked together to portray how scenarios at multiple scales interact with each other. Zurek and Henrichs (2007) categorize different strategies for linking scenarios across scales. The categorization is based on the mechanism of the scenario development process which establishes the 'strength' of the link (e.g., *consistent*, *coherent*, *comparable*) (Figure 4). Link strength is defined by how similar (or different) the scenario elements (logics, drivers, assumptions) used by different developer teams are. For instance, *consistent* means that scenarios produced by different developer teams must use the same scenario logics and drivers, but the assumptions for how the drivers can play out in different scenarios are relaxed. By virtue of having the same scenario logics and drivers, scenario outcomes portray developments across scales that are lockstep, meaning that, for example, when the world is decarbonizing, Canada would also decarbonize. For *coherent*-across-scales, scenarios must have the same logics, but drivers and assumptions used may differ. By virtue of having the same scenario logics, these scenarios will have the same scenario archetypes. *Comparable* scenarios address the same issue, but the scenario logics, drivers, and assumptions used by these scenarios may differ. Zurek and Henrichs (2007) define the linking strategies for consistent, coherent and comparable as ‘soft links.’ Linked scenarios across scales (e.g., global and regional) should aim to be *equivalent* or *consistent* across scales, meaning that lower level scenarios must be downscaled or must have the same logics and drivers. This aim, however, is challenging because regional scenarios require drivers operating at regional levels that may not be represented explicitly under the scope of the global scenarios. Moreover, such rigidities of constraining scenario element selection do not exist in the real world. Still, scenarios produced by different developer teams should aim to be consistent according to the definition whereby “*the higher scale scenarios provide strict boundary conditions for lower scale scenarios*” (Zurek and Henrichs, 2007, p. 1288). On this point, however, not everyone would agree with Zurek and Henrichs (see e.g., Kok et al., 2019; Wiek et al., 2013; Zandersen et al., 2019).

The term ‘consistent’ used in Zurek and Henrichs’ categorization can be misleading and may cause confusion (Figure 4). For instance, scenarios that are not *consistent* but are *coherent*, *comparable*, and *complementary* across scales may be misinterpreted as ‘inconsistent.’ Because the requirement for linking scenarios produced independently by different developer teams is to be at least consistent (or equivalent), scenarios developed for different scales will be required to use similar, if not the same, scenario elements. That means any deviation from these requirements would render scenarios ‘inconsistent.’ Biggs et al. (2007), however, have a different and even more stringent take on this. They suggest that scenario consistency can be defined by how scenarios across scales are tightly or loosely coupled. Tightly coupled refers to the ‘hard link,’ meaning that the scenarios should be produced by quantitative downscaling, retaining all the characteristics of scenario elements in developing lower level scenarios. These tightly coupled scenarios are considered consistent scenarios across scales. Loosely coupled scenarios, on the other hand, allows some flexibility whereby scenarios at different scales could incorporate different scenario elements. Such loosely coupled scenarios would be considered inconsistent nonetheless (Biggs et al., 2007).

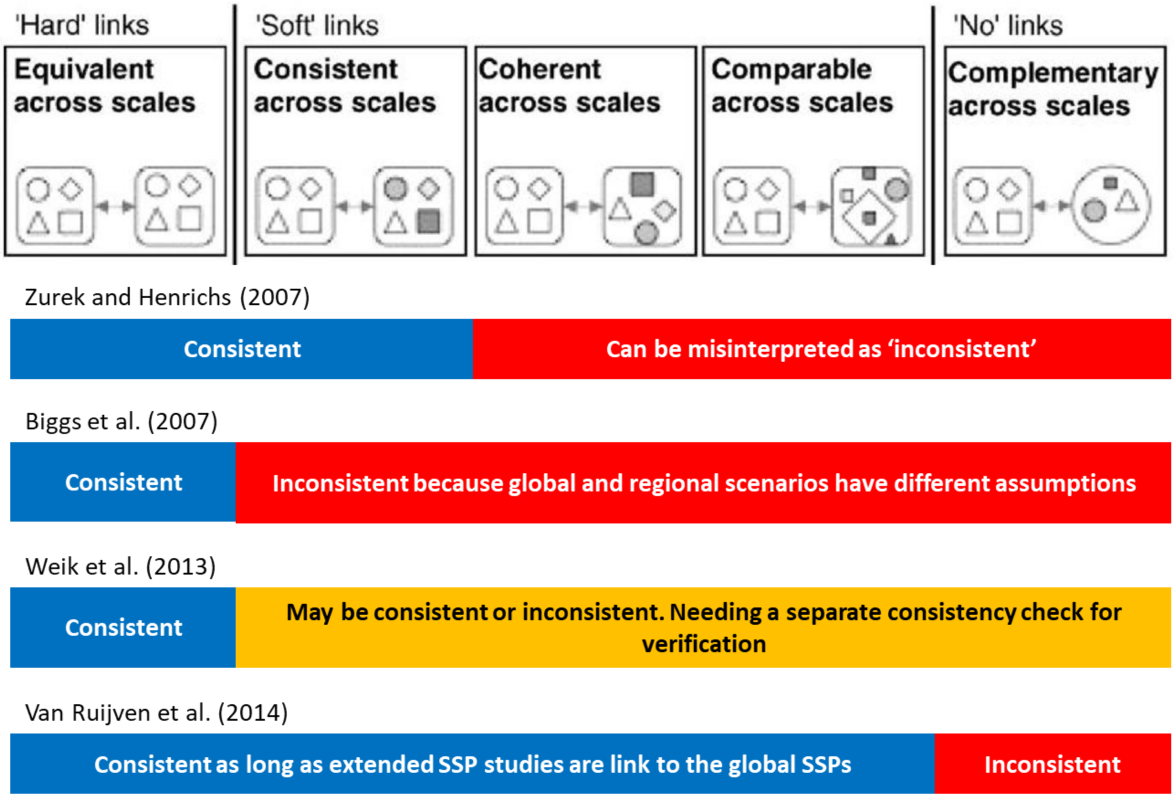


Figure 4 Different meanings of scenario consistency across scales

Assessing the consistency across scales for scenarios produced by different developing or modelling teams would ultimately rely on the interpretations of the analysts. However, when working on sub-global scenarios, it will be challenging for the analysts to maintain vertical and horizontal consistency across scales through verbal analysis (Absar and Preston, 2015; Schweizer, 2020). As scenario outcomes tend to conceal the assumptions, logics, and drivers used in developing the scenarios (Potvin et al., 2016), the analyst must make an educated guess to assess whether scenario elements used by different developers are the same or similar.

Ensuring that scenarios across scales are consistent this way can be challenging. While it may be straightforward to identify how scenarios across scales are consistent when these scenarios are hard-linked (e.g., by model coupling or quantitative downscaling), it may be difficult to assess scenario consistency across scales when these scenarios are interfaced via soft-links. For multi-scale scenario analysis, regional or local level scenarios are developed by incorporating different elements. Some elements are used to model global developments, but there are different elements that are operating at regional or local scales, which could also be relevant in multi-scale scenario analysis (Lloyd and Schweizer, 2014; Schweizer and Kurniawan, 2016). Further, soft scenario linkages are hypothetical links, which are based on interpretive arguments (Zandersen et al., 2019); these links do not explicitly represent the underlying meaning of the scenario outcomes (Kosow, 2015) as these linkages do not take into account whether their storylines make any sense or are feasible (Kok et al 2019). Therefore, the need for consistency checks is in order to assess whether scenario outcomes for two or more different scales are contradicting and therefore implausible. Wiek et al. (2013) argue that assessing scenario consistency should be rigorous. In their article, the authors suggest that scenario developers and researchers should validate scenario consistency using methods such as cross-impact balance (CIB) analysis (Weimer-Jehle 2006). In CIB, consistent scenarios consist of elements that are self-reinforcing.

Under the Shared Socioeconomic Pathways (SSPs) scenario framework, the definition of cross-scale scenario consistency refers to the requirement that the lower scale scenarios (i.e., extended SSPs) must be developed and linked to the global scenarios (or global SSPs) (van Ruijven et al., 2014). That means the global framing would be incorporated when developing these scenario extensions. In addition to incorporating global assumptions, more localized drivers and assumptions can be introduced into the scenario development. In so doing, these SSP extension scenarios, according to Zurek and Henrichs (2007), may be only *coherent* or *comparable* with the global SSP. But, according to Biggs et al. (2007), these SSP extensions will be considered *inconsistent* by virtue of having different assumptions (see Figure 4). However, scenario consistency should not only reflect the process, i.e. how scenarios across scales are coupled or linked. Rather, scenario consistency should reflect that the scenario content is not conflicting (Kok et al., 2019), meaning that these scenario outcomes are not contradicting viz. implausible (Wiek et al., 2013).

Most researchers have their personal beliefs about what is consistent and what is not. Nonetheless, the dominant definition of scenario consistency currently is based on the Zurek and Henrichs (2007) linking categorization. Recently, the research community began questioning whether the linking categorization will misguide multi-scale scenario analysis (Kok et al., 2019; Rohat et al., 2018). Zandersen et al. (2019) offer alternatives to the ‘interpretive’ assessment of consistency, highlighting novel methods such as the factor-actor-sector approach (Absar and Preston, 2015; Kok et al., 2006) and the linked CIB analysis (Schweizer and Kurniawan, 2016) that promise more robust systematic internal consistency checks. Yet these two new approaches to date remain under explored. Specifically, the linked CIB was demonstrated using only a ‘toy’ model, and the practical deployment of linked CIB for multi-scale scenario analysis is urgently needed (Rohat et al., 2018).

2.3 Shared Socioeconomic Pathways

The Shared Socioeconomic Pathways (SSPs) is a scenario framework that is multi-scale to support more in-depth and policy relevant investigations of the linkages between climate change, economic development, adaptive capacity, and socio-cultural aspects of energy use and technological change (O'Neill et al., 2014). Although scenarios produced for climate impact assessments include empirical and theoretical information from computational models, they also embody qualitative assumptions that are difficult to determine predictively, namely possible qualitative socioeconomic trends such as shifts in cultural values and social acceptance of emerging technologies. The SSP framework incorporates both mitigation and adaptation, which are expressed in the architectural framework (Figure 5). Like MA, the SSP framework adopts the 2x2 matrix architecture, where the vertical axis denotes socioeconomic challenges to mitigation and the horizontal axis denotes socioeconomic challenges to adaptation (O'Neill et al., 2014). The two axes produce four quadrants that represent the varying degrees of challenges for mitigation and adaptation. From the four quadrants, four contrasting SSP archetypes are defined. Also, one more scenario archetype that represents moderate challenges to mitigation and adaptation is added. These marker scenarios are labelled SSP1 to SSP5:

- SSP1: Low challenges for both mitigation and adaptation
- SSP2: Moderate challenges for both mitigation and adaptation
- SSP3: High challenges for both mitigation and adaptation
- SSP4: Low challenges for mitigation but high challenges for adaptation (adaptation challenges dominate)
- SSP5: High challenges for mitigation but low challenges for adaptation (mitigation challenges dominate)

Source: O'Neill et al. (2017)

Figure 5 The shared socioeconomic pathways scenario framework

2.3.1 Challenges to Mitigation and Adaptation

Defining challenges to mitigation usually falls back on technological innovations to remove GHG emissions from the atmosphere and to reduce emissions through the efficient use of energy. Essentially, the availability of backstop technology is posited as one of the determinants for mitigating climate change. However, Tompkins and Adger (2005) argue that challenges to mitigation should be defined with respect to the society's response capacity as well. They add that the response capacity of society is derived from both the availability of new technology and society's willingness (and ability) to change. Without willingness to change, society may resist certain technological innovations even though they are useful for mitigating climate change. As observed, social acceptance of electric vehicles took a bumpy ride in the early 2000s because of certain social actors' refusal to change (e.g., automakers, policymakers, regulators) (Paine, 2006). In addition to the factors that lead to higher GHG emissions, socioeconomic factors that can influence mitigative capacities are also part of the SSP scenarios (O'Neill et al., 2014).

Challenges to adaptation characterize the human dimensions of exposure and vulnerability to climate hazards or impacts as well as their capacity to respond to these impacts (Rothman et al., 2014). Many socioeconomic factors (e.g., poverty, inequality, institutional governance) can provide indications of vulnerability (Kelly and Adger, 2000). To what extent a community can be vulnerable and their ability to recover from climate impacts depend partly on the adaptive capacity of those impacted by climate change (Smit and Wandel, 2006). For the new scenario framework, the socioeconomic factors that may have an adverse effect on the adaptive capacities (e.g., income and educational attainment) are included as the elements of the SSPs (O'Neill et al., 2014).

Through a series of meetings and workshops, a number of candidate elements were identified and subsequently used to produce development pathways for individual SSPs (O'Neill et al., 2014). Further, the elaboration for how these SSP elements interact was investigated in two studies (Rozenberg et al., 2014; Schweizer and O'Neill, 2014). Schweizer and O'Neill (2014) applied CIB analysis (Weimer-Jehle, 2006) to search for interacting elements. The judgments for how these elements interact were obtained through an expert elicitation workshop and documented in a cross-impact matrix. Their study identifies 1000 of the most consistent scenario configurations, which were then mapped to the corresponding SSP archetypes. Because the scenario configurations produced by CIB analysis along with the if-then statements embedded in the cross-impact matrix can provide information for how different elements interact, this information was subsequently used for developing the SSP qualitative components (O'Neill et al., 2014).

2.3.2 Quantitative and Qualitative Components

The SSP framework has two output components (quantitative and qualitative) that can be utilized for impact and vulnerability assessments (Moss et al., 2010). The qualitative components are the SSP narratives (or storylines). These narratives describe societal development pathways that cannot be quantified such as quality of governance, social attitudes and preferences (O'Neill et al., 2017). Drawing from the study by Schweizer and O'Neill (2014), the narratives also describe the interrelationships among SSP elements. The narratives are the shared assumptions that can be used by the scientific community for more detailed regional, national, or sectoral analyses.

O'Neill et al. (2017) explained three considerations for developing the SSP narratives. First, the narratives are intended for 'general purpose,' meaning that they should encompass as much as possible the broadest context of societal developments. Second, the narratives should describe a particular challenge to mitigation and adaptation. For instance, the narratives for SSP1 and SSP3 should be distinguishable as the challenges to both mitigation and adaptation for SSP1 and SSP3 are different. Third, the framing of the narratives should take into account the storylines developed under the IPCC legacy scenario frameworks including other scenarios related to climate change. As O'Neill et al. (2017) put it, there are consistent recurring themes (e.g., economic growth, environmental sustainability) across scenario narratives even though these are developed by different teams (Carpenter et al., 2005; Raskin et al., 2002). The narratives for SSP1 to SSP5 are shown in Appendix A.

The quantitative components of the SSPs are the numerical projections of the SSP elements, which will be useful as inputs to computational models (e.g., IAMs). The quantification data are curated and made publicly available by the International Institute for Applied Systems Analysis (IIASA)[5] (Riahi et al., 2017). Central to the SSP framework is the 'raw' data on the basic elements of the SSPs such as population (K.C. and Lutz, 2017), GDP (Crespo Cuaresma, 2017; Dellink et al., 2017; Leimbach et al., 2017), and urbanization (Jiang and O'Neill, 2017). Additionally, data for individual SSP marker scenarios are available (Calvin et al., 2017; Fricko et al., 2017; Fujimori et al., 2017; Kriegler et al., 2017; van Vuuren et al., 2017). Data are also available for studies on limiting temperature increase below 1.5 degrees (Rogelj et al., 2018).

Some identified scenario elements are relevant to both mitigation and adaptation. Of course, some of these elements may need further unpacking to distinguish in what context they are relevant to defining socioeconomic challenges to mitigation or adaptation. For example, an element such as 'governance' could be considered effective for mitigation but poor for adaptation. Governance in the SSPs framework represents an umbrella term. While this may seem to be a limitation, it is, nonetheless, more feasible to unpack the meaning of *governance* in the extended SSP studies (O'Neill et al., 2014).

2.3.3 Basic and Extended SSPs

Basic or global SSPs can be considered as the starting point for a more detailed regional/local and sectoral analyses (or extended SSPs). The initial global framing can be useful in understanding local dynamics because many factors operating at the global scale can exert influence on regional

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[5] https://tntcat.iiasa.ac.at/SspDb/

or local developments (O’Neill et al., 2017). Recognizing that many driving forces are multi-scale is critical to support studies on climate impacts, adaptation and vulnerability (IAV) (Rothman et al., 2014; Wilbanks and Ebi, 2014). For instance, prices of commodities (e.g., wheat) are determined based on the analyses of global demands, and global prices are also important for regional or local scale analyses (Valdivia et al., 2015).

For more detailed regional/local and sectoral analyses, the research community can extend the global SSPs (O’Neill et al., 2014). The SSP extension studies can incorporate a broader scope of scenario elements, which are not already part of the global SSPs. For example, studies on disaster risk management in a local community can include many elements such as the availability of flood risk maps, financial instruments for risk transfer, social capital, building codes—these elements are not part of the global SSPs but they are useful for local decision makers. Studies can extend the global SSPs to different contexts (regional, local, or sectoral). Also, studies can extend the global SSPs to produce a framework (like the basic SSPs) that can support further development of localized scenarios (O’Neill et al., 2014). However, it is important for the extension studies to link to the global SSPs. Studies on extending the SSPs should inherit the global ‘boundary conditions’ to ensure that scenarios under the extended SSPs are consistent with the global developments (Ebi et al., 2014; O’Neill et al., 2014; van Ruijven et al., 2014).

The prevailing guidance for conducting SSP extension studies explains two approaches to link to the global SSPs (van Ruijven et al., 2014). Firstly, the SSP qualitative components can be extended using narrative downscaling (Kok et al., 2006). For narrative downscaling, the SSP narratives will be translated to similar but more relevant narratives at the local scale. Typically, narrative downscaling can be conducted in a scenario planning workshop by engaging local stakeholders to participate in producing the narratives of the SSP extension studies. Remember, this process typifies the scenario-as-a-process and, therefore, reaps the benefits associated with the scenario-as-a-process (e.g., mobilizing knowledge and internalizing problems among the participants). Secondly, SSP extension studies can be linked to the global SSPs through quantitative downscaling; this approach is synonymous with scenario-as-a-product. Accordingly, such a study would produce quantitative projections of some variables to serve as a scientific assessment. In terms of the benefits of scenario studies under the SSP framework, the research community has the flexibility to choose which approach is more suitable according to the objective of their scenario studies.

In some situations, the scope of the global SSP might not be broad enough to be extended usefully since many SSP extension studies would require scenario elements that are operating at a more localized scale. This situation can happen when the scope of an extended SSP study is vastly different (e.g., oceanic systems, food systems, financial systems). As mentioned, the global SSPs are comprised of socioeconomic factors that can be generalized at the global scale. In so doing, many socioeconomic factors operating only at regional or local scales are excluded in the scope of the global SSPs. Consequently, studies on extending the SSPs whose scopes are vastly different may prove challenging.

An important point for consideration is that studies on extending the SSPs in different contexts are unlikely identical (Absar and Preston, 2015; Frame et al., 2018). This is because the SSP framework allows more flexibility to incorporate socioeconomic driving forces operating at a more localized scale. In this respect, studies on extending the SSPs need to embody the 'boundary conditions' provided by the global SSPs (O'Neill et al., 2014). Alhough global scenarios cannot be 'downscaled' in a deterministic fashion, the global SSPs can provide a mechanism to 'restrict' the extended SSPs studies from producing scenario outcomes that deviate immensely from the global developments (Ebi et al., 2014; van Ruijven et al., 2014). For a more detailed regional, national, and sectoral analyses, the global SSPs provide the initial framing allowing key assumptions for how scenario elements operating at the global scale be included in the extension studies. Subsequently, new scenario elements operating at a more localized scale will be incorporated (O'Neill et al., 2014). However, incorporating new elements—other than those that already defined the global SSPs—means that the SSP extension studies may possibly be 'incompatible' with the representative developments at the global level and, therefore, these studies can only be either *coherent* or *comparable*.

2.4 Extending Shared Socioeconomic Pathways

The basic or the global SSPs are already defined, the research community can now extend the global SSPs for more detailed regional, national, or sectoral analyses. The main criterion for SSP extension studies to be consistent with the global SSPs is that these extension studies must be linked to the global SSPs (Ebi et al., 2014; O'Neill et al., 2014; van Ruijven et al., 2014).The aims of extending the SSPs are (1) to develop a small number of extended SSPs at different scales (e.g. levels or sectors) and (2) to use the extended SSPs to support further development of a large number of scenarios which are more refined to address specific spatial or sectoral context (O'Neill et al., 2014; Schweizer, 2018). The extended SSP studies could produce either quantitative elements or qualitative storylines or a combination of both. Many studies align with the prevailing guideline for developing the extended SSPs, published in *Climatic Change* as part of the first special issue during the formalization of the SSP framework (van Ruijven et al., 2014). In this guideline, two modes of entry for extending the SSPs are proposed. First, studies can use the quantification of key SSP elements (i.e., the quantitative components of the SSPs) as the 'entry-point' to develop the extended SSPs (van Vuuren et al., 2010). Second, studies can also use the SSP narratives (i.e., the qualitative components of the SSPs) as the entry-point, especially when studies require SSP elements that can only be described qualitatively. This second mode is called narrative downscaling (Kok et al., 2006). Accordingly, these two modes are the most common approaches employed by SSP extension studies.

Some extended SSPs studies, however, do not lend themselves to these two approaches. This happens when the qualitative and quantitative components of the SSPs do not provide sufficient information related to the main driving forces operating at a more regional/local scale. Although the global SSP narratives are designed to capture a broad scope of socioeconomic factors, regional/local and sectoral analyses may require elements that are beyond the scope of the global SSPs. For instance, the roles of specific actors and institutional governance, which are considered relevant in impact, adaptation, and vulnerability (IAV) research, appear to be lacking in the global SSP narratives (Absar and Preston, 2015). Furthermore, the components of the SSPs lack the necessary elements to usefully describe the development (or deterioration) of a biophysical system (e.g., Maury et al., 2017) and/or a niche social system (e.g., Palazzo et al., 2017; Valdivia et al., 2015).

2.4.1 Modes of Entry for Extended SSPs

Since the formalization of the SSP framework in 2014, research communities have conducted more than 60 SSP extension studies and counting. In addition to the two approaches prescribed by van Ruijven et al. (2014), there are two other approaches innovated by the research communities that tap into different entry-points. One study has chosen to 're-specify' the extended SSP elements to develop a more detailed socioeconomic pathway(s) relevant in the context of New Zealand (Frame et al., 2018). As the authors explain, many socioeconomic variables necessary to represent the development pathways in New Zealand cannot be captured by simply downscaling the global SSP quantitative and qualitative components.

Table 1 SSP extension studies linked to the global SSPs differently

Authors/Year	**Entry-point**	**Context: Sector**	**Context: Spatial**	**Study Description**
Sanderson et al. (2019)	SSP Quantifications	Wildlife Conservation (tiger population)	Regional: Tiger conservation landscapes	Utilized SSP quantitative elements (e.g., gridded population) and superimposed known tiger conservation areas to calculate the decline in conservation areas, hence, declining tiger population can be estimated
Huang et al. (2019)	SSP Quantifications	Socioeconomic (population)	National: China	Presented alternative population projections for China under three fertility policy assumptions
Kemp-Benedict et al. (2014)	SSP Narratives	Sustainable Forest Management	Regional: Europe	Downscaled SSP narratives to identify the enabling conditions for sustainable forest management and applied CIB analysis to produce internally consistent scenarios
Absar and Preston (2015)	SSP Narratives	Resilience/ Adaptation	National/ Subnational: US / US Southeast	Produced corresponding national and subnational narratives by downscaling SSP1,2,3 and 5 narratives
Frame et al. (2018)	SSP Elements	Socioeconomic (all relevant factors)	National: New Zealand	Re-specified the elements for SSP extension study that are relevant in the New Zealand context
Maury et al. (2017)	SSP Archetypes	Ocean Biodiversity	Global	Produced an equivalent framework called Oceanic System Pathways (OSPs) that correspond to the global SSPs
Palazzo et al. (2017)	SSP Archetypes	Agriculture	Regional: Southern Africa	Produce an equivalent framework called Representative Agricultural Pathways (RAPs) that correspond to the global SSPs

Another approach is to tap into the SSP archetypes as the entry-point. This does not mean that studies using this approach would utilise the SSP archetypes. Rather, they would produce new scenario frameworks that are compatible to the SSP archetypes. For each SSP representative pathway, a corresponding development pathway would be produced by these new scenario frameworks. For instance, Maury et al. (2017) produced a framework to assess socioeconomic and biophysical changes of the oceanic system called Oceanic System Pathways (OSPs). Under the OSP framework, a representative pathway was developed to be compatible with each SSP (i.e., OSP1 is compatible with SSP1 and so on). Table 1 details the illustrative studies reviewed to examine the mode of entry of these SSP extension studies and in what context (sectoral/spatial) these studies are directed.

2.4.2 Quantitative Downscaling and Extending Gridded Quantification of SSP Elements

Research communities have published various studies on the quantification of the key SSP elements in a special issue in *Global Environmental Change* (Riahi et al., 2017). The quantification of key SSP elements includes data on population, urbanization, and economic growth. Extending the quantification of SSP elements is typical in any model-based assessment (see e.g., van Vuuren et al., 2010). Within the IAM research community, studies using similar approaches are well established (see e.g., Sarofim and Reilly, 2011), including studies under the Story and Simulation framework (Alcamo, 2008; Carpenter et al., 2005; Trutnevyte et al., 2014). The use of quantification of SSP elements as an entry-point for extending the global SSPs lends itself well to research disciplines or areas that are traditionally computational or modelling intensive such as food systems (Bai et al., 2018b, 2018a; Hasegawa et al., 2014; Mullon et al., 2017), the water sector (Fischer et al., 2016; Graham et al., 2018; Hanasaki et al., 2013; Neverre and Dumas, 2015) and biophysical or geophysical systems (Mogollón et al., 2018b, 2018a; Nauels et al., 2017).

Study methods to extend the treatments of the SSP quantitative components tend to vary. For example, gridded quantification will utilize spatial data on population and income used in land-use models, e.g., estimate the size of agricultural land and determine the prerequisite demands for reactive nitrogen and phosphorous (Mogollón et al., 2018b, 2018a). Research communities have also shown to be very innovative in developing SSP extension studies through the use of gridded quantification. At times a generic quantitative component of the SSPs such as population was applied creatively to produce a superficially unrelated data like tiger population (Sanderson et al., 2019). To account for the number of tigers in their natural habitat, Sanderson et al. (2019) used a geospatial population forecast (Jones and O'Neill, 2016) to determine the extent of land-use change due to population concentration and urban development adjacent to tiger conservation landscapes (TCLs). A TCL is defined as an area for effective habitat for tigers. Spatial data of known TCLs were super-imposed on the SSP geospatial population forecast to determine the extent of population concentration encroaching on the known TCLs. Coupling the information on potential loss of TCLs with the evidence on minimum requirement for habitat area to maintain the current tiger population, the world's tiger population can be estimated and projected to 2100 under different SSPs.

Alternatively, a quantitative downscaling approach can be applied for specific spatial analyses that incorporate more detail and local-specific data. For instance, Huang et al. (2019) extended the quantification of the SSP population projections at a national level for China. The entry-point that links to the global SSPs is the quantification of the SSP population (K.C. and Lutz, 2017). The existing SSP population data for China are aggregated and may not account for potential changes in non-climate policies. However, this extension study considers changes in China's fertility policies (i.e., one-child, two-child, and full liberalization). In this study, the updated population data are provided by calculating 'offsets' for each SSP projection under three different policy considerations. Each SSP population data for China now comprises not just one representative pathway (i.e., SSP1 through SSP5) but three projections under different policy assumptions—for example: population under SSP1 with the one-child policy, with a two-child policy or with a full liberalization of fertility policy. This new extended SSP population data for China can serve as inputs to spatial/sectoral-specific analyses or modelling exercises to produce a wider range of alternative scenarios.

2.4.3 Downscaling SSP Narratives

Another entry-point for SSP extension studies to link to the global SSPs is the SSP narrative (van Ruijven et al., 2014). For narrative downscaling, the global SSP narratives will transfer their boundary conditions when being 'downscaled' to produce extended SSP studies. Narrative downscaling thus suggests that the extended studies are nested within the global development pathways (Kok et al., 2006). In theory, such an approach can constrain the production of regional/local and sectoral development pathways so that only consistent scenarios are produced. Further, narrative downscaling approaches allow researchers to incorporate any scale-specific element necessary for more detailed local or sectoral analyses. Extension studies that use SSP narratives as the entry-point will usually employ other scenario development methods to construct qualitative scenarios relevant to the study context. The qualitative scenarios can be translated to quantitative trends to serve as inputs to regional models for further analyses. Since the SSP narratives are developed with 'general purpose storylines,' covering a wide range of topics or issues (e.g., water, energy, technological development) in the context of climate change (O'Neill et al., 2017), SSP narratives are intended to appeal to broader research communities.

In some cases, the narrative downscaling approaches are useful for constructing scenarios whose scope are different from those of the global SSPs. For instance, elements in the context of sustainable forest management (SFM) may be different from the global SSP elements as evidenced in a 2014 SFM study by Kemp-Benedict et al. (2014). Their study aims at examining factors important for SFM in the European region, which was done by subjecting SSP narratives to a qualitative analysis to identify what they called 'prerequisite conditions.' The process includes scoping for factors or drivers that may present a condition necessary for SFM in a world depicted by individual SSP narratives. For example, an excerpt from the narratives of the SSP1 (Sustainability) world indicates good progress toward sustainability; this translates into an enabling condition that needs long-term commitment to SFM. The enabling conditions are scenario elements necessary for constructing storylines in the context of SFM.

The contextual scenarios with their respective narratives for the SFM study were produced using cross-impact balance analysis (Weimer-Jehle, 2006) through stakeholder engagement workshops. These contextual scenarios were evaluated whether their respective scenario narratives would be plausible in a given SSP world. Thereafter, the author team assigned these contextual scenarios to the closest SSP. Mapping contextual scenarios to the SSPs is a valuable exercise to assess whether local developments could deviate from global developments (van Ruijven et al., 2014); this is critical in IAV research.

The IAV research community recognizes that multiple stressors from different scales, levels, and sectors can influence the resilience and the adaptive capacities of local communities (O'Brien et al., 2004; Rothman et al., 2014; Smit and Wandel, 2006). In IAV research, extending the SSPs may appear complex and challenging; however, that may not be the case as the study by Absar and Preston (2015) has shown. Their study on the extended SSPs is grounded on the context of resilience and adaptation for communities in the US Southeast. Their study remarkably performed two-level narrative downscaling, meaning that the downscaling was done not once but twice. Firstly, the global SSP narratives were downscaled one level (to the national level) to produce narratives for the US. Then, the scenario narratives for the US were downscaled another level (to the subnational level) to produce narratives for the US Southeast.

The scenario narratives for the extended SSPs in their study were produced using the Factor-Actor-Sector (FAS) framework (Kok et al., 2006). Several elements described by the global SSP narratives already correspond to factors that lend themselves well to the FAS framework. Accordingly, these factors were teased out from the four SSP narratives [6]. Specific actors who are involved in the governance of natural resources in different sectors (e.g., energy, water, agriculture) at the national and subnational levels were identified through a series of stakeholder workshops. Within the context of their research, the author team has found that the global SSPs

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[6] In Absar and Preston (2015), the SSP4 is excluded in the study because, according to the authors, the SSP4 narratives, which depicts low socioeconomic challenges to mitigation but high socioeconomic challenges to adaptation, was considered less plausible in the context of developed nations.

lack detailed information for national/subnational and sectoral analyses. Elements necessary for the analyses that were not articulated by the global SSP narratives must be re-defined in the extended SSP study. The lack of detail forced the author team to use current data on socioeconomic situations from other sources for extrapolating development pathways at national and subnational levels. This issue presents a challenge in assessing both vertical and horizontal cross-scale consistencies for such a multilevel study, which requires disparate elements for different levels of analyses. Under Zurek and Henrichs' (2007) linking categorization, such scenarios produced by narrative downscaling will be considered either *coherent* or *comparable* rather than *consistent*.

2.4.4 Re-specifying SSP Elements

There can be a situation when the scope of the SSP components (quantification of key SSP elements and qualitative narratives) are not sufficiently broad to be useful in constructing the extended SSPs. This can happen, for instance, for characterizing the formal and informal economy. While the formal economy is market-based and highly concentrated in the urban and industrialized areas, the informal economy is non-market based and may be geographically sparse, located in rural areas that may include subsistence activities operating at different scales (Larsen and Huskey, 2015). The existing data on the economy (e.g., GDP or income in monetary values) do not usually account for informal economic activities, many of which do not involve monetary exchange (e.g., customary practices of giving and sharing, see Ford et al.(2006)). However, the informal economy can be important for understanding socioeconomic challenges in a rural context. Such a situation demands that extended SSP elements be re-specified to better reflect the local or sectoral dynamics. Re-specification of the SSP elements may appear confusing at first because the SSP framework has been so closely associated with its quantitative and qualitative components to the extent that these components have become synonymous with the SSPs, and therefore the SSPs are not 'mutable.' However, one can strip the SSPs to a bare minimum to access the key elements of the SSPs. These key elements can be retained as well and re-specified to include new elements necessary for regional/national and sectoral extension studies. Studies on extending the SSPs by re-specifying the (extended) SSP elements as the entry-point are still uncommon; nonetheless, such an approach can permit some form of flexibility for researchers to incorporate more detail and contextually relevant driving forces that are different from the original scope of the global SSPs.

In the development of the extension study for New Zealand, the author team (Frame et al., 2018) began by selecting several SSP key elements described in O'Neill et al. (2014). Subsequently, they introduced more elements that are relevant in the New Zealand context. Further, this study also incorporates many qualitative elements necessary to assess climate risks at the local scale. These qualitative elements include, for example, attitudes towards international trade, technological capacity, and migration policies (Frame et al., 2018). Additionally, this study taps into the SSP quantitative elements such as data on population in addition to the acquired domestic data. Overall, this study draws many elements necessary to model the socioeconomic futures for New Zealand. For an extended SSP study, such a scope is comprehensive and more detailed than the original scope of the global SSPs. A detailed SSP extension study like this one proves useful to support other localized scenario studies (see e.g., Ausseil et al., 2019). However, the use of new scenario elements in the extension studies would deem the produced scenarios as either *coherent* or *comparable* with the global SSPs.

2.4.5 Adapting SSP Archetypes

The SSP narratives and the quantification of SSP elements may not necessarily cover many elements relevant for regional or sectoral extension studies. For example, potential crop yields and price trends are important elements for the regional and local scales in the agricultural sector (Valdivia et al., 2015), but this information is part of neither the storylines nor the quantification of SSP elements. In response to this limitation, researchers innovate new ways to link their studies to the global SSPs by adapting the SSP archetypes. Such studies can either retain the SSP archetypes or develop a new but compatible framework.

The representative agricultural pathways (RAPs) are the 'SSPs' of the agriculture sector, meaning RAP1 is compatible with SSP1 and so on (Palazzo et al., 2017; Valdivia et al., 2015). The development of the RAPs for regional level analyses follows a bottom-up approach. The bottom-up model describes studies on extending the global SSPs, which are performed independently at first, but are afterwards linked to the global SSPs to ensure scenario consistency across scales (Ebi et al., 2014; van Ruijven et al., 2014). Like the SSPs, the process of developing the RAPs began with the construction of a 2x2 matrix; yet unlike the SSPs, four (not five) scenario archetypes are produced. These archetypes are called *Cash, Control, Calories; Self-determination*; *Civil Society to the Rescue?* and *Save Yourself* (Valdivia et al., 2015). The RAP framework and narratives were produced from a series of scenario planning workshops, involving regional stakeholders to assess regional impacts of biophysical and socioeconomic changes and identify scenario elements in the respective regional context (Palazzo et al., 2017). The narratives of the RAP were quantified and then used as inputs to global models (i.e., AgMIP or the Agricultural Model Intercomparison and Improvement Project) to produce trend indicators such as crop yields and prices (Valdivia et al., 2015). Finally, the author team employed a one-to-one mapping to match RAP trend indicators and narratives with the global SSPs.

Another extension study that links to the SSP archetypes, the Oceanic System Pathways (OSPs), describes the socioeconomic challenges for global oceanic ecosystems (Maury et al., 2017). The aim of the OSPs is to lay the foundation for more detailed regional/local and sectoral analyses related to the oceanic system. Like the RAPs, the development of the OSPs is also bottom-up, which means the OSP framework was developed independently of the global SSPs, only to be linked to the global SSPs afterward. Three major domains related to oceanic social systems were first identified, namely management, governance and the economy. For each domain, key elements were selected by the participants of the scenario planning workshops. Subsequently, scenario narratives for the OSPs were individually constructed from these elements, making sure that the OSP narratives produced were compatible with each SSP, and therefore 'consistent.' In leading to the development of the OSPs, the author team found that operationalizing the transfer of boundary conditions from the global SSPs to the extension study was challenging. Because neither the SSP narratives nor the quantifications are sufficiently detailed to determine the boundary conditions of the oceanic system, the OSPs could not be developed through other modes of entry described earlier. Since the RAPs or OSPs only have similar scenario archetypes, by definition according to Zurek and Henrichs (2007), these studies are only *complementary*.

2.5 Are Extended SSPs Consistent Across Scales?

In scenario research, it is imperative that scenarios developed for multiple scales are consistent so that these scenarios do not contradict each other (Biggs et al., 2007; van Ruijven et al., 2014; Wiek et al., 2013; Zurek and Henrichs, 2007). However, there is a lack of consensus over the accepted definition of cross-scale scenario "consistency"; researchers are adamant that consistency across scales is a must-have, but many researchers have different takes on what it means. Drawing upon the SSP literature, consistency can refer to the 'constraint' where regional/local development pathways should not deviate immensely from the SSP reference pathways (Ebi et al., 2014; van Ruijven et al., 2014). However, the dominant definition of scenario consistency in environmental scenario research is entrenched to scenario linking categories, a seminal work of Zurek and Henrichs (2007). Ultimately, developing scenarios for extended SSPs that are linked to the global SSP will often use different scenario elements and assumptions; thus, these scenarios can be wrongfully categorized as 'inconsistent' as depicted in Figure 4.

Studies that are linked to the SSP quantifications (i.e. by quantitative downscaling) can be categorized as either *equivalent* or *consistent* across scales according to Zurek and Henrichs (2007). When extension studies are linked to the SSP narrative by means of narrative downscaling, such extensions can be considered 'consistent' across scales as long as there are no new scenario elements introduced into the process of developing the extended SSPs. However, when extended SSPs were developed by incorporating new scenario elements that are different in terms of the assumptions for how the driver would play out in the future (Absar and Preston, 2015; Kemp-Benedict et al., 2014), such studies will be either *coherent* or *comparable*. Studies could also re-specify SSP elements and include new regional or local scenario elements; therefore, these studies are only considered *comparable*. For extension studies that adopt the SSP archetypes such as RAPs and OSPs, they retain only the SSP framework; additionally, these studies utilize drivers and assumptions different from the global SSPs. In this case, RAPs and OSPs may be considered *complementary* across scales. In other words, quantitative downscaling will produce scenarios that are *equivalent* or *consistent* across scales, whereas techniques such as narrative downscaling, re-specifying SSP elements and producing compatible scenario frameworks may be considered 'inconsistent' across scales.

Thus there is a pressing need to clarify what *consistency* actually means (see e.g., Kok et al., 2019). For scenarios developed through narrative downscaling, it involves selecting and using the same key elements of the global SSP strictly for developing the extended SSPs in order to be consistent with the global SSPs. However, Kok et al. (2019) expressed two challenges: first, (1) to what extent the scenarios at different scales must be similar to be considered consistent. Second, (2) many key assumptions for both global SSPs and extended SSPs (e.g., regional, provincial) may not be compatible. Therefore, many SSP extension studies will not be consistent with the global SSPs. As Rohat et al. (2018) rightly put it, a clear direction is needed to explore more options for systematic consistency checks. One way to assess scenario consistency is to use cross-impact balance (CIB) analysis (Schweizer and Kurniawan, 2016; Schweizer and O'Neill, 2014; Weimer-Jehle, 2006), which will be further elaborated in Chapter 4 and 6.

2.5.1 Linking Global SSPs Via Cross-impact Matrix

The key elements of the global SSPs are socioeconomic variables of societal futures necessary for identifying higher or lower challenges to mitigation and adaptation (O'Neill et al., 2014). And these key elements will influence regional or national developments in many sectors such as domestic energy systems. However, using only SSP elements may not be sufficient for examining national energy futures in the different geographical context for a couple of reasons. First, there may be variables that are important domestically that are not part of the global SSPs. For instance, certain sub-sectors (e.g., transportation, oil and gas production) may have significant influences in the development of nation's energy systems. For example, oil sand production can be considered an important sector for Canada for national level analyses. However, oil sands are generalized as an economically substitutable energy resource for global analyses, while their substitutability may be less true in the Canadian context (i.e., they are more of an asset). Second, socio-technical aspects relevant to the energy sector are also underrepresented by the global SSPs. Although one of the SSP elements, 'technological change in energy efficiency', relates to socio-technical change, this element presents an 'umbrella' term that aggregates all socio-technical changes. As research has shown, the rate of technological transition for different technologies varies (Sovacool, 2016). In this respect, SSP extension studies in the Canadian context require new elements to be specified. New candidate elements for national and sectoral analyses can be identified to support the development of more detailed national energy scenarios.

To find self-consistent multi-scale energy scenarios, the CIB analysis was deployed. The CI matrix that models national energy systems was constructed and then joined to the CI matrix for the global SSPs developed by Schweizer and O'Neill (2014). The resultant multi-scale CI matrix is comprised of scenario elements related to global socioeconomic driving forces and nations' energy development. The method employed to link this extension study to the global SSPs re-specifies SSP elements, including introducing new elements for national level analysis. This means that in the CIB analysis, the scenario elements for the global SSPs are used in conjunction with the new scenario elements useful for developing national or sectoral scenarios on energy futures.

2.6 Conclusion

The goal of this chapter is to review existing literature on multi-scale environmental scenarios. Multi-scale scenario literature has discussed cross-scale consistency as a requirement. Although the scenario research community agrees on the importance of ensuring cross-scale consistency, their agreement ends there. Currently, there is no consensus on what is meant by cross-scale consistency. This issue on scenario consistency across scales should not be taken lightly, especially with the small but growing number of SSP extension studies for climate change research. This review is used to introduce the SSP framework. Under the SSP framework, the requirement is that all extension studies must be linked to the global SSPs so that scenarios extended to regional, local or sectoral scales are consistent with the global SSPs. In this dissertation, linking the national energy scenario study to the global SSPs was done by re-specifying the SSP elements, meaning that the relevant elements for domestic energy futures were incorporated along with the existing global SSP elements. Next, Chapter 3 will introduce the study context, Canada.

Chapter 3: Canadian Energy Scenario Studies

This dissertation was set out to develop globally linked internally consistent scenarios by extending the Shared Socioeconomic Pathways for national or sectoral analyses. The case of Canadian energy futures was used in this dissertation. As discussed in Chapter 2 previously, it is imperative to incorporate new scenario elements necessary for developing energy scenarios in different national contexts as these elements are not specified under the scope of the global SSPs since the key SSP elements are meant to be generic. The existing CI matrix of the global SSPs developed by Schweizer and O'Neill (2014) would be extended to incorporate scenario elements for developing national energy scenarios. This Chapter 3 introduces the study context (i.e. Canada) and reviews recent energy scenario studies in Canada.

3.1 Introduction

An energy system is comprised of interconnected sub-systems that produce and deliver energy sources to energy services (Potvin et al., 2016). In the face of climate change, efforts to limiting global average temperature increases to 2˚C will transform global energy systems drastically (Bataille et al., 2015; Schweizer and Morgan, 2016; WEC, 2017). Traditionally, energy transitions were primarily motivated by cost, convenience, and the availability of technological innovations (Verbong and Geels, 2010). Recently, energy strategies undertaken by individual countries to address accelerating climate change can also include transitioning to low carbon energy alternatives domestically (Potvin et al., 2016).

Domestically, the focus of the Canadian energy strategy is expressed in the Pan-Canadian Framework on Clean Growth and Climate Change (Government of Canada, 2017), which is to transition to a lower carbon economy (Potvin et al., 2016). Not only does the low carbon economy pertain to the energy sector, it encompasses most, if not all, economic sectors such as agriculture, tourism, transportation, and fisheries. Nevertheless, the Pan-Canadian Framework has identified several primary sectors, which will be key in reducing Canada's greenhouse gas (GHG) emissions. These sectors are:

- Electricity (focus on electricity generation from low-carbon or alternative fuels such as renewable resources)
- Built environment (focus on energy conservation and energy efficiency for commercial and residential buildings)
- Transportation (focus on low-carbon transportation systems)
- Industry (focus on energy efficiency of industrial heat production and clean technology investments)
- Forestry, agriculture, and waste (focus on increasing carbon sinks and electricity generation from bioenergy)

While the goal of the Pan-Canadian Framework is already expressed, it remains unclear how certain Canadian provinces could decarbonize their economy. As identified by Potvin et al. (2016), one of the challenges is the large export-oriented fossil fuel production sector, and by extension the mining sector, in these provinces (e.g., Alberta, Saskatchewan, Newfoundland). Fossil fuel production is largely concentrated in specific provinces (i.e., Alberta, Saskatchewan), and they would need to venture to other green economic sectors as alternative to fossil fuel production. By investing and supporting alternative green sectors, the Canadian economy can possibly relinquish its dependence on the national income generated by the fossil fuel production sector since both fossil-fuel and mining sectors contribute to a large proportion of Canadian GDP (8.4% of total GDP in 2017)[7]. However, development pathways towards decarbonization require the Canadian economy to be 'decoupled' from fossil fuel production, meaning that the economic performance of oil and gas sectors domestically and globally could have hardly any impact on the Canadian economy. Such an ambition thus requires Canada to transition to low-carbon energy futures; yet, this is not an easy feat. Although the federal government is the one that pledged an emissions reduction target (i.e., to reduce its GHG emissions by 30% below 2005 levels by 2030) on the international stage, provincial governments are the main actors to legislate aggressive policies for emission reductions.

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[7] Data on GDP by industrial sector were retrieved from Statistics Canada (https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3610043402). The oil and gas sector alone contributed to 6% of total GDP in 2017. Together with mining and quarrying, this industrial sector is the third largest industrial sector in Canada since 1997 (8.4% of total GDP) behind real estate (13% of total GDP) and manufacturing (10.3% of total GDP).

3.2 Scenario Studies on Canada's Energy Future

Transitioning to low-carbon energy futures is challenging for Canada since the current state of the Canadian energy system is based on the legacy carbon-intensive economic and social structures (Potvin et al., 2016). Canada can be expected to undergo societal and structural changes in the future, reshaping the future of Canada's energy system. But changes take time, nonetheless, since there is no abrupt change in energy transition as historical accounts have shown. For instance, the energy (supply) transitions to coal, oil, and gas took almost 100 years (Sovacool, 2016). Foresight exercises have been used to explore and better understand what would be plausible in 50 to 100 years. Researchers have used scenario techniques to explore many development pathways under different assumptions of global or domestic conditions for how Canada's energy system will take shape in the future.

Studies on Canada's energy transition also incorporate different global assumptions. Notably, studies such as Re-Energizing Canada (REC) (Potvin et al., 2016), Deep Decarbonization Pathways in Canada (DDPC) (Bataille et al., 2015), the 2018 study by the National Energy Board (NEB, 2018), and three scenarios under the Trottier Energy Futures Project (TEFP) (TEFP, 2016) envision alternative pathways for Canada to be decarbonized with the assumption that the world is decarbonizing. Alternatively, studies such as the NEB 2016 study (NEB, 2016) and eight scenarios under TEFP (TEFP, 2016) assume that the world remains carbonized; accordingly, Canada would remain carbonized like the rest of the world. The depictions of a carbonized world are used to highlight, perhaps unjustly, how a carbonized world would continue to exert influence on Canada to remain carbonized. As a result, Canada's effort to decarbonize become increasingly challenging because of external global driving forces.

Nonetheless, a common theme, which can be drawn from REC, DDPC, TEFP, and NEB studies, is that the developments at the global and Canadian levels are in lockstep. That means Canada could possibly decarbonize in a decarbonized world, but it is also possible for Canada to remain carbonized in a carbonized world. These two portrayals of the future are considered plausible since local developments reflect global developments closely—in this sense, local and global developments are consistent. However, studies rarely examine whether it would be plausible for Canada to remain carbonized while the world decarbonizes or vice-versa (Figure 6). The interest, however, is to explore whether counter-intuitive assumptions (e.g., Canada remains carbonized in a decarbonized world and Canada decarbonizes whilst the world remains carbonized) are even plausible scenarios, viz consistent.

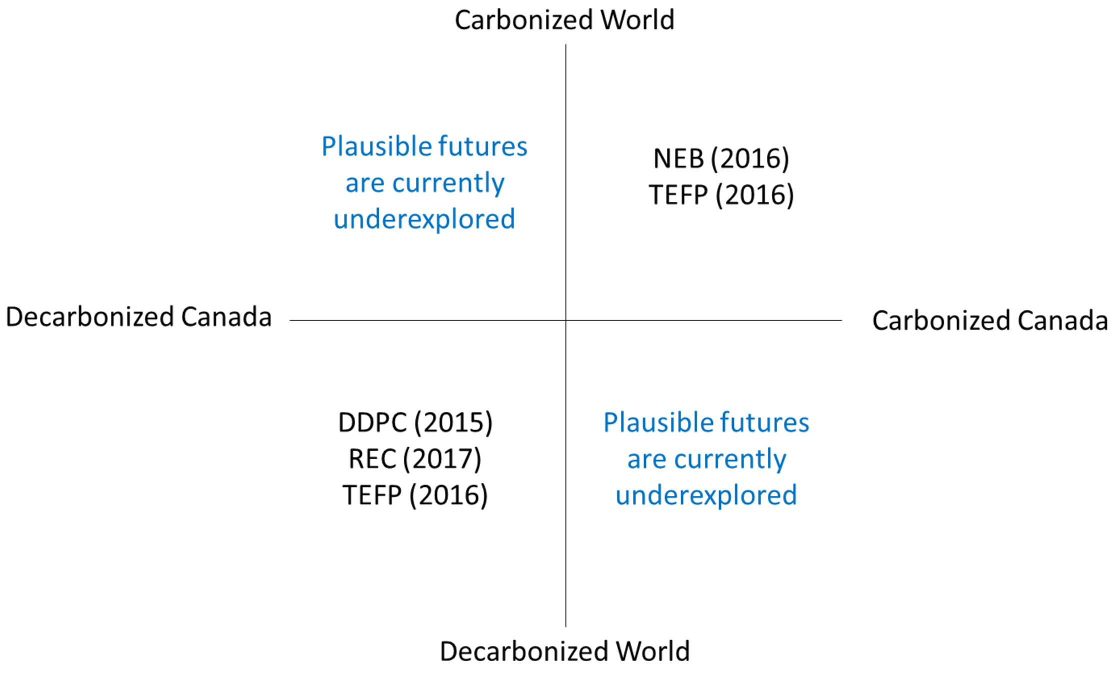

Figure 6 Assumptions used by the four scenario studies on Canada's energy future

3.2.1 Re-Energizing Canada

The Re-Energizing Canada (REC) Report is a scoping study[8] (based on peer-reviewed literature and data) that presents recommendations for which Canada could transition to low-carbon development pathways in a decarbonized world (Potvin et al., 2016). The REC study aims to identify a broad range of driving forces (i.e. scenario elements) that would be useful for examining Canadian energy futures. For the REC study, the author team conducted literature review and highlighted key elements relevant to Canadian energy futures. The study delves deep into provincial differences. That means driving forces or elements that can be considered important in one province could be of less importance to some extent in other provinces. For instance, the reliance on ‘dirty’ coal-fired power generation might be considered important in Saskatchewan and Alberta, but in other provinces or territories such as British Colombia, Quebec, and Yukon --

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[8] In futures studies, this scoping process is also known as environmental scanning (or horizon scanning) which is a step prior to the scenario development process (Glenn and Gordon, 2009).

who rely on ‘clean’ hydroelectric resources—coal may not be considered to be an important issue in the energy transition.

3.2.2 Trottier Energy Futures Project

Technology to support energy transition in Canada is the main theme of the Trottier Energy Futures Project (TEFP, 2016). The TEFP is a quantitative modelling study for combustion emissions. The scenarios produced by the TEFP are based on currently deployed technologies and extrapolate future technological improvement and cost reduction. The overarching aim is to examine the possibility to reduce GHG emissions using known technologies. The TEFP study produces eleven scenarios of which eight scenarios assume that there would be no constraint imposed on the export of fossil fuel, meaning that the world remains carbonized and the demand for Canadian exports of fossil fuel would continue to persist. The remaining three scenarios assume that there would be some constraints due to concerted global actions to reduce GHG emissions, lowering the global demand for fossil fuel and consequently the fossil fuel production in Canada. An interesting situation depicted by the reference scenarios (scenario 1 and 1a) is that Canadian freight transportation could become a major sector contributing to GHG emissions. The most aggressive scenario (scenario 8) shows that, while energy consumption could remain at the 2011 level, the GHG emissions would reduce over time. The emission reduction could be attributed to the ongoing improvements in energy efficiency as well as the shift from combustion to electricity for motive power. However, given the significant reduction required under the most aggressive scenario for mitigating climate change, Canada would still fall short of the 80% emission reduction from 1990 level (425 Mt CO2e) in 2050. As a result, the acquisition of negative emission technologies (NETs) would be crucial towards supporting Canada’s energy transition and meeting the emission reduction goal (TEFP, 2016).

3.2.3 National Energy Board

The National Energy Board (NEB) publishes Canada’s energy supply and demand projections every two to three years (e.g., 2016 and 2018). The 2016 NEB study assumes that fossil fuel remains the primary source of energy in Canada, meaning that GHG emissions would continue to rise over the projection period (i.e., 2040) (NEB, 2016). In the follow-up study in 2018, the assumption (fossil fuel as the primary source of energy in Canada) has changed. Instead, the 2018 study assumes decreasing global and domestic demand for fossil-fuel (NEB, 2018). The local demand for energy, albeit decreasing, could be serviced by alternative low-carbon energy sources such as renewable energy to align with the Pan-Canadian Framework (Government of Canada, 2017). The global demand for Canadian fossil fuel resources could also decline with the increasing ambition of transitioning to low-carbon economies across the world. The NEB studies use the information about existing policies and technological developments to forecast the supply and demand of Canadian oil and gas. These studies rarely include environmental and socioeconomic considerations, unless they are already part of existing policies or technological developments. In the latest 2018 study, four scenario cases were presented: a reference case, a technology case, and high-price and low-price cases (future oil and gas prices). Since the latest study uses the assumption that there will be greater forces and drive towards decarbonization locally and globally, the low-price scenario portrays oil production that would decrease by 25% in 2040 (NEB 2018).

3.2.4 Deep Decarbonization Pathways in Canada

Forecasting the demand and supply of fossil fuel energy resources is challenging due to price volatility of oil and gas in the global market. Instead, the Deep Decarbonization Pathways in Canada (DDPC) study explores plausible scenarios, ensuring economic prosperity as well as contributing to global effort in reducing GHG emissions (Bataille et al., 2015). DDPC assumes that the world is decarbonizing, and Canada will follow suit. The decarbonization efforts at the global level could motivate Canada to decarbonize as well. One should note that the DDPC study does not consider emission targets because the goal of deep decarbonization exceeds the national mitigation ambition. DDPC uses quantitative modelling and scenario analysis to produce six different but overlapping pathways. Each pathway emphasizes a specific theme: (1) decarbonized electrification; (2) improving energy productivity; (3) reduce, cap, and utilise non-energy emissions; (4) move to zero-emission transport fuel; (5) decarbonize industrial processes; and (6) structural economic change. Each pathway contributes a certain amount of GHG emission reduction as projected by the model. If the pathways were to be undertaken separately, it would be hard for each pathway to achieve the projected emission reduction individually. For example, to realise the full reduction potential of zero-emission transport fuel (Pathway 4), decarbonized electricity (Pathway 1) should also be implemented at the same time; hence, 'deeper' decarbonization would be possible, potentially reducing close to 600 Mt CO2e that is more than

80% below Canada’s GHG emissions in 2017 (720 Mt CO2e). The significant reductions would come from three pathways: decarbonized electricity, zero-emission transport fuels, and decarbonized industrial processes.

3.3 Common Threads Across Canadian Energy Scenario Studies

There is a consensus among the four Canadian energy scenario studies that low-carbon electricity generation could be key in Canada’s energy transition. Additionally, the three major energy consuming sectors identified by these studies are transportation, commercial and residential buildings (built environment), and manufacturing. Transportation is 20% of total primary energy consumption, while the consumption for commercial & residential buildings followed by manufacturing are at 18% and 17% respectively (Potvin et al., 2016).

3.3.1 Electricity Generation Sector

Low-carbon electricity generation is one of the major themes across the four studies. According to the TEFP (2016) study, the best scenario shows that rapid decarbonization of electricity generation could be realized by 2030. This is driven largely by the adoption of alternative cleaner fuels such as renewable energy sources (i.e. solar, wind, and hydro). However, from the global perspective, the installed capacity of large-scale grid connected renewable energy system such as solar power in Canada remains modest (2.3 GW) even though many areas in Canada such as the prairie regions have better solar potentials (insolation) than Germany (NEB, 2016)—one of the countries that has the highest installed capacity of solar power in the world (45 GW by the end of 2018) (IRENA, 2019).

Renewable energy such as solar, wind, and hydro are contextualized spatially because the availability of these energy resources is based on geographical location. Generalizing the mitigative capacity based on renewable energy will be too coarse as Canada is a large country and only specific renewable energy resources can be harnessed in certain provinces. For instance, solar and wind energy potentials vary among provinces, and tidal or wave energy potentials may be available in coastal provinces only. Therefore, mitigative capacities are better understood at a local scale (i.e. provincial or municipal levels, which are subnational). In this respect, renewable energy, as the driving factor of Canada’s energy transition, may not be suitable for national level analysis. Instead, as will be discussed further in Chapter 6, carbon intensity was chosen, which can be referred to as the average amount of carbon emissions per unit energy produced. Of course, there is a limitation in using carbon intensity to infer low-carbon energy produced in the country by virtue of which different provinces may have different level of mitigative capacities. Nonetheless, this study on Canada's energy scenarios can be further extended to the provincial level in the future to better account for provincial differences and to provide detailed analysis of individual province capacities towards decarbonization.

3.3.2 Transportation Sector

If only the electricity generation were decarbonized, transportation would remain one of the main contributors to GHG emissions in Canada (TEFP, 2016). Historically, the GHG emissions between 1990-2017 by road and railroad transportation have increased by 43%[9]. Based on the four Canada's energy scenario studies, the potential for major GHG reductions in the Canadian transportation system would come from personal transport, public transport, and freight transport.

Personal transport is related to lifestyle choices of Canadians, which have partly contributed to the increased demand for mobility. Canada is a large country; thus, it is convenient for Canadians to own personal vehicles to travel long distances. According to the DDPC report (Bataille et al., 2015), almost all personal vehicles in Canada (>98% market share) run on fossil fuel, but this trend will change. Under the DDPC scenario, fossil-fueled vehicles could be phased out potentially by 2045 and be replaced by electric vehicles (EVs) (>90%) by 2050. While the adoption of EVs largely depends on societal preferences, it can also be supported by policy instruments (e.g., green vehicle rebates in BC[10] and formerly in Ontario[11]).

Another key area in reducing GHG emission is the societal shift towards public transit. In large metropolitan areas, urban mobility demands (i.e., local and intercity travel) are served by public transit systems. Electrification of public transit would be a viable option for reducing GHG emissions in clean electricity generating provinces. Studies suggest that the public transit system could be served by different modes of transport such as electric railways for regional and intercity

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[9] Source: Environment and Climate Change Canada (2019) National Inventory Report 1990-2017: Greenhouse Gas Sources and Sinks in Canada, retrieved from https://www.canada.ca/en/environment-climate-change/services/climate-change/greenhouse-gas-emissions/inventory.html.

[10] Source: Clean Energy Vehicle Program for BC, retrieved from https://www2.gov.bc.ca/gov/content/industry/electricity-alternative-energy/transportation-energies/

[11] Source: Recently cancelled Electric and Hydrogen Vehicle Incentive Program, retrieved from http://www.mto.gov.on.ca/english/vehicles/electric/electric-vehicle-rebate.shtml

travel, electric buses and shared autonomous vehicles for city commuting (Potvin et al., 2016). Already, Canada has the means to transition to greener transportation quickly because Canadian transport companies such as Bombadier in Quebec have the technology (electric railways) to realize such a goal (Potvin et al., 2016).

Another dimension of the transportation system is freight. Canada has many natural resources (e.g., oil, gas, forestry, and agricultural products) that demand energy to produce, process, and more importantly transport. The NEB (2016) study considers freight transport a major issue, since the extraction, production, and processing facilities as well as the end-users of these natural resources (including agricultural and forest resources) are not in close proximity; hence these products must be transported. Freight transportation in Canada is largely served by trucks, instead of more efficient trains. Although freight trucks that run on LNG are currently available, LNG engines are less efficient than diesel engines. Consequently, fuel-switching does not translate to immediate cost-savings to fleet operators (NEB, 2016). In this respect, the development and deployment of second-generation biofuels, which are produced from non-food crops such as food waste and agriculture residue, for use in heavy freight and rail transport will be crucial (TEFP, 2016). However, whether fleet operators would eventually switch to biofuels remains unclear. Nonetheless, the reluctance of switching to cleaner fuels due to cost has largely contributed to the slow uptake of green freight transport technologies.

3.3.3 Commercial and Residential Sectors (Built Environment)

Commercial and residential buildings are the second largest energy consuming sector after transportation (Potvin et al., 2016). Energy for space heating in residential and commercial buildings are basic necessities in cold countries like Canada. The TEFP (2016) modelling study shows that the reduction in energy demand for space heating in residential and commercial sectors tends to be relatively achievable due to lower cost options (e.g., heat pumps, energy-saving appliances). As cost-savings will directly benefit consumers, consumers will likely be enticed to adopt these technologies. Further, urban forms can be redesigned to reduce the overall infrastructure cost by adopting promising GHG emission reduction approaches such as greener public transit, co-generation plants, district heating, waste to energy, and local energy storage. Many areas in Canadian provinces and territories might not be urbanized and the energy profile (supply and demand) in these areas would likely be different across provinces (NEB, 2016; Potvin et al., 2016). For instance, the Northern Canadian territories (with the exception of Yukon) still rely on fossil fuel energy resources (i.e. oil) for space heating and electricity generation. In these territories, oil must be transported by trucks into these regions, further contributing to GHG emissions. The solar and wind resource poor areas could consider alternative fuels such as biomass to reduce the demand for oil. For instance, wood pellets in the Northwest Territories (NEB, 2016) and municipal solid waste (Potvin et al., 2016) present an alternative fuel (i.e. biogas), which can be harnessed inexpensively via anaerobic digestion[12], pyrolysis[13] or gasification[14] for community district heating systems.

Fuel switching to low-emitting energy fuels such as LNG is also an option in some provinces that are heavily dependent on coal for electricity production (NEB, 2016). However, the lack of LNG infrastructures in these territories presents another challenge. Transporting LNG requires expensive onsite facilities such as liquefaction (converting natural gas to liquid form at a molecular level for transporting and storage) and regasification (converting the liquid form back to natural gas for end-use). Further work is needed to reduce the overall infrastructure cost. Other GHG reduction approaches such as combined heat and power generation, including district heating and local energy storage for remote communities, are also worth exploring.

3.3.4 Carbon-Intensive Economic Sectors

Canada's fossil-fuel resource extraction and production sectors are major contributors of GHG emissions. When using the fossil fuel production data forecasted by the NEB (2016) as the inputs to the modelling exercise, the results suggest that even the most aggressive scenarios would not reduce much of the GHG emissions (TEFP, 2016). Even if they do, the cost of abatement would not be economically feasible. This raises a concern, since decarbonizing fossil fuel (including mining) extraction and production sectors would require aggressive emission reductions of these sectors (Bataille et al., 2015). While being critical of this notion, the TEFP (2016) study, however,

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[12] Anaerobic digestion is a 'natural' decomposition process of organic matter, for example: animal manure, food waste, crops waste etc. The process will produce biogas (used for gas turbines) and residual compost (used as fertilizer).

[13] Pyrolysis is a process of heating biomass in the absence of oxygen at high temperature (+700 degree Celsius). This process produces a mixture of carbon monoxide and water, which can further be oxidized. Further processing may be required to obtain biodiesel.

[14] Gasification is a process of heating biomass in the presence of limited oxygen, though some combustion may be required to provide heat for pyrolysis to occur. The process will produce gaseous fuel and some volatile organic gases. Solid residues in a form of char can also be further re-used for combustion fuel.

remains hopeful that the development and the deployment of Negative Emissions Technologies (NETs) could be crucial for decarbonization.

The common thread across the four studies undoubtedly is the availability of NETs. Under the NET umbrella, carbon capture and sequestration or CCS is considered key in supporting decarbonization efforts in Canada (Bataille et al., 2015; NEB, 2016; Potvin et al., 2016; TEFP, 2016). High emitters such as oil and natural gas producers may not have to wait too long to benefit from CCS, since other countries like Norway for example have been experimenting with different ways to put carbon (emissions) back into the 'ground.' However, acquiring CCS can be capital intensive especially for Direct Air Captured CCS (Minx et al., 2018). The requirement of high-capital investment can often face a problem in getting funded since investors consider such projects highly risky with low return on investment (Potvin et al., 2016). To nurture key innovations in energy systems such as NETs, investments in technology research and development are necessary. Despite the positive reception for which NETs could bring to Canada, Canada's contribution to research and development in NETs is nonetheless modest from the global perspective (Bataille et al., 2015; Potvin et al., 2016). Although research on NETs are lacking domestically, Canada can still benefit from global technology spillovers (Bataille et al., 2015). Also equally essential is the willingness of businesses to take risks when adopting new technologies. Government can play a part in providing clear long-term directions and support through the use of policy instruments to enable markets to align investment in low-carbon technologies across Canada's economy (Bataille et al., 2015; Potvin et al., 2016).

3.4 Conclusion

There are still significant uncertainties in our knowledge about low-carbon energy futures in Canada – including understanding the local, regional and global development of energy systems; the drivers; and the outcomes of climate negotiations at the global level. For instance, high oil prices can motivate Canada to continue extracting oil and natural gas resources (NEB, 2016); conversely, high oil prices can also drive changes in consumers' behavior in various sectors such as transportation by switching to alternative non-fossil fuel-based energy resources (Bataille et al., 2015).

Scenario research on Canada's energy future has used different methods of scenario analysis to address policy questions. For the most part, the drivers, factors, and assumptions used by author or modelling teams are not transparent (Potvin et al., 2016). What is needed is well-documented and 'open source' scenarios that are transparent for what, how, and why such scenarios were constructed in the first place. The transparency of scenario studies allows users and practitioners to question the assumptions and compare results (Potvin et al., 2016). These assumptions are: (1) Canada can be decarbonized in a decarbonized world and (2) Canada remains carbonized in a carbonized world. In other words, scenarios are considered consistent when the future energy developments at the global level and Canada are aligned. However, we still do not know whether counter-intuitive assumptions (i.e. Canada can decarbonize while the world is not and vice versa) are consistent.

In this dissertation, such assumptions will be further investigated—whether global development pathways and Canada's energy development must be lockstep or not. I used CIB as a tool for performing consistency checks as Wiek et al. (2013) suggested. Consequently, consistency checks will address the question of whether it would be plausible for Canada to be decarbonized when the world remains carbonized and vice versa.

Chapter 4: Overview of Research Methods

This dissertation employs a sequential research design where phases of data collection and analysis are in sequential order. Due to the abstract nature of the CIB analysis including how and what kind of data is required for CIB analysis, the research methods in this thesis can be better explained in sequence. Therefore, subsequent Chapter 5 will dive deep into the application of network analysis to identify and rate candidate scenario elements useful for developing energy scenarios for Canada (Phase 2). Chapter 6 details the scenario development process using cross-impact balance analysis (CIB) to produce globally linked internally consistent national energy scenarios as extended SSPs. Nonetheless, Chapter 4 provides an overview of these methods and explains how data collected in one phase be used in the next phase. Figure 7 presents a useful illustration of the research design in Phase 2 and Phase 3.

4.1 Introduction

The analysis of complex problems such as energy systems requires multi-scale approaches to scenario analysis because the complexity of this sort can manifest in multiple levels, sectors, and scales. The scientific community has developed the global version of the Shared Socioeconomic Pathways (SSPs) (Ebi et al., 2014; O’Neill et al., 2014). The SSP scenario framework provides the entry point for extension studies such as national energy scenarios to link to the global SSPs so that national scenarios produced in this thesis are informed by the different plausible global development pathways (van Ruijven et al., 2014). This thesis uses ‘re-specifying of SSP elements’ (discussed in Chapter 3) as the starting point for developing extended SSPs for Canada’s energy scenarios. This entry point is suitable for incorporating scenario elements that are too different from the original scope of the SSPs components.

In this thesis, the scenario development process takes an approach that is multi-scale. This is a significant refinement to traditional methods that often apply a single-scale perspective. Moreover, the dominant approach to multi-scale scenario analysis is to link scenarios at different scales (e.g., global and local) using soft-links as explained in Chapter 2 (Zurek and Henrichs, 2007). It is possible for a scenario analyst to identify how different scenario studies can be linked (e.g. assessing how one study can corroborate or contradict another study); nevertheless, such interpretation is a still subjective exercise. A promising method that increases the transparency and rigour of scenario analyses is cross-impact balance analysis (CIB) (Kemp-Benedict et al., 2019; Schweizer and Kurniawan, 2016; Weimer-Jehle, 2006). Analyzing cross-impact relationships of scenario elements from different scales, levels, or sectors is fundamental to CIB analysis. With information regarding how different factors interrelate, CIB analysis helps scenario analysts and users better understand the overall system's behaviour resulting from cascades of influences. In this thesis, the cross-scale interactions between the world region (i.e., the global SSPs) and the Canadian region (i.e., Canada's energy systems) were assessed.

In this dissertation, developing globally linked internally consistent scenarios under the SSP framework began by reviewing the scenario development process and by identifying elements (drivers, trends or events) for developing energy scenarios for Canada. These candidate elements were selected by consulting existing energy scenario studies on Canada (i.e., Bataille et al., 2015; NEB, 2016; Potvin et al., 2016; TEFP, 2016). From these studies, elements that are described or inferred to be interrelated were extracted and subjected to a network analysis to prioritize (or select) variables for the next step of scenario development (see Chapter 5).

4.2 Research Design Overview

As mentioned in the introduction chapter, this dissertation encompasses three distinctive but interconnected phases. Phase one is literature review on the scenario framework, the Shared Socioeconomic Pathways (see Chapter 2). More specifically, I am interested in reviewing how the research community has conducted studies on extending the SSPs. One of the requirements for extending the SSPs is that these studies should use 'basic' (or global) SSPs as the global framing for more detailed regional, national, and sectoral analyses. As suggested, the research community can link their studies to the global SSPs by quantitative and qualitative downscaling. Alternatively, studies can be linked to the SSPs through other means such as utilizing only the key SSP elements as well as adding new elements relevant in the study context. The latter is used in this dissertation.

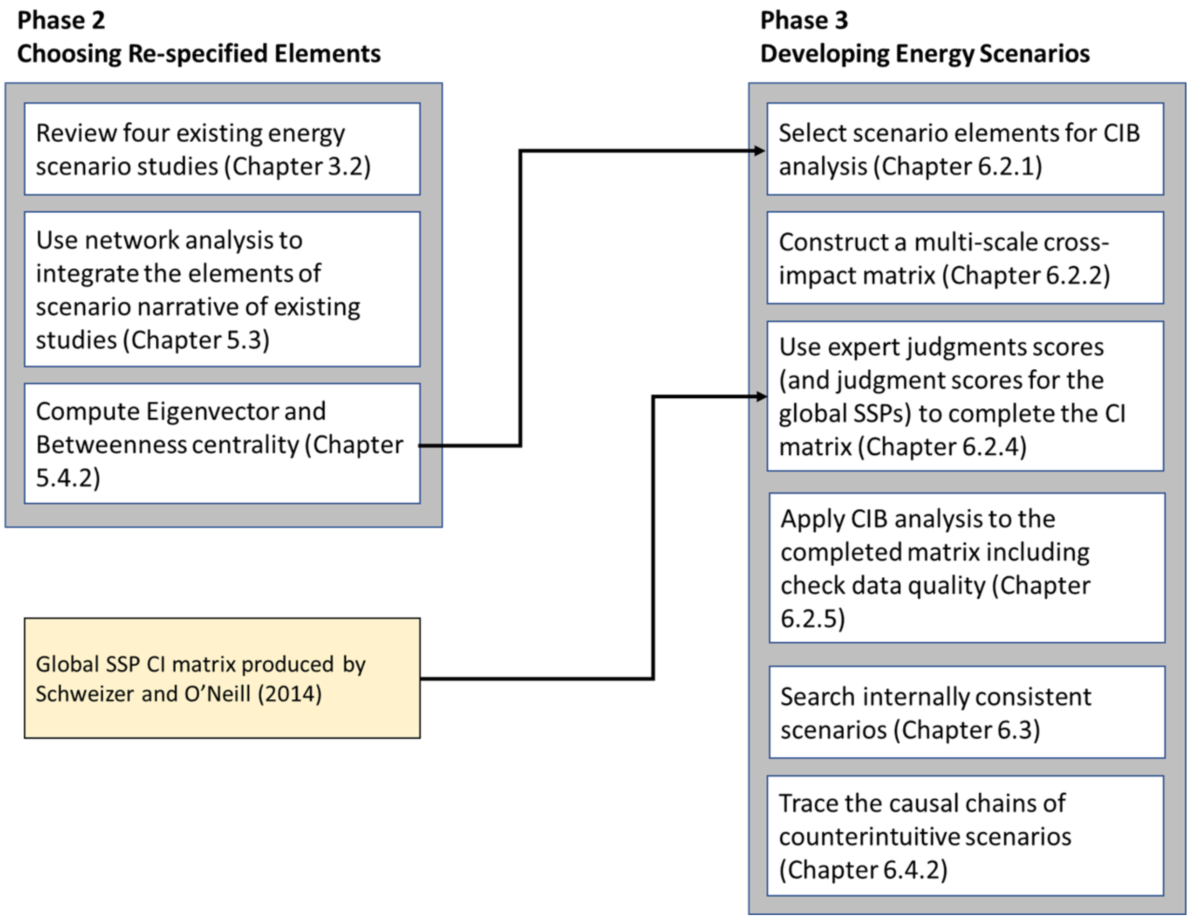

Figure 7 Phase 2 and Phase 3 research processes

In Phase 2, I set out to identify new scenario elements that are relevant for developing energy scenarios for Canada. Scenario elements were extracted by ‘deconstructing’ the published reports of four Canadian energy scenario studies. The extracted elements were mapped as a network to visualize and identify the key elements that these four studies have agreed on. Node centrality metrics were used to rate these elements; scenario elements were then selected based on their scores. Data collected in Phase 2 are the list of scenario elements for Canada—these elements were used as variables to construct a cross-impact matrix.

Phase 3 is the scenario analysis that takes on a multi-scale perspective using CIB analysis. The scenario elements deduced from the network analysis as well as the key SSP elements were used to construct a multi-scale cross-impact (CI) matrix. Each cell in the matrix characterizes the influence between two elements (i.e. receiving or exerting influence, or no effect); these influence judgments were elicited from a panel of experts. The data collected from expert elicitation are judgment scores that correspond to different cells in the CI matrix. Experts’ judgment scores were utilised to complete the matrix (i.e. putting numerical scores into the respective cells). Once the CI matrix is completed, it can be subjected to CIB analysis to search for internally consistent scenarios; this was done using ScenarioWizard (a software for CIB analysis) (Weimer-Jehle, 2018).

4.2.1 Extending Basic or Global SSPs

The key elements of the global SSPs are socioeconomic variables of societal futures necessary for identifying higher or lower challenges to mitigation and adaptation (O'Neill et al., 2014). However, the scope of the global SSP elements is meant to be generic; hence it may not be comprehensive for extending the SSP for national analysis such as developing energy scenarios for Canada. There may be variables that are important for developing energy scenarios for Canada that are not part of the global SSPs. For instance, certain segments of the Canadian economy have a significant influence in the development of energy systems domestically. For example, oil sand production is considered an important segment at the national (Canadian) level that influences national carbon intensity and average income growth while oil sands are generalized as a substitutable energy resource for global analyses. Another consideration is the socio-technical aspects relevant to the energy sectors. Not all socio-technical aspects are represented by the global SSPs. Although one of the SSP elements, 'technological change in energy efficiency', relates to socio-technical change, this element presents an 'umbrella' term that aggregates all socio-technical changes. As research has shown, the rate of technological transition for different technologies varies (Sovacool, 2016). In this respect, SSP extension studies in the Canadian context require new elements to be specified. The incorporation of new elements lends itself to the entry point called 'Re-specifying SSP elements' as explained in Chapter 2.4.4.

4.2.2 Choosing Re-specified Elements: A Network Analysis Approach

The motivation of using network analysis is to situate the scope of different national scenario studies produced by different author teams to better understand what scenario logics are overlapping or different (namely what scenario factors, or elements, were included or excluded across studies). This dissertation examines four existing energy scenario studies on Canada published in 2015 to 2016. Understanding the coverage of each scenario study and obtaining a more holistic perspective on how the studies together characterize the key elements for Canada's energy development is important for making headway on subsequent steps of the research (i.e. producing globally linked internally consistent scenarios under the SSP framework). A holistic perspective helps to identify what scenario elements (i.e. drivers, trends or events) all studies agree are significant in developing energy scenarios for Canada.

Previous scenario research using some sort of network structure often produce an incomplete picture of the future (see Chapter 5.2.1). Network structures have been leveraged in futures studies to select scenario elements through two approaches: (1) social networks (e.g., Nugroho and Saritas (2009)) versus (2) causal networks (e.g., Futures Wheels (see Bengston 2019), Fuzzy Cognitive Mapping (see Kermagoret et al. 2016), Cross-impact Balance or CIB analysis (Weimer-Jehle, 2006)). The different applications of network approaches (i.e. social or causal) are silent on how scenario elements should actually be chosen. Usually social actors make the choice, such as through voting. This will tell us what elements are popular but may misguide whether the elements are influential in a causal network. Alternatively, scenario elements can be extracted through textual analyses such as literature review or horizon scanning. I employ the latter and innovate on existing textual analysis methods by decomposing the scenario narratives of multiple studies rather than a single scenario study.

Since scenario narratives are constructed in the first place by interpreting the expected ‘behavior’ of several scenario elements, these narratives can be deconstructed to distil only the elements of the scenarios and their interactions (Scheele et al., 2018; Schweizer and Kriegler, 2012). The extracted scenario elements can be analyzed as a network to understand the coverage of different scenario studies. When scenario elements and their interactions across multiple studies are reconstructed as a fulsome network, the limitations and broader implications of what different scenario studies are saying can be better understood. This approach was employed for examining and integrating different scenario studies and applies them to the case of Canada’s energy futures. This technique builds on the novel approach for deconstructing scenarios used in Schweizer and Kriegler (2012) to extract scenario elements and their relationships from natural language statements appearing in different scenario studies. Subsequently, these scenario elements were interconnected to produce a multi-study network. The research method is detailed in Chapter 5.3.

When these scenario narratives are deconstructed, the causal relationships among these elements can be assessed using network statistics (Barabási, 2016; Wasserman and Faust, 1994). Networks have an exploitable property that can be useful in identifying which elements are more central in a causal network. In network terms, node centrality relates to the strategic position of the nodes, in this case scenario elements. Nodes with higher centrality scores are more ‘central’ in the network (Koschützki et al., 2005). Node centrality metrics are useful for identifying influential candidate elements. Eigenvector centrality and betweenness centrality were chosen. The choice of having two centrality metrics is motivated due to the need for comparison. If an element has high scores for both Eigenvector and Betweenness centrality, selecting such an element is less controversial. However, when an element has a high score in one metric and a low score in the other metric, selecting this element will not be straightforward. A discussion on these issues can be found in Chapter 5.2.4.

4.2.3 Developing Energy Scenarios: A Cross-impact Balance Analysis Approach

This thesis uses cross-impact balance analysis (CIB) for the scenario development process (Weimer-Jehle, 2006). CIB is a method of systematic exploration for how different scenario elements influence each other. The multi-scale scenario analysis examines cross-scale interactions for how global and local development pathways interact. The linked CIB is a recent methodological advancement of the CIB for multi-scale scenario analysis (Guivarch et al., 2017; Schweizer and Kurniawan, 2016). Linked CIB introduces a systematic method for documenting cross-scale interactions. Many localized or sectoral scenario studies rarely account for cross-scale interactions explicitly. In theory, the cross-impact (CI) matrix used for CIB analysis can model the interactions of many (and potentially unlimited) scenario elements in different scales or sectors. Although a CI matrix can be developed to incorporate scenario elements across multiple scales, such a CI matrix will become large and may be computationally intractable. When analyzing a large multi-scale CI matrix, the computational burden can be reduced by applying linked CIB (Schweizer and Kurniawan, 2016). The linked CIB takes a large CI matrix and partitions it to produce smaller sub-matrices that can be subjected to CIB analysis individually to search for internally consistent scenarios.

4.3 Conclusion

Chapter 4 elaborates two of the three phases of the research design: choosing re-specified scenario elements and developing multi-scale energy scenario using CIB analysis. The network analysis approach for selecting candidate scenario elements is a three-step process: (1) deconstruct multiple studies to extract the elements of scenario narratives, (2) interconnect these elements and visualize them as a network, and (3) calculate node centrality score. The data collected from phase 2 is a list of candidate scenario elements which were incorporated into the scenario development process using CIB analysis in phase 3. Simply put, the CIB analysis is done in two sequential steps: (1) collect the data for the matrix (i.e. through expert elicitation) and (2) analyze the data in the matrix to identify self-consistent multi-scale scenarios. The subsequent Chapter 5 details an approach to identify key elements of multiple scenario narratives using a computational social science technique (network analysis).

Chapter 5: Using Network Analysis to Find Key Elements of Canada's Energy Scenarios

Previously in Chapter 2, the mode of entry to develop an extended SSP study on national energy systems is re-specifying SSP elements. That means new elements relevant in the study context were identified first. This chapter presents the results of deconstructing multiple energy scenario studies using network analysis to identify and select key elements that these studies have agreed on. The edited version of this chapter has been accepted for publication in *Society and Natural Resources*. Chapter 5 also addresses research question 2.2: How can one identify and select elements for developing national / sectoral scenarios under the SSP framework? Identifying scenario elements relevant to the study context can be done by eliciting experts' opinions. Previous scenario research using some sort of network structure often produced an incomplete picture of the future (see Chapter 5.2.1). Network structures have been leveraged in futures studies to select scenario elements through two approaches: (1) social networks (e.g., Nugroho and Saritas, 2009) versus (2) causal networks (e.g. Futures Wheels (see Bengston, 2019), Fuzzy Cognitive Mapping (see Kermagoret et al., 2016), Cross-impact Balance or CIB analysis (Weimer-Jehle, 2006)). The different applications of network approaches (i.e., social or causal) are silent on how scenario elements should actually be chosen. Usually social actors make the choice, such as through voting. This will tell us what elements are popular but may misguide whether the elements are influential in a causal network. Alternatively, scenario elements can be extracted through textual analyses such as literature review or horizon scanning. Here I employed the latter and innovate on existing textual analysis methods by decomposing multiple studies rather than a single scenario study. To do this, I first deconstructed the existing studies on national energy scenarios to extract the scenario elements used by each study. Then, I analysed these scenario elements using network analysis to assess which scenario elements are candidate to include in the subsequent steps of scenario development process.

5.1 Introduction

In global environmental change research, scenario analyses, and by extension research methods for future studies, have been used to harness different expertise and knowledge to understand what kind of energy systems will be plausible in the future (Alcamo, 2008; Bauer et al., 2017; Bengston, 2019; Guivarch et al., 2017). The main drawback to scenario studies is that such studies are produced by different author or modelling teams (e.g., non-governmental organizations, research institutes) with limited documentation, and as such these studies may agree or disagree on what would be plausible in the future, producing vastly different scenario narratives or storylines. While having many different scenario narratives can be useful for scenario users (including policymakers) as a means to identify which decisions are robust across a wide range of futures (Berntsen and Trutnevyte, 2017), there is also the risk that scenario users may choose to 'cherry-pick' a specific study that supports their personal or political agenda (Pielke, 2007).

Studies on energy futures present scientifically informed future depictions in a form of scenario narratives, storylines, or projections with regards to energy systems. Yet how energy systems could be developed in the future is a complex issue especially with the impact of climate change looming. Research suggests that critical engagement with experts and laypersons is key, which can provide insight into plausible alternative development pathways leading to the desired (or undesired) future (Bengston, 2019; Bishop et al., 2007; Bradfield et al., 2005; Wilkinson and Kupers, 2014). While society could support or resist certain types of development pathways, which alternative futures to pursue is often uncertain in part due to political, economic, and social context. The logics underlying alternative energy transitions are seldom considered.

Understanding what scenario elements are significant is important for making headway on commitments to reduce greenhouse gas emissions causing climate change. With the ratification of the Paris Agreement, which is to limit the average global temperature increase well below 2.0 degree C by 2100, developed countries like Canada are now required to set aggressive mitigation targets and to transition to a low-carbon energy future (Hilton and Kerr, 2017; Rogelj et al., 2015; Schleussner et al., 2016). Nonetheless, setting long-term social agendas and staying the course is ultimately a political act. This explains why there are multiple energy futures studies that produce a variety of scenarios for how energy systems could take shape. The findings of these studies are influenced in part by their funding mechanisms, methodology used to develop scenario narratives and different backgrounds or expertise of the study participants. The latter may introduce biases in the scenario development (Lloyd and Schweizer, 2014; McLevey, 2014; Scheele et al., 2018; Trutnevyte et al., 2014). Moreover, decision-making that relies on a single and narrowly defined study can overlook important information that may be presented by other studies. To better understand the coverage of each scenario study and provide a more holistic perspective on what the studies together imply for a nation's energy future, I used network analysis to integrate the scenario elements of multiple qualitative scenario narratives from different studies.

Since scenario narratives were constructed in the first place by interpreting the expected 'behavior' of several scenario elements; accordingly, these narratives can be deconstructed to distil only the elements of the scenarios and their interactions (Scheele et al., 2018; Schweizer and Kriegler, 2012). The extracted scenario elements can be analyzed as a fulsome network to understand the broader implications of what different scenario studies are saying. This chapter introduces an approach for examining and integrating different scenario studies and applies them to the case of Canada's energy futures. Here, we present a technique that builds on the novel approach for deconstructing scenarios used in Schweizer and Kriegler (2012) to extract scenario elements and their relationships from natural language statements appearing in the study reports. Subsequently, these scenario elements were interconnected to produce a multi-study network that can be subjected to a network analysis holistically.

The objective is to situate the scope of energy scenario studies produced by different author teams to better understand what scenario logics are overlapping or different and to help identify what scenario elements (i.e., drivers, trends, or events) that would be significant in shaping the nations' energy future. For the case of Canada, the energy sector is the third largest contributor to Canadian GDP. The reliance on the economic performance of the energy sector makes Canada's economy highly vulnerable to different global development pathways. The Canadian energy sector may interact with global developments and is already playing a key role in driving climate change, both as a high carbon emitter and as a major exporter of fossil fuels. Canada will most likely be influenced by global developments; additionally, Canada may potentially influence global developments.

This chapter explains how network analysis can be applied to examine the coverage of different scenario studies and to identify what scenario elements are needed for developing the SSP extension study on a national energy future (see Chapter 6). In the next Chapter 5.2, I introduce the concept of network analysis and the application of network analysis in scenario research. More specifically, I will evaluate how one can deconstruct scenario narratives to produce a network. The method of deconstructing qualitative scenario narratives is outlined in Chapter 5.3.1. Based on four scenario studies on Canada, I identified scenario elements that are unique to each study as well as areas where they overlap. Also, I identified how scenario elements are interconnected and use this information to produce a comprehensive multi-study network. Finally, Chapter 5.3 discusses the results that detail the differences and areas of conceptual agreement among the scopes of four scenario studies.

5.2 Subjecting Diverse Scenario Studies to Network Analysis

Previously, Chapter 2.1 (i.e. Introduction: Environmental Scenarios) touches on the overview of scenario research methods; Chapter 5.2.1 builds on this overview to distinguish how networks have been applied in futures studies as well as to identify opportunities for applications of network analysis. In Chapter 5.2.2, I elaborate the focus on the case of Canadian energy futures.

5.2.1 Networks in Scenario Research

Network analysis is based on a mathematical function of a graph structure, $G = [V, E]$, where V is a vertex (or a point or a node) and E is an edge (or a line or an arc). Network analysis is a study of relational properties of entities (Wasserman and Faust, 1994). Entities can be persons, public policies, geographic locations, human genes, or articles in academic journals, and they are interrelated. The interrelationship can be established when, for example, two individuals are friends, or two policies have the same objective such as to reduce greenhouse gas (GHG) emissions. Moreover, the interrelationships between these entities can be visualized and analyzed as a network. Many scenario methods have used network structure as the underpinning conceptual framework for constructing scenario narratives (Ernst et al., 2018). One way is to identify what scenario factors are popular in the mental models of particular social groups (a social network approach). An alternative approach is to identify how scenario factors are interrelated and influence each other (a causal network approach).

The causal network approaches focus on characterizing networks of influences between scenario elements. The earliest documented futures research method that makes use of causal network is the Futures Wheel (Bengston, 2019). Jerome Glenn developed the Futures Wheel for scenario developers to evaluate how various scenario elements (e.g., drivers, trends, or events) may influence one another (Glenn and Gordon, 2009). This information will be used to develop scenario narratives. The number of Futures Wheels constructed will correspond to the number of scenario elements required to construct the narratives describing how the world revolves around these elements. A Futures Wheel has a structure that resembles a network and visually depicts primary, secondary, and tertiary consequences resulted from a scenario element (i.e., the main node), which is being evaluated (Note: in network terms, these scenario elements are nodes). The visual produced by a Futures Wheel shows three levels of consequences arising from the 'main' node or the hub. The main node will connect to several primary consequences. Consequences are also nodes, which can be other scenario elements resulting from the main node. The nodes identified as the primary consequences will subsequently connect to secondary consequences and so on. The main node is the focal point with consequences depicted as concentric rings surrounding it. The consequences may or may not intersect with other scenario elements; so, it is possible that a Futures Wheel may not 'interact' with other Futures Wheels produced for different elements. When interacting Futures Wheels are combined, a network would be produced. However, the network produced by non-interacting Futures Wheels would be fragmented. A fragmented network comprises smaller disjointed sub-networks, making it difficult for one to visualize the 'big picture.' This can happen when the information from the Futures Wheels for how all scenario elements interrelate is insufficient.

Scenario elements that are exerting influences and/or receiving influences are critical in developing scenario narratives because the storylines are developed to revolve around these interactions. Therefore, identifying the 'real' influencing elements is crucial in this respect (Schweizer and Kriegler, 2012; Schweizer and O'Neill, 2014). More recently, research on scenario techniques has addressed this limitation. For instance, Jetter and Kok (2014) applied a technique called Fuzzy Cognitive Maps (FCM) in scenario development by connecting scenario elements based on 'real' influence (not popularity) (Kermagoret et al., 2016). The network developed using FCM acts like a mental model created under a specific scenario context (Jetter and Schweinfort, 2011). In this method, nodes are concepts (also they can be scenario elements) that can be described qualitatively. The edges are influences that contain information such as the direction and the weight of these influences. The scenario process under the FCM method starts by identifying many key concepts to be incorporated in a scenario. For each concept, a causal map will be produced by the study participants. For example, a causal map for concept 'A' could indicate the causes (events, trends, or drivers) that would promote or influence concept ‘A’ and the consequences resulting from concept ‘A.’ All concept maps are simple networks that can be pieced together to produce a giant network.

Alternatively, an example of the social network approach is Nugroho and Saritas (2009) who mapped all scenario elements and their interconnections in a single network; this was done by engaging the study participants to identify different scenario elements as nodes that could be relevant in a given scenario. When these elements are elicited by participants from the same affiliation (e.g. government, academia, business) or the same world region, a connection between the two elements is established. For example, two participants from academia could express ‘renewable energy’ and ‘carbon capture and storage’ as the elements relevant in the scenario context; then an edge would be created connecting these two elements (or nodes). Actually, these two nodes are not really influencing each other, but they are posited to have an interrelationship because these two nodes happen to be elicited by the participants. In other words, these nodes are ‘popular’ among the participants. However, one should not assume that the interconnections in this network are direct linkages. Just because a scenario element is popular among study participants, it does not mean that the element is empirically important in the scenario context. This popularity can misguide scenario users to think that the well-connected nodes are influential nodes.

Traditionally, a broad range of scenario elements are identified through expert or stakeholder elicitations; however, only a few elements will be incorporated in the scenario development process. The selection process is usually conducted in a stakeholder workshop, where participants discuss and choose elements that they consider important. Eventually, participants will cast their votes individually; elements are selected according to the tallied votes. The selection of elements by voting can help to minimize biases and is intended to be based on consensus. In some instances, though, a participant may influence the voting process by casting his/her votes on one particular scenario element. However, as mentioned previously, approaches that select scenario elements because they are popular can misguide scenario users to think that popular nodes would also be influential nodes in a causal network.

Alternatively, scenario elements can be elicited through literature review or horizon scanning (Bengston, 2019). Scenario elements can be extracted from published studies (Schweizer and Kriegler, 2012). The process of extracting scenario elements is called ‘deconstructing’ scenarios (Scheele et al., 2018). In this study, the deconstructing technique for extracting scenario elements is adapted based on a study by Schweizer and Kriegler (2012). These authors deconstructed scenarios in the Special Report on Emissions Scenarios (SRES) (Nakicenovic et al., 2000). For this thesis, I went beyond the deconstruction discussed by Scheele et al. (Scheele et al., 2018), which applies to only one scenario study. Rather, I deconstructed four of Canada's energy scenario studies and then integrated their respective causal networks in one holistic network. These studies are the Trottier Energy Futures Project (TEFP, 2016), Deep Decarbonization Pathways in Canada (Bataille et al., 2015), Re-Energizing Canada (Potvin et al., 2016), and Energy Supply and Demand Projections to 2040 (NEB, 2016). Then, I used network analysis to qualitatively map the network coverage of the respective studies and use network statistics to identify scenario elements that the four studies agree on, which are important to include in the subsequent scenario analysis (Chapter 6).

5.2.2 Research Context: Canada's Energy Futures

The current state of the Canadian energy system bears some imprints of legacy carbon-intensive economic and social structures (Potvin et al., 2016). In the face of climate change, Canada can be expected to undergo societal and structural changes in the future, reshaping Canada's energy system. Nonetheless, changes take time. There is no abrupt change in energy transition as historical accounts have shown. For instance, the energy (supply) transition to coal or oil or gas takes almost a century (Sovacool, 2016). According to studies such as Deep Decarbonization Pathways in Canada, Canada's low-carbon energy transition could be plausible in 50 to 100 years with aggressive planning and actions (Bataille et al., 2015).

Scenario analysis has been used to explore different pathways that Canada's energy system could take over time under different assumptions of global or domestic developments. Not surprisingly, scenarios produced by different author teams have presented alternative pathways. The produced scenarios may differ by virtue of using different assumptions and engaging different participants. For instance, the 2016 study by the National Energy Board (NEB) (NEB, 2016) forecasts the demand and supply of fossil fuel-based energy resources in Canada under the assumption that fossil fuel will remain the primary source of energy in Canada in the future. In contrast, the 2018 follow-up study (NEB, 2018) assumes decreasing demand for fossil fuel globally and domestically due to uptake of renewable energy technologies. Moreover, price volatility of oil and gas in the global market adds another layer of challenge to forecast the supply and demand of fossil fuel energy resources.

In addition to quantitative forecasting, studies have also produced qualitative narratives or storylines that describe plausible future development pathways. Studies such as Deep Decarbonization Pathways in Canada (DDPC) have used a variety of scenario techniques to envision pathways towards decarbonization for Canada, contributing to global effort in reducing GHG emissions (Bataille et al., 2015). The DDPC study is based on the assumption that the world decarbonizes, therefore Canada follows suit. In another study, the Trottier Energy Future Project (TEFP) (TEFP, 2016) places technology development as the central theme of low-carbon energy transition. The TEFP is a quantitative modelling study, which produced energy transition scenarios based on currently deployed technologies, extrapolated future technological improvements, and the potential cost reduction of acquiring those technologies. The TEFP scenarios examine the possibility of reducing GHG emissions under the assumption that there would be no other significant technological breakthrough in mitigating climate change. Both DDPC and TEFP were developed prior to the Paris Agreement, which came into force in November 2016. These reports contribute to policy dialogue—whether it would be plausible for Canada to decarbonize its economy should the Paris Agreement be ratified. However, this consideration has not been fully resolved, and alternative decarbonization strategies have been produced by more recent studies. Scenarios produced are bound in numerous ways to the core assumptions adopted by the participants and differences will be represented by different pathways.

The Re-Energizing Canada report (REC) (Potvin et al., 2016) is a horizon scanning study (Bengston, 2019). Based on peer-reviewed literature and data, REC presents recommendations for how Canada could transition to low-carbon development pathways in a decarbonized world. REC aligns with the Pan-Canadian Framework (Government of Canada, 2017), whose goal is to decarbonize the Canadian economy. While the goal of the Pan-Canadian Framework is clear, it is nonetheless challenging for Canada. A particular consideration goes to the large export-oriented fossil fuel production sector, and by extension the mining sector, which has contributed a large portion of Canada’s GDP (Potvin et al., 2016). Fossil fuel production is largely concentrated in specific provinces, and these provinces would need to venture to other green economic sectors as an alternative to fossil fuel production. By investing and supporting alternative green sectors, the Canadian economy could relinquish its dependence on the national income generated by the fossil fuel production sector. With this development pathway, the economic performance of Canada's oil and gas sectors, domestically and globally, would have reduced or little impact on the national economy.

Although these four studies have a common goal—to explore plausible development pathways of Canada's energy systems—these plausible pathways may differ in some respects. One way to aggregate such diverse scenarios is to have analysts 'aggregate' the scenario narratives manually. Another way, which is the method adopted in this thesis, is to integrate these studies using the more objective approach of network analysis to better understand what scenario logics are overlapping or different (namely what scenario factors, or elements, were included or excluded across studies). Doing so helps to identify what scenario elements (i.e. drivers, trends or events) all studies agree could be significant in shaping Canada's energy futures. Understanding such scenario elements is important for making headway on national commitments to reduce greenhouse gas emissions causing climate change.

5.3 Methods and Materials

The analytical process in this research is adapted from data science and computational social science techniques involving steps in getting, cleaning, visualizing and analyzing data (Foster et al., 2016). Semantic analysis was employed to produce network data (nodes and edges). Semantic analysis is concerned with expression through the use of language and extracts the underlying meanings such as symbolic representations and worldviews (Creswell, 2013). Subsequently, network analysis was implemented in Python using NetworkX (Hagberg et al., 2008).

5.3.1 Getting the data: extracting nodes and edges for energy futures

What all scenario methods have in common is the foundational step of identifying basic elements (also known as variables, factors, or drivers) that must constitute the scenario. This study looks at finished scenarios (i.e., study reports) developed by different author teams to construct a causal network of nodes (scenario elements) and undirected edges (relationships). These reports provide only the textual descriptions or narratives, yet textual data may also contain the description of elements and their relationships. The data on the nodes and edges were identified by extracting statements that imply some scenario elements influence other elements in the future. In this research, the focus is on 'future' rather than past or present interactions because the existing and historical relationships of different elements may not hold in the unprecedented future. Therefore, statements describing interactions between two or more elements posited to happen in the future were extracted for analysis. The approach to extract textual data is similar to the method employed by Schweizer and Kriegler (2012). For example, consider a sentence extracted from the REC study: "[…] the second measure is the phase-out of coal-generated electricity, which as announced would result in a reduction of about 5 MtCO2-eq" (Potvin et al., 2016, p. 28). This statement suggests that banning coal power plants will decrease GHG emissions. Since this statement refers to what could happen in the future, the interacting elements were extracted as nodes. The extracted nodes were labelled as 'banning of coal power plants' and 'GHG emissions' and then appended into an edge list dataset (Figure 8). The corresponding documents for the four Canadian energy futures studies were analysed in this manner to produce the dataset.

Node labels are meant to be generic. For instance, a node labeled as 'GHG emissions' may refer to different end-states or final conditions (e.g., either increase or decrease GHG emission levels). After basic scenario elements have been identified, the scenario development process utilizes such generic labels to elaborate how particular end-states of 'driver' elements might result in different end-states of consequent scenario elements. Additional methods that might be used for this purpose are cross-impact balance analysis (Weimer-Jehle, 2006) and morphological analysis (Ritchey, 2018).

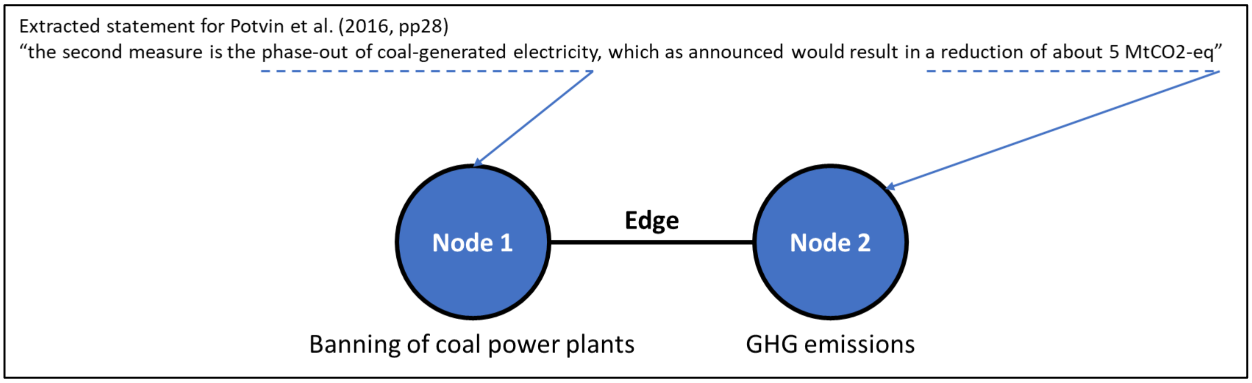

Figure 8 Creating nodes and edges from a statement

5.3.2 Cleaning the data: 'normalizing' unstructured data

The edge list collated from different studies is unstructured textual data. One of the challenges encountered working with unstructured data is the issue of 'normalization.' Normalization is a process of checking for similarities in data structures from different sources to ensure that each field represents the same meaning or concepts (Foster et al., 2016). When cross-referencing the underlying meanings of each node description across these studies, I found several statements that describe a node using different terms, but they mean the same thing. For instance, terms like electrification of cars and adoption of electric vehicles imply the same concept that points to electric vehicles, or EVs. These different descriptions can be considered as two nodes that really are only one node. To prevent these nodes from being treated as separate nodes, nodes that have similar meanings were searched and re-labelled with the same description.

5.3.3 Visualizing the data

From the edge list data produced earlier, a visualization of a multi-study network for Canadian energy futures was produced using a Python library for network analysis called NetworkX. The full analytical steps written in Python are posted on a public repository site.[15]

5.3.4 Analyzing the data

Scenario elements that are interacting with others are more useful in developing narratives than scenario elements that are isolated or not well-connected. In network analysis terms, highly interacting scenario elements can be identified by calculating network statistics called 'centrality' that indicate which nodes are most 'central' (see e.g., Koschützki et al., 2005). The definition of 'central' varies by context or purpose and is mainly defined by different algorithms that evaluate the node centrality. Each node centrality metric has its own merit. For example, degree centrality defines nodes with higher degree—nodes with more connections—as more central. The metric may be applicable in social settings in which people with more connections may be more visible. Nonetheless, the choice of node centrality metrics rests upon the scenario developers themselves. The metrics chosen must correspond to what is meant by 'important' scenario elements. One can also select several node centrality metrics (a.k.a. multi-component centrality measures) that can be tailored for a specific purpose (Sciarra et al., 2018). This study employs a multi-component metric consisting of betweenness centrality (BC) and Eigenvector centrality (EC) to rank scenario elements.

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[15] https://github.com/judekurn/energy-futures/blob/master/SNR/SNR-network_analysis_rev3_16022020.ipynb

As discussed below, the two node centrality metrics have complementary strengths and were computed to determine how central a node is in a multi-study network. The choice of having two centrality metrics is motivated due to the need for comparison. If a scenario element has high scores for both Eigenvector and betweenness centrality, selecting such an element for scenario development is less controversial. However, when an element has a high score in one metric and a low score in the other metric, selecting this element will not be straightforward. Differences in EC and BC scores suggest that further inspection is warranted to assess whether the scenario element would have the right fit to support the development of scenario narratives. To enable comparison, a network visual was produced to observe the position of the nodes with respect to their BC and EC scores (Figure 9) as well as a scatterplot (Figure 10).

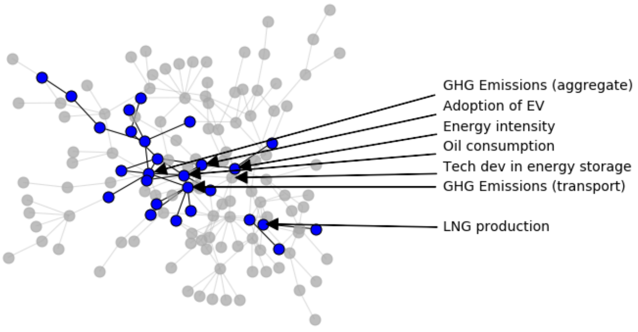
The EC defines well-connected nodes as important (Wasserman and Faust, 1994), meaning that nodes with higher EC scores tend to be connected to other high-scoring nodes. EC is appropriate because the interrelationships between scenario elements are important for defining the overall system behavior. Nodes that are not well-connected in the network would play little or no role in affecting the overall system behavior. Also, nodes with high EC scores indicate ‘busy’ or ‘heavily utilized’ nodes and these tend to be positioned at the ‘core’ of a network. These nodes tend to be more highly connected than nodes situated at the ‘periphery’.

The BC reflects the position of a node concerning how it lies on the geodesic path between different groups of nodes (or sub-networks). Since nodes tend to cluster at a sub-network level, the BC indicates the ‘bridging’ nodes that connect different sub-networks are important. Nodes with high BC scores are, therefore, connected to more sub-networks. In the case of energy futures, subnetworks can represent energy subsectors, and certain scenario elements could be considered significant as they hook to many sub-sectors. The energy system covers all aspects from the production of energy resources to the consumption of these resources, which may comprise many different subsectors including service, manufacturing, and agricultural systems. Some energy subsectors such as transportation can play a significant role in shaping the national energy system. This is especially true for Canada because Canada is a large country where people are geographically spread out. The movement of people and goods within the country demands a substantial energy requirement (see e.g., Potvin et al., 2016). There are certain elements which are not only relevant to the main energy system but also to other subsectors of energy systems. These ‘bridging’ nodes are key in characterizing cross-scale relationships which can explain how different sub-sectors interact.

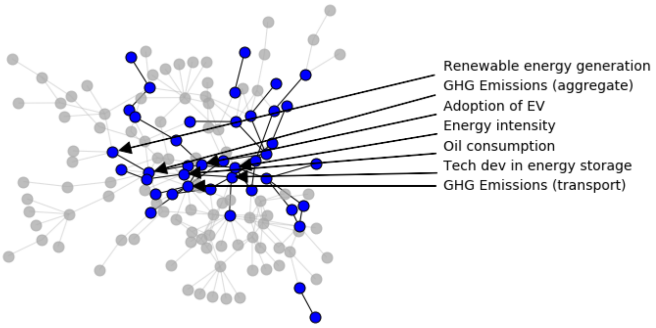
5.4 Results and Discussion

5.4.1 Visualizing the Structure of the Multi-study Network

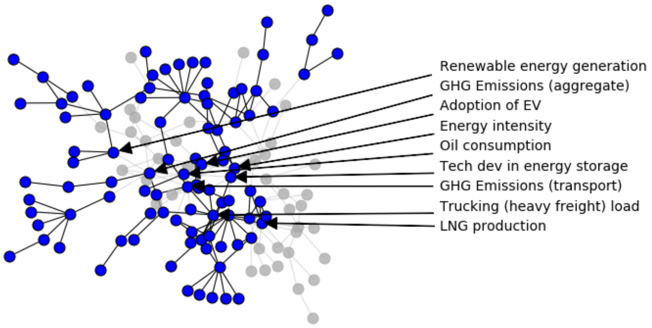
Network analysis can visualize the structure of energy futures scenario studies along with what portion of a multi-study network each study occupies. Figure 9 shows all the nodes and edges extracted from the four studies. Nodes that are extracted from an individual study are colored blue so that the extent to which each study spans across the multi-study network can be better visualized. The broader the span, meaning that the more nodes attributed to a particular study, the broader the scope of the individual study. At a glance, the REC study (Figure 9-C) has the broadest scope whereas the NEB study (Figure 9-D) appears to be more constrained. Nodes in the NEB study were found to be related mostly to economy (i.e., with nodes describing, for example, oil and gas demand and infrastructure development). Furthermore, the NEB study emphasizes environment less and economy more. While the NEB study can be viewed as focussing on the economy, the DDPC study (Figure 9-B) has a different scope entirely that focuses on the environment (i.e., comprising of nodes describing environmental issues such as ‘renewable energy generation,’ ‘energy efficiency policy mandate,’ ‘banning coal/oil-fired generation’). Alternatively, counting the number of nodes in individual network can also provide a reasonable assumption for defining the scope of these studies. For instance, the REC study has the broadest scope with 95 out of a total 134 nodes. In contrast, the NEB study has the narrowest among the four studies with 18 nodes. Despite occupying a small portion of the multi-study network, the NEB study comprises nodes that are not the focus of other studies. The study of NEB has ten nodes that are not attributed to other studies. Although the scope of the NEB study covers different ground, it can complement other studies by bridging a gap that other studies have missed. Overall, the scope of the four studies tends to vary. But the broadest scope is exhibited when the four studies are analyzed holistically.



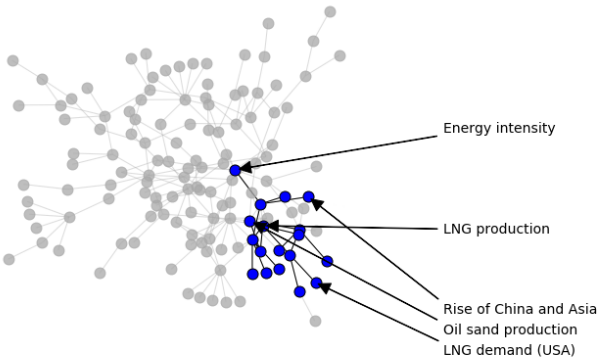
A. Trottier Energy Futures Project (TEFP)



B. Deep Decarbonization Pathways for Canada (DDPC)



C. Re-Energizing Canada (REC) Pathways to a Low-Carbon Future



D. National Energy Board (NEB) Canada Energy Future 2016

Figure 9 Visualizing different scope of energy scenarios

When the scope of a futures study is too narrow, policymakers may perceive limited options for pursuing potential future energy developments. By and large, studies usually present future developments that are desirable, but the undesirable futures may be policy relevant. For example, a study by Schweizer and Kreigler (2012) found that 77% of storylines in SRES are internally inconsistent casting doubt on whether the scenarios should have been considered equally plausible. Moreover, Schweizer and Kriegler found that consistent stories are those describing the current trajectory labeled as 'coal-powered growth.' Yet, energy futures depicted by coal-powered growth are under-represented in SRES. The problem of underrepresented yet policy-relevant scenarios is cautionary for the multi-study network of Canadian energy futures. Since different studies vary in their coverage of relevant scenario elements for the Canadian energy system, relying on one scenario study to base our decisions upon is less than optimal. Integrating several studies that have different scopes, and therefore a wide range of alternative futures, can better inform policy decisions.

Scenario narratives are developed to corroborate the interrelationship among scenario elements selected by individual studies. It is possible that different studies will use different elements and model the interrelationships among these elements differently. When relying on a single study, scenario users could unintentionally be blind-sided, potentially missing other scenario elements and interconnections that are modelled by other studies. It may be challenging to integrate different qualitative narratives together, yet with network analysis, it is feasible to integrate the elements of these scenarios. When the scenario elements and their interrelationship are extracted from multiple studies, they can be mapped onto a single blueprint as a multi-study network. It is possible to produce a similar network by eliciting responses from the scenario developers themselves, but such a process takes time. Since there are existing scenario studies on Canada's energy future, these scenarios can be consulted to extract scenario elements, bypassing the time-consuming process of expert elicitation. The application of network analysis in this thesis is not specifically aimed to produce a 'combined' or 'aggregated' storyline; rather the approach unpacks the underlying scenario logics, drivers, and assumptions across different studies so we can understand what elements and interrelationships they have agreed on and what issues (i.e. network coverage) the respective scenario studies could have missed.

5.4.2 Isolating Key Scenario Elements

Traditionally, ranking scenario elements is based on subjective interpretation of the study participants or the scenario developers (Lloyd and Schweizer, 2014). For instance, a typical participatory scenario planning will invite study participants to identify important elements by means of participants' votes to decide which elements are to be incorporated into scenario development (Ogilvy and Schwartz, 2004; Rounsevell and Metzger, 2010). Nonetheless, this process is vulnerable to coercion, when a voter's decision is persuaded by others, and collusion, when individuals conspire as a group to influence the voting outcomes. As a result, certain individuals can influence scenario outcomes to produce a depiction of the future that is aligned with personal or political agendas of the influencers. In this respect, prioritising scenario elements must be performed with impartiality without introducing additional biases. However, this exercise can be challenging as most scenario methods rely mostly on subjective judgments to rank or rate the importance of candidate scenario elements. Subjective judgments can be more transparent when there is a metric that can tell us how candidate scenario elements stack up. Networks have exploitable statistical properties useful in this situation.

Node centrality metrics provide an empirical approach for prioritizing relevant scenario elements. This approach can potentially replace the conventional 'voting' process in a typical scenario planning workshop. In participatory scenario planning, only a handful of scenario elements will be selected. This is because of the limited time available for participants to elaborate multiple scenario elements and construct accompanying scenario narratives or storylines (Ogilvy and Schwartz, 2004). If scenario elements are nodes in a network, node centrality scores can be calculated for each node. These scores can be ranked to identify which scenario elements are more central in the network (Table 2 and Figure 10).

Table 2 List of top ten Betweenness and Eigenvector centrality scores

Betweenness Centrality			Eigenvector Centrality		
Rank	**Scenario Element**	**Score**	**Rank**	**Scenario Element**	**Score**
1	GHG Emissions (aggregate)	0.339049	1	GHG Emissions (transport)	0.344127
2	Energy Intensity	0.233946	2	Oil consumption	0.291998
3	GHG Emissions (transport)	0.216002	3	Trucking (heavy freight) load	0.267228
4	Tech. Dev. in energy storage	0.183621	4	GHG Emissions (aggregate)	0.256534
5	Trucking (heavy freight) load	0.150394	5	LNG production	0.237551
6	LNG production	0.115559	6	Adoption of EVs	0.231423
7	Renewable energy generation	0.108577	7	Energy Intensity	0.204339
8	Active mobility	0.102942	8	Export	0.202214
9	Oil consumption	0.100315	9	Tech. Dev. in energy storage	0.199930
10	Sectoral coordination	0.097289	10	Oil sand production	0.189331

When EC and BC scores are visualized as a network (Figure 10), the nodes with the higher EC and BC scores (i.e., represented by the node size that corresponds to either EC or BC scores) are often found on the 'center' of the network. Some usual suspects such as elements associated with fossil-fuel energy consumption or production are considered important drivers of Canada's energy futures. Also, elements associated with transportation are another important driver. A highly ranked node like 'GHG Emissions (transport)' underscores Canadians' propensity to driving. Also, nodes such as 'Active mobility' and 'Adoption of EVs' can underlie the potential for alternative modes of transportation that are greener and more sustainable.

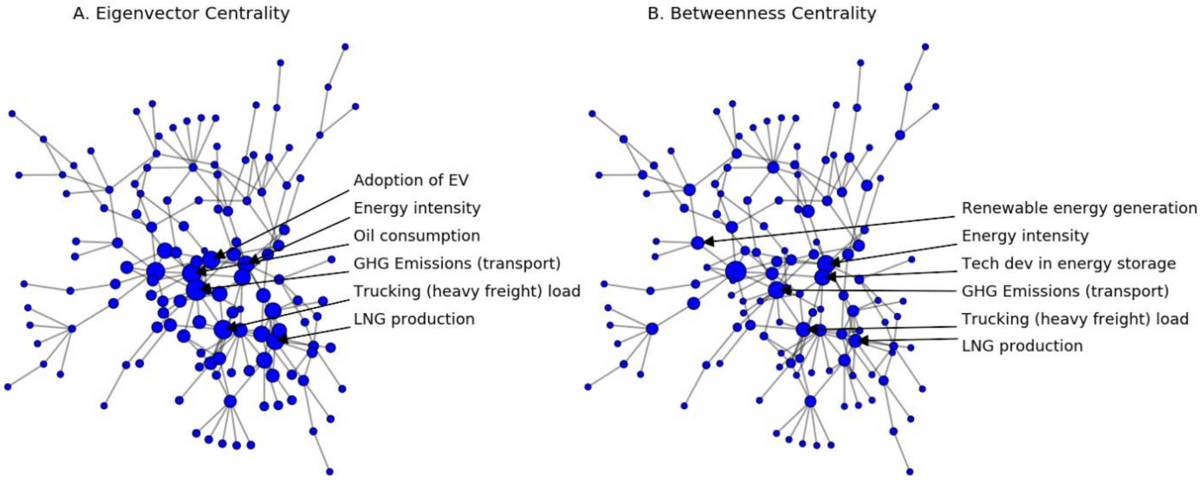


Figure 10 Network visualizations for Eigenvector centrality and Betweenness centrality

Initially, I had set out to explore two centrality metrics to select scenario elements, which allows us to perform a comparison between the metrics. When an element scores highly on both EC and BC, selecting this element is less controversial. If an element scores highly in only one centrality metric, it signals the need to dive deeper into inspecting this specific node. For instance, one of the elements that has a high score for BC but not for EC is 'renewable energy generation' (Figure 11). The high BC score suggests that this node behaves as a bridge connecting different subnetworks; however, this node hardly interacts with other well-connected nodes. Certain scenario analysis techniques such as CIB will require nodes that are well-connected, meaning that these nodes are interacting with other nodes either as an 'impact source' exerting influence on other nodes or as an 'impact sink' receiving influence from other nodes. I also would like to point out that how different end-states interact with other elements would be eventually captured in subsequent steps of a scenario analysis using CIB (see Chapter 6). In CIB analysis, non-interacting elements in CIB analysis rarely have any significant role in altering system outcomes.

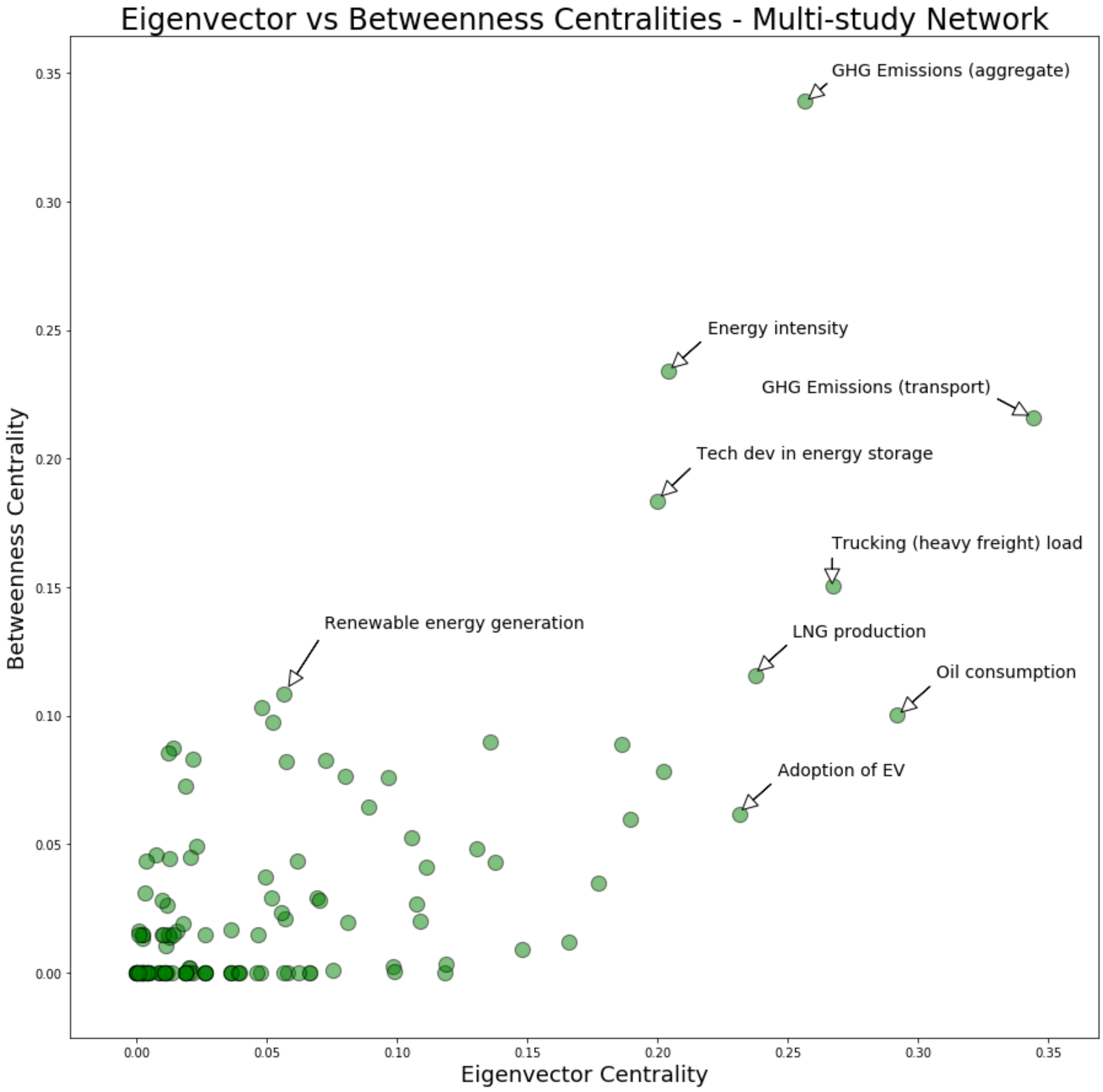


Figure 11 Betweenness centrality vs. Eigenvector centrality

5.4.3 Objectivity of Network Analysis

Futures studies addresses a different type of inquiry compared to empirical research, as futures are non-observable. One may think rightfully that futures studies are prone to speculation; however, applying objective and transparent methods can better discipline futures studies to avoid producing futures that lack credibility. Integrating different studies as demonstrated using network analysis is more objective than having human study participants and scenario analysts do the task. In Lloyd and Schweizer (2014), objectivity can mean that the research output would be (1) publicly available for inspection, (2) independent from one's will or wishes, (3) unbiased, (4) independently existing, (5) real, and (6) replicable. When the task of integrating diverse scenarios is handed to the analysts, many of the objectivity criteria cannot be met. For instance, human readers may unknowingly inject their own personal biases, and their assumptions for how different elements interact are inaccessible to others. What makes a network analysis approach more objective is that the interactions among these elements can be inspected publicly by tracing the nodes and edges in the network.

Moreover, two or more scenario analysts or developers may produce results that are hardly identical, hence the studies conducted by human readers may not be replicable. When aggregating different qualitative scenarios, the produced result could be a story that corroborates different scenario narratives. While it is possible for human readers to identify what part of the scenario narratives corroborate (and/or contradict), such opinions would be a subjective interpretation, nonetheless. That means another human reader doing the same task may not necessarily produce the same result. In network analysis, once the data on nodes and edges are defined, the same network can be reproduced anytime. Besides the replicability of the results, the process of developing the multi-study network is transparent and procedurally objective.

Nevertheless, there are biases rooted in these individual studies. While the application of network analysis proposed does not remove biases inherent in any individual study, it counterbalances the biases of the individual studies by integrating studies together into a more holistic network. Solomon (2006) in Lloyd and Schweizer (2014) explains that the inclusion of counterbalancing information leads to epistemically superior (i.e. more objective) outcomes because "...[I]t preserves and makes use of all of the information available to the community" (Solomon 2006; in Lloyd and Schweizer 2014, 2073). Thus, the network analysis is more objective since the assumptions used by the analysts are 'open' for inspection, the results are replicable, the procedure for constructing a multi-study network is transparent, and the multi-study network makes use of much more of the information available to decision makers.

I acknowledge that there are some limitations of this study. First, the text mining process for extracting nodes and edges from the study reports was done by a single human coder and I did not engage another coder for intercoder reliability. In future research, it may also be possible to automate the text mining process by developing a machine learning model that uses Natural Language Processing and Machine Learning to identify statements about the future.

5.5 Conclusion

This chapter has introduced an empirical approach using network analysis to integrate elements of diverse scenario studies depicting different futures. This provides a way to examine the underlying logics of different scenario studies and to uncover patterns of meaning across them. Individuals who conduct or participate in scenario studies have opinions about how significant different scenario elements are, but such beliefs are subjective, making it difficult to tease out which elements should be considered relevant. This chapter has presented an application of network analysis to different scenario studies to integrate different elements of their narratives. Network analysis can be deployed to assess these studies by mapping the causal relationships of all scenario elements to identify the key elements in the multi-study network. Application areas for such assessments making use of scenario research include climate change and biodiversity. As demonstrated, this method has highlighted key elements critical in developing energy scenarios for the Canadian context.

The multi-study network is suitable for examining how scenario elements of different studies on the same topic (in this case, Canada's energy futures) interface. Even though these studies were conducted by different author teams and sometimes in parallel, the studies have scenario elements that are common. That means the study scopes might be different, but they also overlap in some respects. For scenario elements that are not overlapping, visualizing how different these elements are in a multi-study network presents scenario users a holistic perspective. Evidently, this network analysis has shown the compatibility of different studies even though these studies were done by different author teams.

The multi-study network created for Canada's energy futures has shown that different scopes are inherent in individual studies. These findings indicate that some studies have a narrow scope, which is biased to focussing on either the economy or the environment. However, scenario users can assess diverse scenario studies to potentially counterbalance biases originating in individual studies. Additionally, this technique is useful for soliciting candidate elements to be incorporated into a scenario process (e.g., participatory scenario planning). When scenario studies are integrated using network analysis, node centrality can be calculated to identify which nodes are more central. Node centrality metrics can be used to evaluate those interacting elements and rank these elements according to how central they are in the network. Although it is possible that the task of integrating qualitative scenarios could be assigned to human analysts, the network analysis approach is more objective due to its procedural transparency.

As previously mentioned, it is fundamental to select scenario elements that are interacting either as an impact source exerting influence on other elements or as an impact sink receiving influence from other elements. In CIB analysis, non-interacting elements rarely have any significant role in altering system outcomes. This chapter concludes by highlighting the scenario elements that were further assessed for their applicability in the inclusion to the scenario development process using CIB analysis detailed in the next chapter (Chapter 6). These elements are GHG emissions (transport), energy intensity, freight transport, adoption of EVs, technology development in energy systems, oil and gas production & consumption.

Chapter 6: Multi-scale Energy Scenarios

This chapter addresses research question 3: What are the implications of global developments on Canada’s low-carbon energy transition? Hence, it details the process of developing a set of globally linked, internally consistent energy scenarios for Canada under the Shared Socioeconomic Pathways (SSP) framework. For this extended SSP study, re-specification of SSP elements discussed in Chapter 2.4.5 was chosen as the entry point, meaning that the scenario elements necessary for developing the cross-impact (CI) matrix for Canada’s energy scenario study were firstly defined and then this CI matrix was combined with the CI matrix of the global SSPs. At first, the selection of candidate elements for developing energy scenarios for Canada is informed by the Eigenvector centrality and betweenness centrality scores (see Chapter 5). Subsequently, these elements were incorporated into the Canadian CI matrix for CIB analysis. As mentioned previously in the introduction, Chapter 1, the scenario development process employed in this dissertation is the cross-impact balance analysis (CIB) (Weimer-Jehle, 2006). The CIB analysis can be applied to analyse multiple scenarios systematically and holistically even though these scenarios were produced independently by different author teams by joining piece-meal matrices into a single large cross-impact (CI) matrix that can be subjected to CIB analysis. In this respect, I produced a CI matrix for Canada comprising of seven scenario elements (a.k.a. ‘descriptor’ in CIB parlance); these elements were identified by deconstructing four reports of Canada’s energy futures to extract the elements of scenario narratives of these studies, including the information for how these elements interrelate. Subsequently, I combined the newly created CI matrix for Canada with the CI matrix for the global SSPs produced previously by Schweizer and O’Neill (2014). As a result, a large multi-scale CI matrix was produced consisting of scenario elements of both the global SSPs and Canada’s energy futures. Chapter 6.1 details the skeletal construction of the global/Canada multi-scale CI matrix used in this dissertation. Subsequently, Chapter 6.2 explains the step-by-step process of obtaining the cross-impact judgements for each cell in the matrix; these judgments were obtained through expert elicitation, and different experts were sought according to their field of expertise—for example, a transportation expert provided impact judgments for transportation related descriptors. The multi-scale CI matrix would then be subjected to CIB analysis. The results are a set of internally consistent scenarios, which will be further discussed in Chapter 6.3.

6.1 Introduction: Multi-scale Scenario Analysis – A Bottom-up Integration

There are two approaches to produce extended SSPs: bottom-up and top-down. The top-down approach will downscale the global SSPs to produce extended SSPs at regional/national or sectoral studies such as Canada's energy futures. For the bottom-up approach, the extension studies (e.g., regional/national scenarios) could be developed independently without considering the global SSPs at first. Instead, finished extended SSPs would be linked back to the global SSP later to ensure that scenarios for the extended SSPs are internally consistent with the global SSPs. The bottom-up approach presents scenario developers with the flexibility to focus first on the contextually relevant scenario elements. This is useful in a situation when the global SSP components (i.e. qualitative narratives and quantitative data) that are meant to be generic cannot be downscaled usefully like in the top-down approach. A top-down approach would use the global SSPs as the boundary conditions so that sub-global scale scenarios produced will not be too extremely different from the global SSPs (van Ruijven et al., 2014). This is good for ensuring that both qualitative and quantitative components of the extended SSPs are consistent with the global development pathways since the extended SSP studies will inherit global characteristics (including boundary conditions) after being downscaled from the global SSPs. However, such a treatment of the boundary conditions in bottom-up approaches is challenging since the extended SSPs are likely developed independently. In that respect, scenarios produced by bottom-up approaches would need to be further assessed whether regional/local development pathways are consistent with the global scenarios (van Ruijven et al., 2014).

Accounting for the transfer of the boundary conditions from global scenario studies to more localized studies is well-documented by Zurek and Henrichs (2007) (Chapter 2). According to them, linking strategies such as soft-links could provide boundary conditions, but the process of scenario development would require scenario developers to constrain scenario elements (i.e. scenario logics, drivers, and assumptions) at the lower scale to be the same as or similar with the elements of the global scenarios. In developing regional and sectoral extension studies, scenario developers will select scenario elements important for the lower scales, meaning that elements for the extended SSPs could be very different from those of the global SSPs. However, scenario developers may or may not investigate how local developments are influenced by the global developments. Multi-scale CIB analysis can introduce a rudimentary process for modelling cross-scale interactions.

6.2 Methods and Materials

The third phase of this research focusses on scenario development using CIB analysis and can be broken down into four steps. First, I selected scenario elements as descriptors that will be used to construct a multi-scale CI matrix for this research; this will be described in Chapter 6.2.1. In the multi-scale CI matrix, the descriptors are mapped as such that each cell in the matrix contains a judgment score that represents how an X descriptor (i.e., the row descriptor) influence a Y descriptor (i.e. the column descriptor). Second, Chapter 6.2.2 details how these impact scores were obtained through expert elicitation. I sought a group of expert participants to elicit their judgments on the influences between the two descriptors. Third, the impact scores elicited from the expert panel were transferred to populate the respective matrix cells; this process is detailed in Chapter 6.2.3. Finally, the completed CI matrix was subjected to CIB analysis using a sfotware application called ScenarioWizard; Chapter 6.2.4 details the scenario development process including checking for data quality before performing a simulation run to search for internally consistent scenarios.

6.2.1 Selecting Scenario Elements

A list of scenario elements was obtained from the key elements of the SSPs (Schweizer and O'Neill, 2014) as well as the results from the network analysis (Chapter 5). The selection criteria are based on:

1. Scenario elements are postulated to have cross-impact relationships. In the CIB analysis, elements that are not interacting have a mathematical property of a 'null operator' that would not alter or contribute to the outcome of the CIB analysis.
2. When several elements are expected to 'behave' in the same manner in the CI matrix, they will be grouped (aggregated) together as one element.

The final list of key elements for this study was vetted by the thesis committee and was subsequently incorporated into the scenario development process. Elements in this study as well as their respective development pathways are listed in Table 3.

6.2.1.1 Selection of interacting global SSP elements

The selection of global SSP elements that interacts with the scenario elements of Canada's energy futures, either by exerting or receiving influence, is based on the interpretation of the researcher through the consultation with the thesis advisor, Dr. Vanessa Schweizer, who was involved in the development of the SSPs framework. The three elements from global SSPs, namely population, carbon intensity and urbanization, were selected and assessed how these elements would interact with scenario elements related to Canada's energy development.

Population (SSP01): Global population is defined as the total number of people living in this world. Population is pertinent to the challenges to mitigation (Schweizer and O'Neill, 2014), which would be relevant to Canada as an exporter of fossil-fuel based energy.

Urbanization (SSP07): Urbanization is defined as the percentage of global population living in urban areas. Urbanization, and by extension cities, is pertinent to both challenges to mitigation and adaptation (Schweizer and O'Neill, 2014). Further, studies on future cities can revolve around energy issues (Moglia et al., 2018).

Carbon intensity (SSP04): Average carbon intensity is defined as the ratio of CO2 emissions (metric tons) to total primary energy consumed (Terajoules). As a major producer and exporter of fossil-fuel based energy, energy development in Canada has a direct influence on global carbon intensity.

Technology development in Negative Emissions Technology (SD03): Additionally, one global element, technology development in Negative Emissions Technology (NET), was included in this study. Even though this element is a 'global' element, it is relevant in the Canadian context. The result of network analysis (discussed in Chapter 5) has shown the importance of several main technologies, as well as supporting technologies, that could be significant in the advancement and uptake of NETs. Furthermore, the uptake of NETs may have significant impacts either positively or negatively on resource extraction economies like Canada (Minx et al., 2018; Nemet et al., 2018).

6.2.1.2 Selection of elements for Canada

The initial list of elements for developing Canada's energy scenarios was informed by the metrics provided by the node centrality scores (see Chapter 5.3.4). The list was further examined to weed out those elements that are not expected to interact with other elements because, in CIB analysis, non-interacting elements would not influence the overall system. For the final selection of the scenario elements, in-house expert as well as academic literature were consulted. Further, some elements, which can be generalized together, were collapsed into one generic variable. This is to limit the number of variables presented to the potential expert participants to a manageable number. Responding to an additional variable means 9 to 18 more questions per module must be attempted by each study participant. Chapter 6.2.2 details the expert elicitation. Since the analytical perspective on this dissertation is on the national context, more generalizable (or more common and accessible) variables were used to model local dynamics at the national level[16] (Note: for sub-national analyses, disaggregated variables may be more useful). The 'local' scenario elements for Canada are as follows:

Carbon intensity (SD04): This element is an extension of the global SSP element, SSP04. Carbon intensity was chosen as a scenario element to represent both energy intensity as well as GHG emissions, which are also highly ranked according to node centrality measures (see Chapter 5.4.2). Furthermore, the multi-scale interaction of Canada's energy exports can be modelled and analysed more usefully using carbon intensity as a scenario element rather than energy intensity. In this respect, carbon intensity posited to interact with other local elements such as income (SD05), economy (SD10), and technologies (SD06, SD07).

Income growth (SD05): This element is an extension of the global SSPs element, SSP02. Income is a driving factor of many elements considered in this research. Conventional wisdom suggests that income may be affected (either exerting or receiving influences) by the decarbonization of the economy (SD10), the adoption of EVs (SD08) as well as technology development in green transit (SD-07). Nonetheless, such conventions were tested here in the expert elicitation.

Technology development in green freight transport (SD06): This element is associated with two highly ranked nodes, 'GHG emissions (transport)' and 'trucking (heavy freight) load' according to node centrality measures (see Chapter 5.4.2). As research has shown, logistic transport is an enabler of energy systems and they are closely interlinked (e.g., railroad and coal, tankers and oil) (Sovacool, 2016). This element also highlights freight and logistics as another important energy sub-sector, which could play a critical role in Canada's low carbon energy

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[16] The author is aware that disaggregated variables or even a completely different set of variables may be more useful for sub-national analyses (i.e., provincial level). For instance, factors related to energy consumption for space heating could be more important for provinces in northern Canada, but its importance cannot be generalized for Canada.

transition. This scenario element, “technology development in green freight transport,’ may interact with carbon intensity (SD04) and decarbonized economy (SD10).

Technology development in green transit (SD07): This element is associated with transportation, an important energy sub-sector, which also underscores some nodes that are highly ranked according to node centrality measures (Chapter 5.4.2) such as ‘GHG emissions (transport)’ and ‘Oil consumption.’ This element is also expected to interact with global elements (e.g., global urbanization (SSP07) since Canada hosts one of the world’s largest rail equipment manufacturers, Bombardier Inc. (Lowe et al., 2010). Domestically, this element may interact with carbon intensity (SD04) and income growth (SD05).

Adoption of EVs (SD-08): This element is one of the nodes with a high EC score which also underscores other nodes with highly ranked nodes such as ‘GHG emissions (transport)’ and ‘Oil consumption’ according to node centrality measures (see Chapter 5.4.2). Furthermore, the adoption of EVs will reduce the domestic demand for fossil fuel, which directly influences whether Canada’s economy is decarbonized or not. The adoption of EVs may also interact with other local elements such as carbon intensity (SD04) and income growth (SD05).

Decarbonized economy (SD10): This element represents whether Canada’s economy is decarbonized, meaning how dependent the country’s GDP is on national income from fossil-fuel based energy production. Because Canada’s fossil-fuel based economy is found to be closely associated with global demand, it is expected there could be some interactions between this element and some of the global SSP elements, namely global carbon intensity (SSP04) and urbanization (SSP07).

6.2.2 Constructing Multi-scale Cross-impact Matrix

The CIB analysis uses a multi-scale CI matrix that combines all scenario elements for regional or sectoral SSP and global SSPs together (Figure 12). Since the CIB algorithm has access to multi-scale interactions, CIB analysis can identify scenario configurations that are consistent across scales. In this dissertation, the CI matrix for Canada was produced independently, denoted as CA Matrix (Partition 2) in Figure 12. This CA Matrix was combined with the CI matrix of the global SSPs, which is denoted as SSP Matrix (Partition 1) in Figure 12. When combined, this newly created matrix is a multi-scale CI matrix. The multi-scale matrix acts as an interface that maps the cross influences of global/Canadian scenario elements; this is denoted as Interaction Space

(Partition 3 and 4) in Figure 12. In the next two sections, how the SSP Matrix and CA Matrix were created individually will be explained.

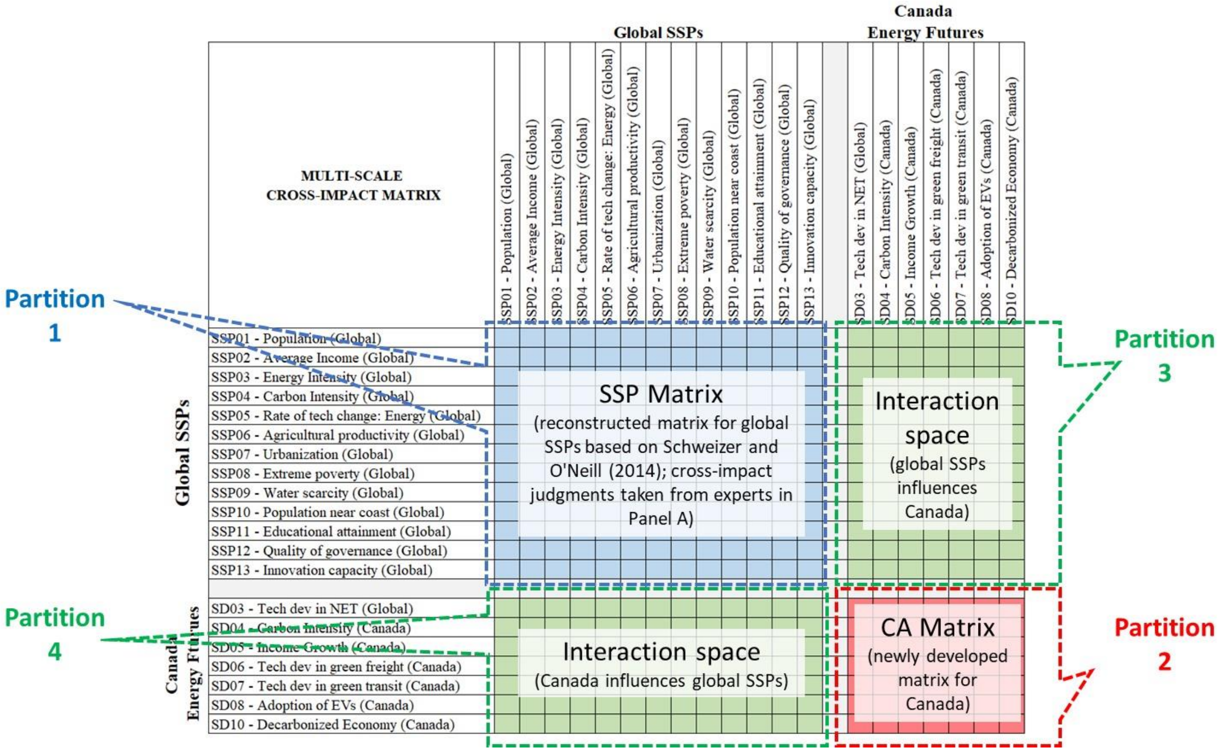
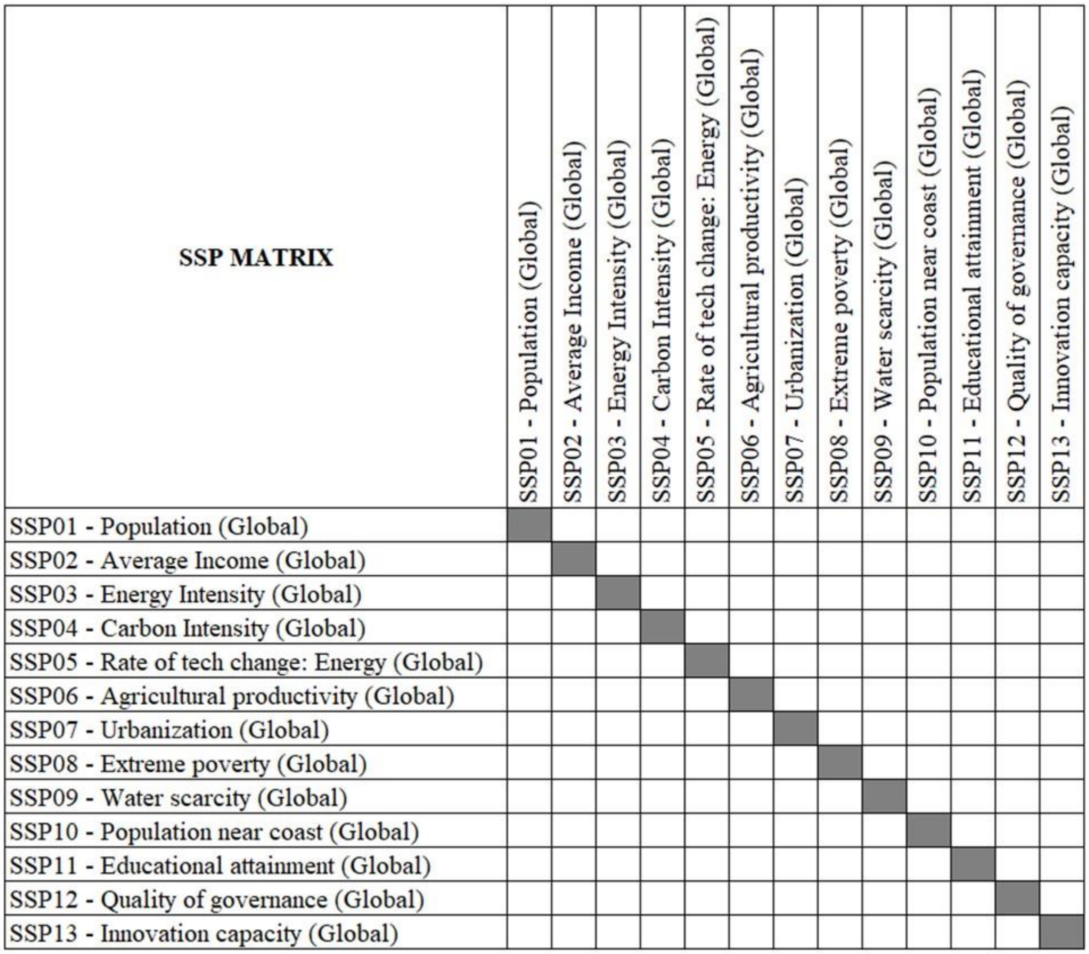


Figure 12 Multi-scale cross-impact matrix showing partitions for CIB analysis

6.2.2.1 SSP Matrix

The CI matrix of the global SSPs (i.e. SSP Matrix) is adapted from Schweizer and O'Neill (2014). In their study, the expert participants were grouped into panel A and B, then the corresponding CI matrices were constructed for both panels. This CI matrix was incorporated as part of the newly created multi-scale CI matrix (see Figure 12; labelled as partition 1). The cross-impact judgments in the CI matrix for the global SSPs (labeled as SSP matrix, also see Figure 13) uses the responses of the experts in Panel A (see Schweizer and O'Neill, 2014); the full matrix with cross-impact judgments is shown in Appendix D.

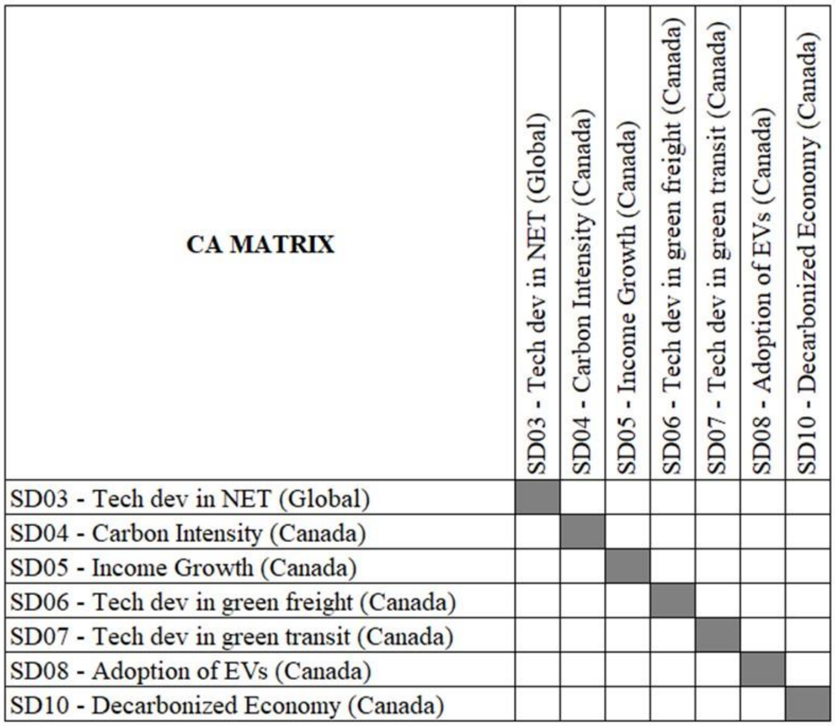


SSP MATRIX	SSP01 - Population (Global)	SSP02 - Average Income (Global)	SSP03 - Energy Intensity (Global)	SSP04 - Carbon Intensity (Global)	SSP05 - Rate of tech change: Energy (Global)	SSP06 - Agricultural productivity (Global)	SSP07 - Urbanization (Global)	SSP08 - Extreme poverty (Global)	SSP09 - Water scarcity (Global)	SSP10 - Population near coast (Global)	SSP11 - Educational attainment (Global)	SSP12 - Quality of governance (Global)	SSP13 - Innovation capacity (Global)
SSP01 - Population (Global)	■												
SSP02 - Average Income (Global)		■											
SSP03 - Energy Intensity (Global)			■										
SSP04 - Carbon Intensity (Global)				■									
SSP05 - Rate of tech change: Energy (Global)					■								
SSP06 - Agricultural productivity (Global)						■							
SSP07 - Urbanization (Global)							■						
SSP08 - Extreme poverty (Global)								■					
SSP09 - Water scarcity (Global)									■				
SSP10 - Population near coast (Global)										■			
SSP11 - Educational attainment (Global)											■		
SSP12 - Quality of governance (Global)												■	
SSP13 - Innovation capacity (Global)													■

Figure 13 A simplified version of the SSP matrix

6.2.2.2 CA Matrix

The CI matrix for Canada (CA matrix) comprises scenario elements that are relevant in the Canadian context (see Figure 14). The CA matrix is a portion of a multi-scale matrix that is labelled as partition 2 in Figure 12. As mentioned previously, there are seven elements selected to be used to construct CA matrix, six of which are ‘local’ scenario elements related to the Canadian energy system. One is a ‘global’ scenario element (i.e. technology development in negative emission technologies), which is not part of the global SSPs but important in the Canadian context. The cross-impact judgments in this CA matrix were elicited by the expert participants in this study.



CA MATRIX	SD03 - Tech dev in NET (Global)	SD04 - Carbon Intensity (Canada)	SD05 - Income Growth (Canada)	SD06 - Tech dev in green freight (Canada)	SD07 - Tech dev in green transit (Canada)	SD08 - Adoption of EVs (Canada)	SD10 - Decarbonized Economy (Canada)
SD03 - Tech dev in NET (Global)	▨						
SD04 - Carbon Intensity (Canada)		▨					
SD05 - Income Growth (Canada)			▨				
SD06 - Tech dev in green freight (Canada)				▨			
SD07 - Tech dev in green transit (Canada)					▨		
SD08 - Adoption of EVs (Canada)						▨	
SD10 - Decarbonized Economy (Canada)							▨

Figure 14 A simplified version of CA matrix

6.2.2.3 Interaction Space

As discussed in the introduction section of this chapter, there are two approaches to CIB analysis: top-down and bottom up (Schweizer and Kurniawan, 2016). This study uses the latter approach where CI matrix for Canada was developed in this research, which was then linked to the CI matrix for the global SSPs. When linking two matrices of different scales (i.e., global and Canada), indicated as partition 1 and 2 in Figure 12 respectively, information about potential cross-scale interactions would also be required for CIB analysis. The cross-scale interaction space refers to the partitions of the matrix labelled as 'interaction space.' This cross-scale interaction space represents how elements for Canada influence elements of the global SSPs and vice versa (i.e., partition 3 and 4 in Figure 12). The cross-impact judgments for partition 3 and 4 were also elicited from a panel of experts.

When this multi-scale CI matrix was constructed, the cross-impact judgments collected from the expert elicitation were transferred to populate the matrix. Judgments obtained from the expert elicitation cover partition 2, 3 and 4, and the cross-impact judgments for partition 1 (SSP matrix) was adapted from Schweizer and O'Neill (2014).

Table 3 Scenario elements of the SSP Matrix and CA Matrix

Element ID	Scenario Element Description	Element End-States	Source
SSP01/SD01	Population (Global)	Low (<8 billion) Medium (8-13 billion) High (>13 billion)	Schweizer and O'Neill (2014)
SSP02	Average Income (Global)	Low (annual growth <1.5%) Medium (1.5% - 2.0% growth/yr) High (annual growth >2.0%)	Schweizer and O'Neill (2014)
SSP03	Energy Intensity (Global)	Low (>1.0% decrease/yr) Medium (0.5% - 1.0% decrease/yr) High (<0.5% decrease/yr)	Schweizer and O'Neill (2014)
SSP04/SD09	Carbon Intensity (Global)	Low (>0.5% decrease/yr) Medium (0.1% - 0.5% decrease/yr) High (<0.1% decrease/yr)	Schweizer and O'Neill (2014)
SSP05	Rate of tech change: Energy (Global)	Low (AEEI~0.5% per yr) Medium (AEEI~1.0% per yr) High (AEEI~1.5% per yr)	Schweizer and O'Neill (2014)
SSP06	Agricultural productivity (Global)	Low (<0.75% improvement/yr) Medium (0.75%-1.25% improvement/yr) High (>1.25% improvement/yr)	Schweizer and O'Neill (2014)
SSP07/SD02	Urbanization (Global)	Low (<70% by 2100) Medium (70% - 80% by 2100) High (>80% by 2100)	Schweizer and O'Neill (2014)
SSP08	Extreme poverty (Global)	Low (>4% decrease/yr) Medium (1% - 4% decrease/yr) High (<1% decrease/yr)	Schweizer and O'Neill (2014)
SSP09	Water scarcity (Global)	Low (<10% global population) Medium (10% - 20% global population) High (>20% global population)	Schweizer and O'Neill (2014)
SSP10	Population near coast (Global)	Low (<40% global population) Medium (40%-50% global population) High (>50% global population)	Schweizer and O'Neill (2014)
SSP11	Educational attainment (Global)	Low (<65% global population) Medium (65% - 75% global population) High (>75% global population)	Schweizer and O'Neill (2014)
SSP12	Quality of governance (Global)	Low (>20% governments fail) Medium (10% - 20% governments fail) High (<10% governments fail)	Schweizer and O'Neill (2014)
SSP13	Innovation capacity (Global)	Low (deterioration) Medium (no/modest improvement) High (substantial improvement)	Schweizer and O'Neill (2014)
SD03	Tech dev in NET (Global)	Low (remove <10 GtCO2/yr by 2100) Medium (10-15 GtCO2/yr removal by 2100) High (remove >15 GtCO2/yr by 2100)	Chapter 5
SD04	Carbon Intensity (Canada)	Low (>1.4% decrease/yr) Medium (+0.38% to -1.4% change/yr) High (>0.38% increase/yr)	Extended from global SSPs
SD05	Income Growth (Canada)	Low (<US$86K per yr by 2100) Medium (US$86K to US$120K /yr by 2100) High (>US$120K per yr by 2100)	Extended from global SSPs
SD06	Tech dev in green freight (Canada)	Low (Uptake after 2030, <50% by 2100) Medium (50% uptake by 2100) High (Fully adopted by 2070)	Chapter 5
SD07	Tech dev in green transit (Canada)	Low (<75% by 2100) Medium (>50% uptake by 2080) High (Fully adopted by 2060)	Chapter 5
SD08	Adoption of EVs (Canada)	Low (>80% uptake after 2075) Medium (>80% after 2050 but before 2075) High (>80% uptake by 2050)	Chapter 5
SD10	Decarbonized Economy (Canada)	Coupled (Econ coupled with fossil fuel income) Decoupled (Econ decupled with fossil fuel inc)	Chapter 5

SSPxx : Key elements of the global SSPs from Schweizer and O'Neill (2014)
SDxx : Elements related to Canada's energy futures

6.2.1.3 Individual elements' development pathways.

Besides specifying the descriptors, it is also necessary to identify their possible end-states. The end-states were informed by literature review and secondary data from various sources (e.g., the International Institute for Applied Systems Analysis, Statistics Canada, the International Energy Agency) and developed in consultation with the thesis committee. For elements that fall outside the expertise of the thesis committee, for example transportation, further advice on the face validity from in-house experts at the University of Waterloo, Faculty of Environment, was sought. The information regarding different end-sates of each element was documented as a set of pathway diagrams; the same document was used to provide 'calibration' for study participants to be on the same page.

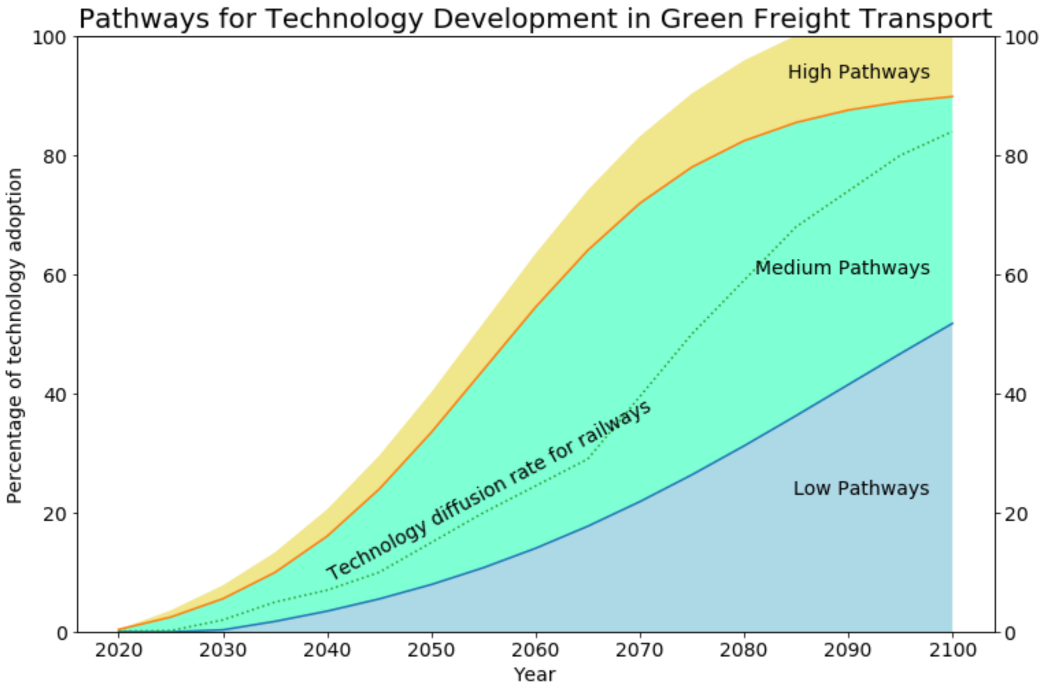


Figure 15 Pathway diagram for technology development in green freight transport

For instance, the technology development in green freight transport mimic the technology diffusion rate of railways in the United States. Technology development refers to how quickly technology is innovated, diffused, and eventually adopted. Technology in green freight transport refers to low carbon means for transporting freight from producers to consumers. These technologies include cleaner alternative fuels (e.g., hydrogen, natural gas) for heavy freight, electric trains, and electric trucks. The rate of technology development is represented by an S-curve. The baseline (i.e. the medium pathway) is based on technology development of the railways, which took about 100 years to be fully adopted in the US (Sovacool, 2016). The high and low pathways are offsets from the medium pathway. That means, for example, the high pathway represents technology adoption that takes shorter than 100 years. This was done by making the gradient of the S-curve steeper. Nonetheless, both high and low pathways retain the S-curve characteristic of the medium pathway (see Figure 15). Pathway diagrams for other descriptors can be found in Appendix B.

6.2.3 Eliciting Expert Judgments

This subchapter describes the third stage that is to collect the impact score for each cell in the newly constructed multi-scale CI matrix. This data collection was done by eliciting a panel of experts for their opinions on the impact score for each cell in the matrix. Here, expert participants were sought and asked to specify their judgments (or assumptions) of how the descriptors are interrelated, taking into consideration the scenario elements' possible end-states. In the study by Schweizer and O'Neill, expert elicitation was conducted in a workshop setting. Alternatively, expert elicitation can also be done in an interview setting; the latter was employed in this study. Expert elicitation is similar to a key informant (expert) interview (Creswell, 2013) that is collecting data from individuals who have a specialized knowledge or expertise on the topic. However, expert elicitation employed here adhered to a strict protocol, obtaining only specific data that was sought after. For this study, the interest is in their judgment scores (or influence) from a panel of experts; the participants would rate specifically how different descriptors (scenario elements) interrelate.

6.2.3.1 Participant sampling

This study employs purposive sampling strategies. Purposive sampling entails researchers determining and selecting the participant sample that is relevant to the objective of the study. The initial participant sample was produced by listing the lead and contributing authors of the recent scenario studies on Canada's energy futures. The list was further refined by selecting authors with an expertise in one of the fields associated with the selected scenario elements. The qualifying process was done by looking at their credentials (i.e. completed a Ph.D.), publications and research interests on the Internet. In some cases, the thesis committee would recommend certain individuals with the relevant expertise to participate, and these individuals were contacted. The initial sample started with 14 experts, and subsequently, another 6 expert participants were approached as recommended.

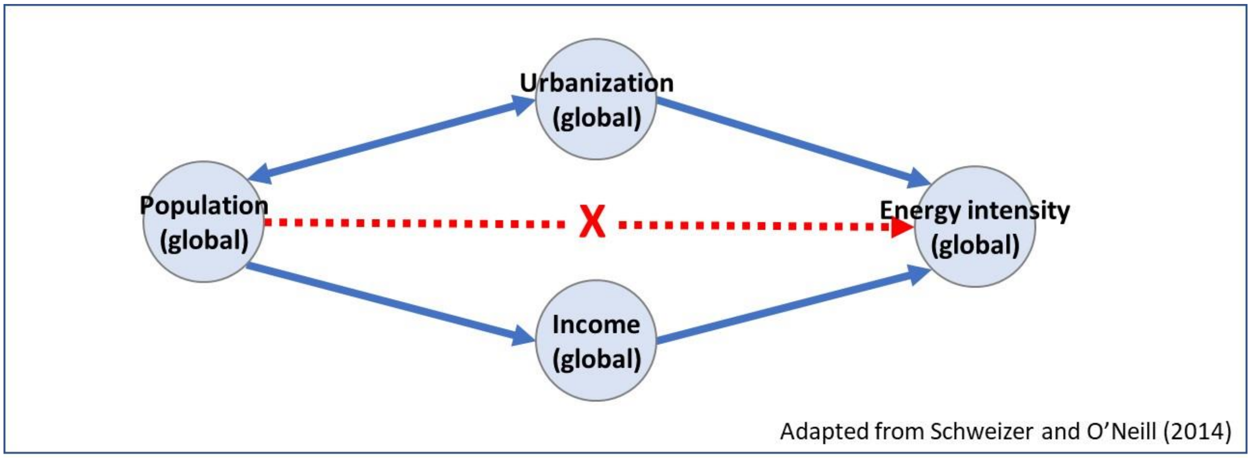
A total of 20 invitations to participate were sent to experts in various disciplines who have a specialized knowledge in one or more topics related to the selected elements; nine responded and eight experts were eventually interviewed; but one decided not to complete with the interview. They were given a choice whether they would like to complete a module of questions in a survey format on their own or a face-to-face interview. A module took no longer than 45 minutes to complete. All participants had opted for face-to-face interview either in person or via Skype. At the beginning of the meeting, the participants were briefed on the elicitation instruments before answering interview questions (slides used during expert briefing are in Appendix C, Part 1).These expert participants are the faculty members at universities across Canada, namely University of Waterloo, University of Toronto, Wilfrid Laurier University, Dalhousie University, Simon Fraser University, and York University.

6.2.3.2 Expert elicitation protocol

Only a relevant portion of the questionnaire was presented to each participant, as the questions follow a standard template where the specific topics of comparison (e.g., population versus income growth) change with each question (see Appendix B). However, the format of the questions is the same. The full instrument consists of hundreds of questions (*n*=546) but each participant responded to only one particular module of questions to complete each module of 10-78 questions (the variation is due to skip logic, which depends on how the respondent answers the questions).

The survey questionnaire (Appendix C, Part 2) is an elicitation instrument for recording experts' judgments for how scenario elements (descriptors) interrelate. The judgments would be recorded according to a discrete seven-point Likert scale (judgment scores ranging from +3 to -3) or linguistically (judgment scores ranging from +VS, +S, +W, 0, -W, -S, -VS, where VS, S, or W stands for very strong, strong, or weak direct influences respectively). Experts participants were asked for judgments for 'direct' influences only, hence, they would need to distinguish direct from indirect influences. To explain what 'direct' influence means, Figure 16 shows the scenario elements connected by blue arrows as direct influences. The variables directly influencing Energy

Intensity (at far right) are Urbanization and Income, whereas Population has an indirect influence on Energy Intensity.



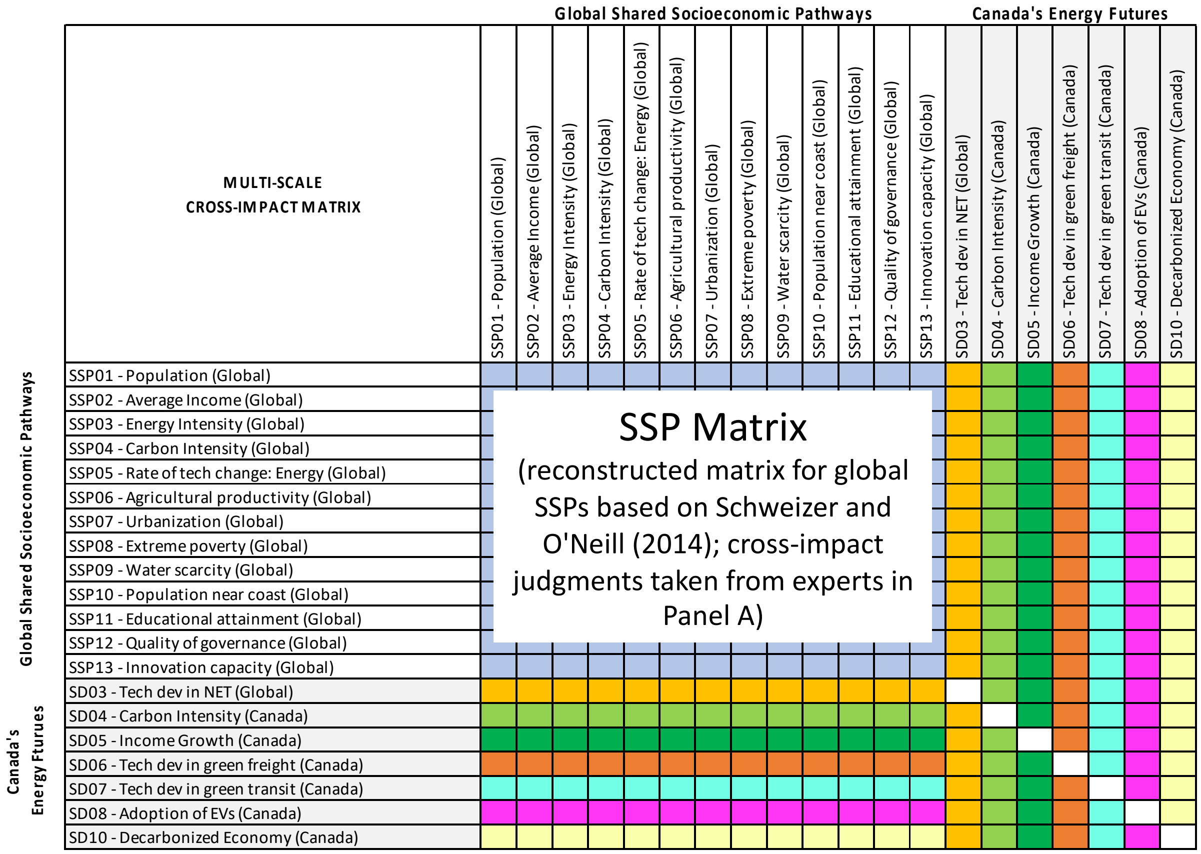
Adapted from Schweizer and O'Neill (2014)

Figure 16 Distinguishing between 'direct' and 'indirect' influences (Schweizer and O'Neill, 2014)

After the participants provided their judgments for how variables interrelate, they were asked to rate the confidence in their judgments according to a five-point Likert scale, which ranges from judgments being viewed as 'accepted' within the discipline to a 'guess.' Finally, the participants provided brief comments that summarize the main reasons for their judgments.

6.2.4 Completing the Multi-scale Cross-Impact Matrix

As mentioned previously, a participant was asked to respond to a module. A module addresses a portion of the multi-scale CI matrix. For example, a participant who responded to SD03 (Technology Development in NET) would provide influence judgments on how other descriptors would influence the SD03 descriptor (i.e., SD03 is receiving influence). Additionally, this participant was also asked to provide influence judgments on how the SD03 descriptor would influence other descriptors of the global SSPs (i.e. SD03 is exerting influence). For each question in a module, it corresponds to a cell in the matrix. In Figure 17, cells that capture the responses from one expert are shown with the same colour. After the influence judgments were collected from seven expert participants, their responses were mapped to complete the CI matrix. Values in each matrix cell are the scores that characterize the descriptor in the row direction influencing the descriptor in the column direction. Hence, the completed matrix defines system model specifications (i.e. descriptors and their respective possible states, and judgments about descriptor interrelations). The complete CI matrix was then subjected to CIB analysis.



SSP Matrix

(reconstructed matrix for global SSPs based on Schweizer and O'Neill (2014); cross-impact judgments taken from experts in Panel A)

Area of Expertise

SD03	**Innovation**
SD04	**Energy, Environment**
SD05	**Economic**
SD06	**Transportation, Energy, Innovation**
SD07	**Transportation, Urban, Innovation**
SD08	**Transportation, Urban, Innovation**
SD10	**Economic**

CA Matrix

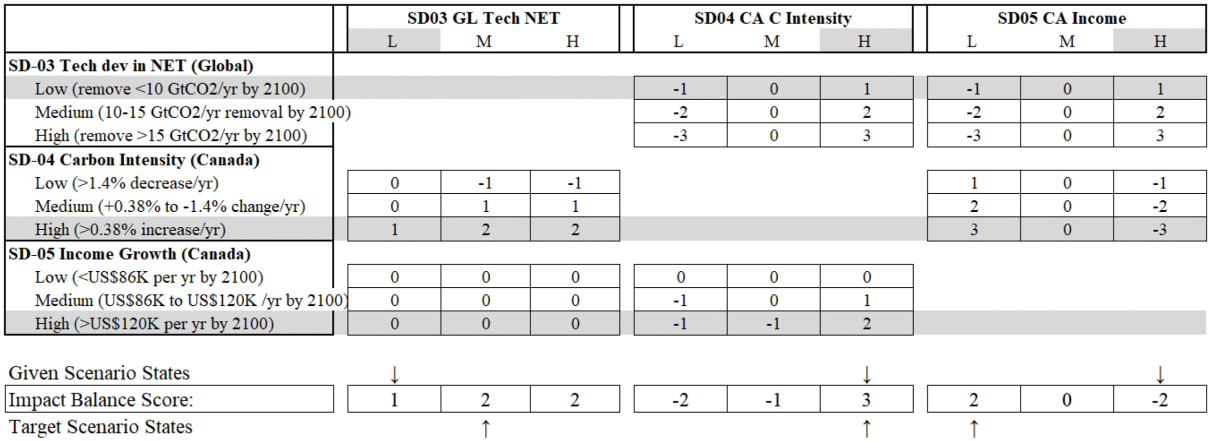
(constructed matrix for Canada is based on collating expert influence judgments, e.g., expert participant for SD03 provided influence judgements for all the orange cells in the matrix)

Figure 17 Mapping expert judgment responses to the multi-scale CI matrix

6.2.5 Applying Cross-Impact Balance Analysis

In CIB analysis, scenarios are depicted as combinations of outcomes or end-states for each descriptor (i.e. scenario element). The CIB analysis was used in this dissertation to evaluate the internal consistency of descriptor-state combinations. The CIB analysis performs a series of calculations to identify which combinations of end-states are internally consistent. Simply put, the calculations use the judgment scores provided by the expert panel and perform mathematical operations to examine all possible descriptor-states combinations that are 'self-reinforcing.' Self-reinforcing descriptor-state combinations are examples of scenarios that are internally consistent, or stable, which means that they describe long-term trends (Weimer-Jehle, 2006). In CIB terms, *consistency* is defined as how particular scenario outcomes would continue to self-reinforce. An example of an internally consistent configuration is the higher income supporting higher education attainment and vice versa. Let us assume that people start to earn higher income; as a result, they also have the desire to attain higher education. In turn, with the higher education, they can potentially earn a better income; and the cycle repeats. This is a self-reinforcing mechanism that makes this particular scenario configuration (high education attainment and high income) more stable and perpetual. However, the configuration comprising of high income and low educational attainment may not be internally consistent because, in theory, low education would discourage high income state. These end-states (i.e. low education attainment and high income) cannot evoke a self-reinforcing mechanism because there is an internal logic problem related to this scenario configuration—this, of course, must be checked by CIB calculation based on the values in the corresponding matrix cells.

To better understand how CIB analysis identifies scenario configurations with internal logic problems, I use a simple example by creating a matrix with three descriptors. This 3x3 matrix is sliced from the multi-scale CI matrix and comprises only three descriptors: SD03 (Technology Development in NET), SD04 (Carbon Intensity), and SD05 (Income Growth). Briefly, technology development in NETs influences both carbon intensity and income growth in Canada. However, only carbon intensity in Canada influences technology development in NETs directly. The intuitive assumption is that high income growth and high carbon intensity are co-supporting (or self-reinforcing). Because of the high carbon intensity in Canada, the technology development in NETs is likely to be low. But does low technology development in NETs also indirectly support high income growth in Canada? In CIB, such a scenario can be tested for internal consistency.



	SD03 GL Tech NET			SD04 CA C Intensity			SD05 CA Income		
	L	M	H	L	M	H	L	M	H
SD-03 Tech dev in NET (Global)									
Low (remove <10 GtCO2/yr by 2100)				-1	0	1	-1	0	1
Medium (10-15 GtCO2/yr removal by 2100)				-2	0	2	-2	0	2
High (remove >15 GtCO2/yr by 2100)				-3	0	3	-3	0	3
SD-04 Carbon Intensity (Canada)									
Low (>1.4% decrease/yr)	0	-1	-1				1	0	-1
Medium (+0.38% to -1.4% change/yr)	0	1	1				2	0	-2
High (>0.38% increase/yr)	1	2	2				3	0	-3
SD-05 Income Growth (Canada)									
Low (<US$86K per yr by 2100)	0	0	0	0	0	0			
Medium (US$86K to US$120K /yr by 2100)	0	0	0	-1	0	1			
High (>US$120K per yr by 2100)	0	0	0	-1	-1	2			
Given Scenario States	↓					↓			↓
Impact Balance Score:	1	2	2	-2	-1	3	2	0	-2
Target Scenario States		↑				↑	↑		

Figure 18 A cross-impact matrix with impact balance calculations

The highlighted rows specify a 'given scenario' being inspected for internal consistency. For the case shown in Figure 18, the scenario configuration being assessed is SD03→L (low), SD04→H (high), and SD05→H (high). These end-states are the highlighted row across. The impact balance score is the sum of the values in the highlighted rows for each column. For example, the impact balance score for SD03→L end-state is 1; this was derived from 1+0. All impact balance scores for each descriptor-states must be calculated like this; then, the CIB can analyse whether the selected scenario configuration (or labeled as 'Given scenario states' in Figure 18) is internally consistent. The internally consistent end-states are indicated by the highest calculated value for each descriptor. For this case, SD03→M (medium) and SD03→H (high) are the two consistent end-states. These consistent states are indicated in Figure 18 as "target scenario states" indicated by the upward arrow. The initial scenario configuration ("given scenario states" indicated with a downward arrow) can be checked for internal consistency by comparing whether the given scenario states and target scenario states are aligned, meaning that the upward and downward arrow are aligned. If the arrows are not aligned, the given scenario (such as the one shown as an example) is inconsistent because it has internal logic problems.

For the full multi-scale CI matrix, the total number of possible combinations is over 2324 million (3^{19} x 2^{1}). However, CIB calculations will identify a small number of scenario configurations that are closely or perfectly internally consistent. By virtue of having a multi-scale matrix (global/national), the internally consistent scenarios identified by CIB calculations mean that these scenarios are also internally consistent across scales.

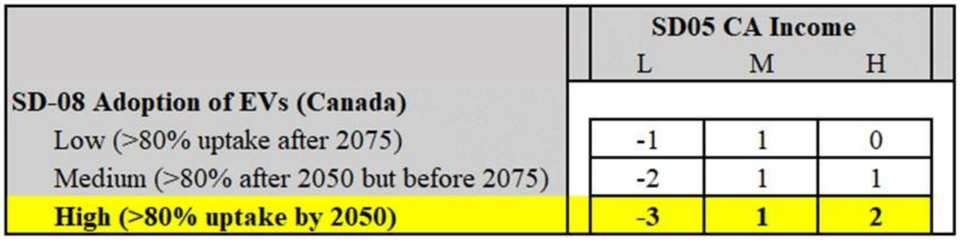
6.2.5.1 Using ScenarioWizard for CIB analysis

When the multi-scale CI matrix is large and intractable, the matrix can potentially be ‘solved’ by partitioning the parent matrix to produce smaller submatrices that can be solved individually, and the ‘mini’ solutions be linked as a complete solution (Schweizer and Kurniawan, 2016). However, linked CIB was not required as the multi-scale CI matrix is tractable, so conventional CIB was deployed. Internally consistent scenarios were searched using the CIB software called ScenarioWizard that was developed by Weimer-Jehle (2018) at the University of Stuttgart. The ‘solver’ algorithm of the software uses a pair-interaction system approach to identify a set of elements (‘descriptors’) whose interactions can adequately describe the system’s behavior.

There are quality checks on input data (cross-impact judgments) that can also be performed: ‘standardization’ and ‘bias statistics,’ which are explained below.

Standardization

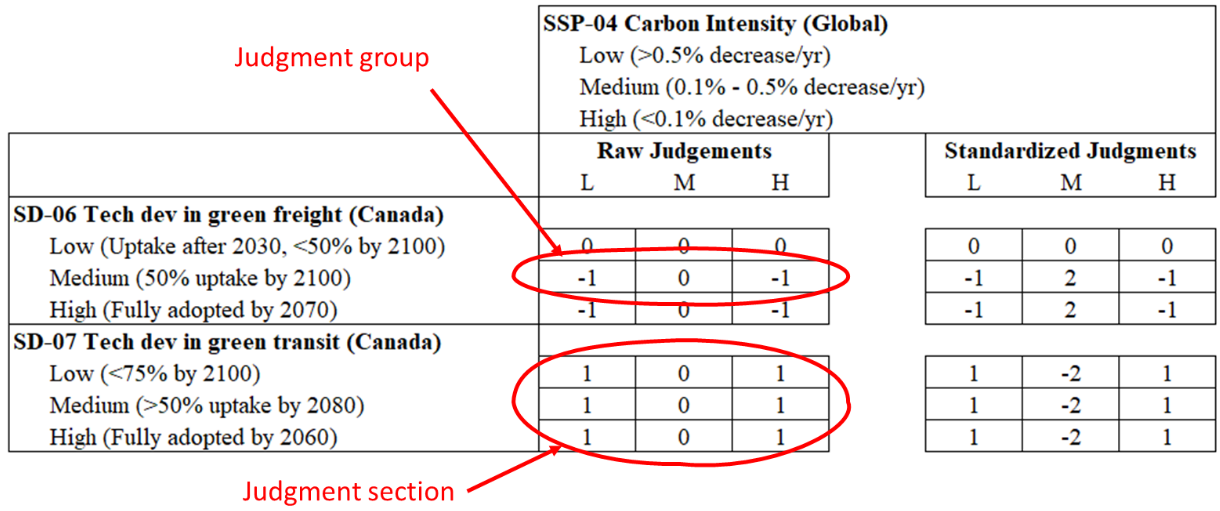
Standardization supports the comprehensibility of the data to suggest that promoting influences towards one end state would discourage the opposite end-states and vice-versa (Weimer-Jehle, 2006, 2009). For example (see Figure 19), SD05 (CA Income) has three different pathways: low, medium, and high (denoted by L, M, H) and can be influenced by the H (high) pathway of SD08 (Adoption of EVs) (the highlighted row). A judgment score of -3 means (the first cell of the highlighted row in Figure 19) that the H (high) pathway of SD08 will very strongly discourage the L (low) pathway of SD05. Because the H (high) pathway of SD08 has already discouraged the L (low) pathway of SD05, the respective opposite pathways of SD05, M (medium) and H (high), will likely be promoted instead by the H (high) pathway of SD08. Simply put, the influences exerted on three possible pathways of SD05 must be compensated. The sum of the judgment scores between two variables across any given row in the CI matrix must be equal to zero (or compensated). ScenarioWizard can check whether judgments of a CI matrix are standardized in this manner.



	SD05 CA Income		
	L	M	H
SD-08 Adoption of EVs (Canada)			
Low (>80% uptake after 2075)	-1	1	0
Medium (>80% after 2050 but before 2075)	-2	1	1
High (>80% uptake by 2050)	**-3**	**1**	**2**

Figure 19 Checking standardization of cross-impact judgments

When the software finds that the standardization is necessary, the software will prompt the user whether to execute the *standardization* feature. In the standardization process, the whole matrix (i.e. all influence judgments in the matrix cells) is multiplied by an integer number. By multiplying with an integer number, the system influence characteristic described by the matrix remains the same (Weimer-Jehle, 2006, 2009). Then, the mean value of each judgment group (e.g. the rows consisting three matrix cells each as shown in Figure 20) will be subtracted to those judgment scores within the group.



	SSP-04 Carbon Intensity (Global) Low (>0.5% decrease/yr) Medium (0.1% - 0.5% decrease/yr) High (<0.1% decrease/yr)					
	Raw Judgements			**Standardized Judgments**		
	L	M	H	L	M	H
SD-06 Tech dev in green freight (Canada)						
Low (Uptake after 2030, <50% by 2100)	0	0	0	0	0	0
Medium (50% uptake by 2100)	-1	0	-1	-1	2	-1
High (Fully adopted by 2070)	-1	0	-1	-1	2	-1
SD-07 Tech dev in green transit (Canada)						
Low (<75% by 2100)	1	0	1	1	-2	1
Medium (>50% uptake by 2080)	1	0	1	1	-2	1
High (Fully adopted by 2060)	1	0	1	1	-2	1

Figure 20 Standardizing the cross-impact matrix

For illustration, take a slice of the CI matrix shown in Figure 20 as an example.

- The judgement group (i.e. the circled row) consist of value (-1, 0, -1)
- The mean value (*M*) for this judgment group is *M* = (-1 + 0 + -1)/3 = -2/3
- Then, subtract the mean value (M) to the original judgment group: (-1, 0, -1) - -2/3 = (-1/3, +2/3, -1/3)
- The multiplier factor (*F*) used by the software is 3 (the denominator of the mean value)
- Hence, standardized judgment is (-1/3, +2/3, -1/3)*3 = (-1, +2, -1)

All influence judgments in the CI matrix were standardized this way by the software. The standardized CI matrix can be found in Appendix E. This standardized matrix was used for CIB analysis to search for internally consistent scenarios.

Bias Statistics

Judgment biases can be identified by ScenarioWizard when certain end-states (e.g., L, M, H) are assigned more frequently than other end-states (Weimer-Jehle, 2006, 2009). The bias statistics computed by the software can be used to check the quality of the judgment scores of the study participants. Assessing bias statistics were performed on the CA matrix only, and not for the SSP matrix as the biases on the SSP matrix would have been resolved by the authors (Schweizer and O'Neill, 2014). The steps for minimizing biases for the CA matrix are documented as follows:

1. Perform a trial CIB analysis for the CA matrix with standardized input data to solve for consistent scenarios. The analysis will also produce bias statistics that can be examined.
2. Check if any bias statistics show close to 100% or 0% for any particular state. Statistics close to 100% mean that an end-state is virtually certain, and statistics close to 0% mean that the end-state is 'forbidden' (Weimer-Jehle, 2018).
3. For any biased judgment scores, revisit the verbal reasons provided by the expert participants.
4. Adjust the scores accordingly when they do not reflect the verbal reasons. This can happen, for example, when participants unintentionally 'flip' the positive and negative sign of the judgment scores in the elicitation instrument (see Appendix C, Part 3).
5. Some 'biases' identified by ScenarioWizard may instead reflect real phenomena with a logical or causal basis, so such judgments will not be modified.
6. After revising the CI judgments, perform another trial to verify that biases are resolved. These steps can be repeated until the bias statistics look satisfactory.

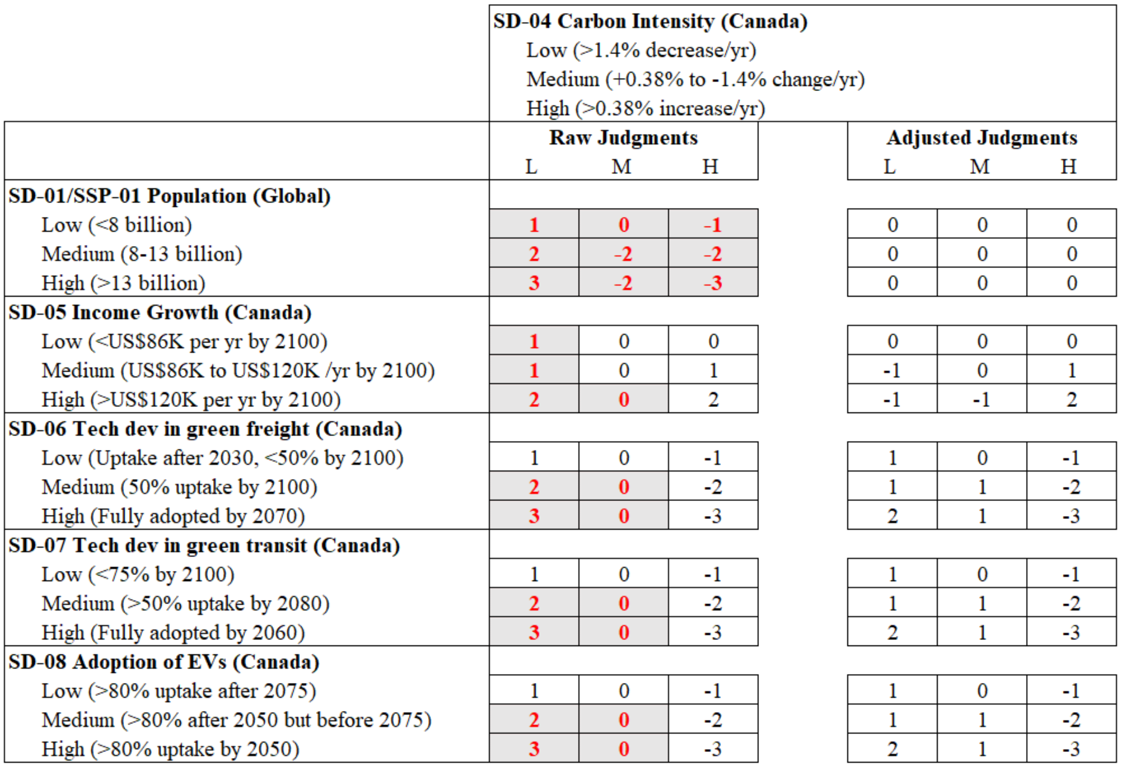
The subsequent paragraphs detail the process of checking data quality for the SD-04 descriptor where the raw judgments were adjusted by cross-referencing experts comments and to minimize biases (please note that the adjustments for other raw judgments are detailed in Appendix C, Part 3. The bias statistics were produced after performing a trial CIB analysis on the CA matrix (see Table 4). Values close to 100% or 0% (shown in red in Table 4) indicate that the respective judgment scores were subjected to closer inspection.

Table 4 Bias statistics based on raw judgment scores

Descriptor		End-states		
SD-03	Tech dev in NET (global)	Low 66.7 %	Med 66.7 %	High 33.3 %
SD-04	Carbon intensity (Canada)	Low 90.7 %	Med 0 %	High 15.8 %
SD-05	Income growth (Canada)	Low 1.2 %	Med 1.0%	High 99.8 %
SD-06	Tech dev in green freight (Canada)	Low 100 %	Med 100 %	High 0 %
SD-07	Tech dev in green transit (Canada)	Low 100 %	Med 33.3 %	High 0 %
SD-08	Adoption of EVs (Canada)	Low 73.5 %	Med 34.6 %	High 3.1 %
SD-10	Economy (Canada)	Coupled 8.2 %	Decoupled 96.3 %	

The Canadian CI matrix documents all influence judgments that were collected from the panel of experts. Also, expert participants provided written comments explaining the reasons for their judgments. The written comments take precedence over the numerical judgments scores. There were situations when expert participants had misrepresented their influence judgments in numerical scores. One common misrepresentation is the flipped positive and negative signs of the numerical scores. Another misrepresentation is when the expert participants were not sure how to input numerical values for descriptor-states that directly or inversely co-vary.

For SD-04 (highlighted row in Table 4), the end-state of Low carbon intensity in Canada occurred more frequently than other end-states (90.7%), whereas the medium level of carbon intensity did not occur with certainty (0%). These percentage values tell us that the judgment scores of the expert participant tend to promote Low state outcomes and discourage Medium outcome. In this case, the corresponding judgments for SD-04 were analysed first and foremost so that the numerical scores corroborate the written comments of the expert.



	SD-04 Carbon Intensity (Canada) Low (>1.4% decrease/yr) Medium (+0.38% to -1.4% change/yr) High (>0.38% increase/yr)					
	Raw Judgments			Adjusted Judgments		
	L	M	H	L	M	H
SD-01/SSP-01 Population (Global)						
Low (<8 billion)	1	0	-1	0	0	0
Medium (8-13 billion)	2	-2	-2	0	0	0
High (>13 billion)	3	-2	-3	0	0	0
SD-05 Income Growth (Canada)						
Low (<US$86K per yr by 2100)	1	0	0	0	0	0
Medium (US$86K to US$120K /yr by 2100)	1	0	1	-1	0	1
High (>US$120K per yr by 2100)	2	0	2	-1	-1	2
SD-06 Tech dev in green freight (Canada)						
Low (Uptake after 2030, <50% by 2100)	1	0	-1	1	0	-1
Medium (50% uptake by 2100)	2	0	-2	1	1	-2
High (Fully adopted by 2070)	3	0	-3	2	1	-3
SD-07 Tech dev in green transit (Canada)						
Low (<75% by 2100)	1	0	-1	1	0	-1
Medium (>50% uptake by 2080)	2	0	-2	1	1	-2
High (Fully adopted by 2060)	3	0	-3	2	1	-3
SD-08 Adoption of EVs (Canada)						
Low (>80% uptake after 2075)	1	0	-1	1	0	-1
Medium (>80% after 2050 but before 2075)	2	0	-2	1	1	-2
High (>80% uptake by 2050)	3	0	-3	2	1	-3

Figure 21 Raw and adjusted judgments for SD-04 (Carbon intensity in Canada)

The raw judgments for how the SSP-01 (global population) descriptor (the row variable) exerting influence on the SD-04 (carbon intensity in Canada) (the column variable) shows that high global population would strongly encourage low carbon intensity in Canada and strongly discourage high carbon intensity in Canada (Figure 21). The reason for this influence judgment provided by the expert respondent is that high global population could put pressure on Canadian government to take action to reduce carbon intensity domestically. This reason suggests that the relationship between global population and carbon intensity in Canada is indirect (with actions from Canadian government as the intermediary variable connecting global population and carbon intensity in Canada). Since the judgments required for CIB analysis constitute to direct influences only, this particular judgement section (i.e. SSP-01 influencing SD-04) was adjusted to reflect 'no influences' (note: zero values in the judgment section represent non-influence or non-interaction).

Next, interactions between the SD-05 (income growth in Canada) (the row variable) exerting influence on SD-04 (carbon intensity in Canada) was assessed. First, expert participant commented that the low pathways of the income growth is a status quo; hence the low pathway was adjusted to reflect status quo with the low pathway of income growth that bears no influence on carbon intensity in Canada. For the medium and high pathways, the expert participant suggested that the influence of high pathways on carbon intensity in Canada could be in two directions. This is also similar for the medium pathway but to a lesser degree. First, people with higher income can be more sustainable and they would adopt more expensive but more efficient energy technologies. That is, of course, based on the assumption that people would presumably be more sustainable in the future ('sustainable'). Alternatively, people can remain in the same situation ('current'), meaning that the higher income would increase carbon intensity. The latter assumption ('current') was used in this research. The judgment scores were adjusted to reflect the 'current' condition. Further adjustments to the judgment scores for how high and medium pathways of income growth exerting influence on the low and medium carbon intensity in Canada were made to reflect expert's comment on the influence of the medium pathway of income growth on carbon intensity in Canada that is less prominent than the high pathway.

For SD-06 (technology development in green freight), SD-07 (tech development in green transit), and SD-08 (adoption of EVs), the expert participant commented that there is a correlation between carbon emissions and various technologies. The judgments were adjusted to add a minimum value for the medium pathways. This adjustment will help to correct the bias for which the outcomes of medium pathways for carbon intensity in Canada was less prominent initially. The adjustments nonetheless maintain the relationships but less optimistic.

Table 5 Bias statistics based on adjusted judgments

Descriptor		End-states		
SD-03	Tech dev in NET (global)	Low 66.7 %	Med 66.7 %	High 33.3 %
SD-04	Carbon intensity (Canada)	Low 49.8 %	Med 41.6 %	High 16.3 %
SD-05	Income growth (Canada)	Low 0 %	Med 59.3%	High 50.0 %
SD-06	Tech dev in green freight (Canada)	Low 44 %	Med 100 %	High 0 %
SD-07	Tech dev in green transit (Canada)	Low 31.7 %	Med 65.0 %	High 24.3 %
SD-08	Adoption of EVs (Canada)	Low 65.4.5 %	Med 43.2 %	High 11.1 %
SD-10	Economy (Canada)	Coupled 19.3 %	Decoupled 84.4 %	

The remaining judgment scores for individual descriptors were checked and adjusted in this manner. After adjustment, the CA matrix is subjected to a trial CIB analysis to produce bias statistics based on the adjusted judgement scores (Table 5). The two areas that are still having issues are the SD-05 (income growth) and SD-06 (tech dev in green freight) descriptor.

For SD-05, the raw judgment scores provided by the expert illustrate that the high, medium, and low pathways are characterized to have a linear relationship with low and high pathways have an opposite effect and medium pathway has no effect. The adjustment to these judgment scores adds minimum values for the medium pathways but maintains the cross-impact relationship. The newly calculated bias statistics (Table 5) does show bias correction for medium pathways. However, the statistics for the low pathway remain close to 0%. Further correction to the low pathway (making the statistic value more than 10%) could potentially change the cross-impact relationships of the SD-05 descriptor; hence, this discrepancy was accepted as is. The expert who provided influence judgment for SD-06 commented that despite having similar technologies, the technology development in green freight transport lags the technology development in green transit. While the support for green transit is instigated by the public, the support for green freight transport should rightfully comes from the private sectors (e.g., transport operators); however, the uptake of the more expensive green freight technologies could be sluggish since transport operators place profit above all, including acquiring and adopting green technologies that can potentially erode their profit margins.

The CI matrix with raw data (i.e. the influence judgments from the panel of experts) is shown in Appendix D. The CI matrix with standardized and bias corrected data used to search for internally consistent scenarios is shown in Appendix E.

6.3 Results of Multi-scale CIB Analysis

After applying bias correction, the completed CI matrix was solved with the traditional CIB analysis. The CIB analysis of the full matrix produces 88 internally consistent scenario configurations (Figure 22). The results were produced by setting the ScenarioWizard to search for ‘strong’ consistency using the ‘complete solver’ (not Monte Carlo) mode. Each scenario configuration consists of all 20 scenario elements: 13 from the global SSPs and 7 from Canada’s energy futures. These scenario configurations can be analysed wholly or in part. For analysis in parts, one can consider the results on the global SSP side or the Canadian side. For the global SSPs, scenario configurations consist of global SSP elements (i.e. SSP01 to SSP13).

For the purpose of analysis, I made two key assumptions. First, whether the world is decarbonized or not depends on the descriptor-state SSP04 (global carbon intensity). ‘Low’ end-state denotes a carbonized world, whereas ‘High’ end-state denotes a decarbonized world. Another assumption for which Canada is decarbonized or not depends on the descriptor-state SD10 (economy) whether the Canadian economy is coupled or decoupled with its fossil fuel sector. These assumptions are:

- Decarbonized world: SSP04 (global carbon intensity) is Low
- Carbonized world: SSP04 (global carbon intensity) is High
- Decarbonized Canada: SD10 (Canada’s economy) is Decoupled from the fossil fuel sector
- Carbonized Canada: SD10 (Canada’s economy) is Coupled with the fossil fuel sector

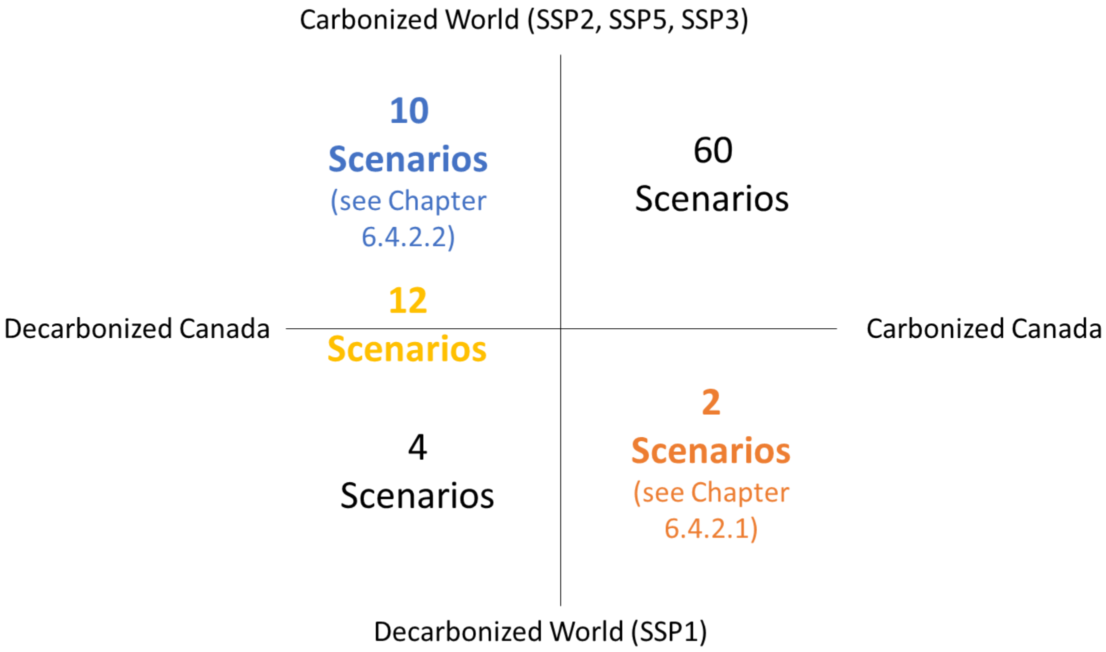
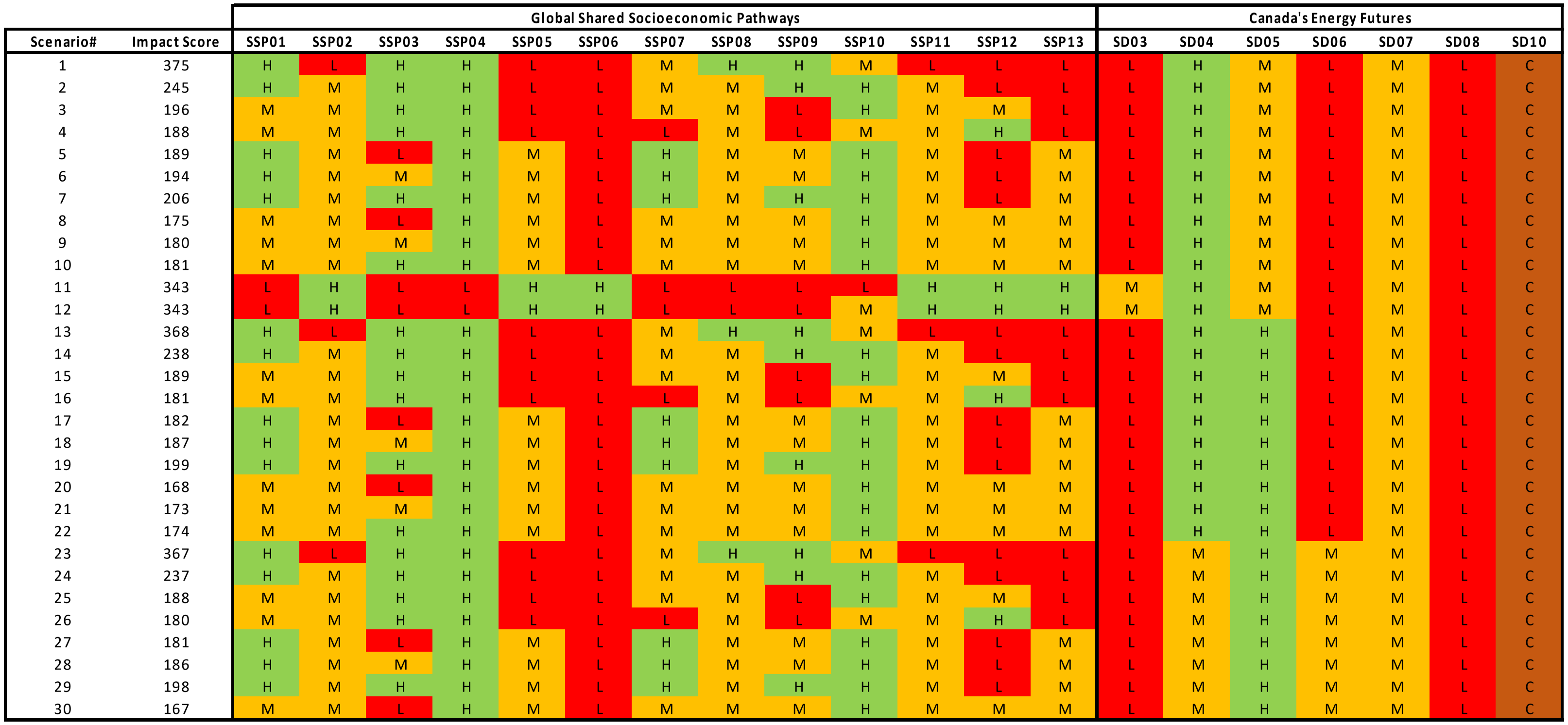


Figure 22 Results of CIB analysis reveal a total of 88 internally consistent scenarios

The consistent scenarios for the global SSPs can be evaluated by truncating the part that belongs to the Canadian side, leaving only the part that belongs to the global SSPs. Of the 88 configurations shown, there are some configurations that would be the same (e.g., such a configuration will likely be consistent with two or more scenario configurations on the Canadian side). For example, scenario# 1, 13, 23 (in Figure 23), 33, 43, 53 (in Figure 24), 65, and 77 (in Figure 25) have the same configuration on the global SSPs side. For those global scenario configurations that are the same, they can be ‘collapsed’ into one. For example, scenario# 1, 13, 23, 33, 43, 53, 65, and 77, have the same global configuration, that is: SSP01→H, SSP02→L, SSP03→H, SSP04→H, SSP05→L, SSP06→L, SSP07→M, SSP08→H, SSP09→H, SSP10→M, SSP11→L, SSP12→L, SSP13→L).



Scenario#	Impact Score	Global Shared Socioeconomic Pathways													Canada's Energy Futures						
		SSP01	SSP02	SSP03	SSP04	SSP05	SSP06	SSP07	SSP08	SSP09	SSP10	SSP11	SSP12	SSP13	SD03	SD04	SD05	SD06	SD07	SD08	SD10
1	375	H	L	H	H	L	L	M	H	H	M	L	L	L	L	H	M	L	M	L	C
2	245	H	M	H	H	L	L	M	M	H	H	M	L	L	L	H	M	L	M	L	C
3	196	M	M	H	H	L	L	M	M	L	H	M	M	L	L	H	M	L	M	L	C
4	188	M	M	H	H	L	L	L	M	L	M	M	H	L	L	H	M	L	M	L	C
5	189	H	M	L	H	M	L	H	M	M	H	M	L	M	L	H	M	L	M	L	C
6	194	H	M	M	H	M	L	H	M	M	H	M	L	M	L	H	M	L	M	L	C
7	206	H	M	H	H	M	L	H	M	H	H	M	L	M	L	H	M	L	M	L	C
8	175	M	M	L	H	M	L	M	M	M	H	M	M	M	L	H	M	L	M	L	C
9	180	M	M	M	H	M	L	M	M	M	H	M	M	M	L	H	M	L	M	L	C
10	181	M	M	H	H	M	L	M	M	M	H	M	M	M	L	H	M	L	M	L	C
11	343	L	H	L	L	H	H	L	L	L	L	H	H	H	M	H	M	L	M	L	C
12	343	L	H	L	L	H	H	L	L	L	M	H	H	H	M	H	M	L	M	L	C
13	368	H	L	H	H	L	L	M	H	H	M	L	L	L	L	H	H	L	M	L	C
14	238	H	M	H	H	L	L	M	M	H	H	M	L	L	L	H	H	L	M	L	C
15	189	M	M	H	H	L	L	M	M	L	H	M	M	L	L	H	H	L	M	L	C
16	181	M	M	H	H	L	L	L	M	L	M	M	H	L	L	H	H	L	M	L	C
17	182	H	M	L	H	M	L	H	M	M	H	M	L	M	L	H	H	L	M	L	C
18	187	H	M	M	H	M	L	H	M	M	H	M	L	M	L	H	H	L	M	L	C
19	199	H	M	H	H	M	L	H	M	H	H	M	L	M	L	H	H	L	M	L	C
20	168	M	M	L	H	M	L	M	M	M	H	M	M	M	L	H	H	L	M	L	C
21	173	M	M	M	H	M	L	M	M	M	H	M	M	M	L	H	H	L	M	L	C
22	174	M	M	H	H	M	L	M	M	M	H	M	M	M	L	H	H	L	M	L	C
23	367	H	L	H	H	L	L	M	H	H	M	L	L	L	L	M	H	M	M	L	C
24	237	H	M	H	H	L	L	M	M	H	H	M	L	L	L	M	H	M	M	L	C
25	188	M	M	H	H	L	L	M	M	L	H	M	M	L	L	M	H	M	M	L	C
26	180	M	M	H	H	L	L	L	M	L	M	M	H	L	L	M	H	M	M	L	C
27	181	H	M	L	H	M	L	H	M	M	H	M	L	M	L	M	H	M	M	L	C
28	186	H	M	M	H	M	L	H	M	M	H	M	L	M	L	M	H	M	M	L	C
29	198	H	M	H	H	M	L	H	M	H	H	M	L	M	L	M	H	M	M	L	C
30	167	M	M	L	H	M	L	M	M	M	H	M	M	M	L	M	H	M	M	L	C

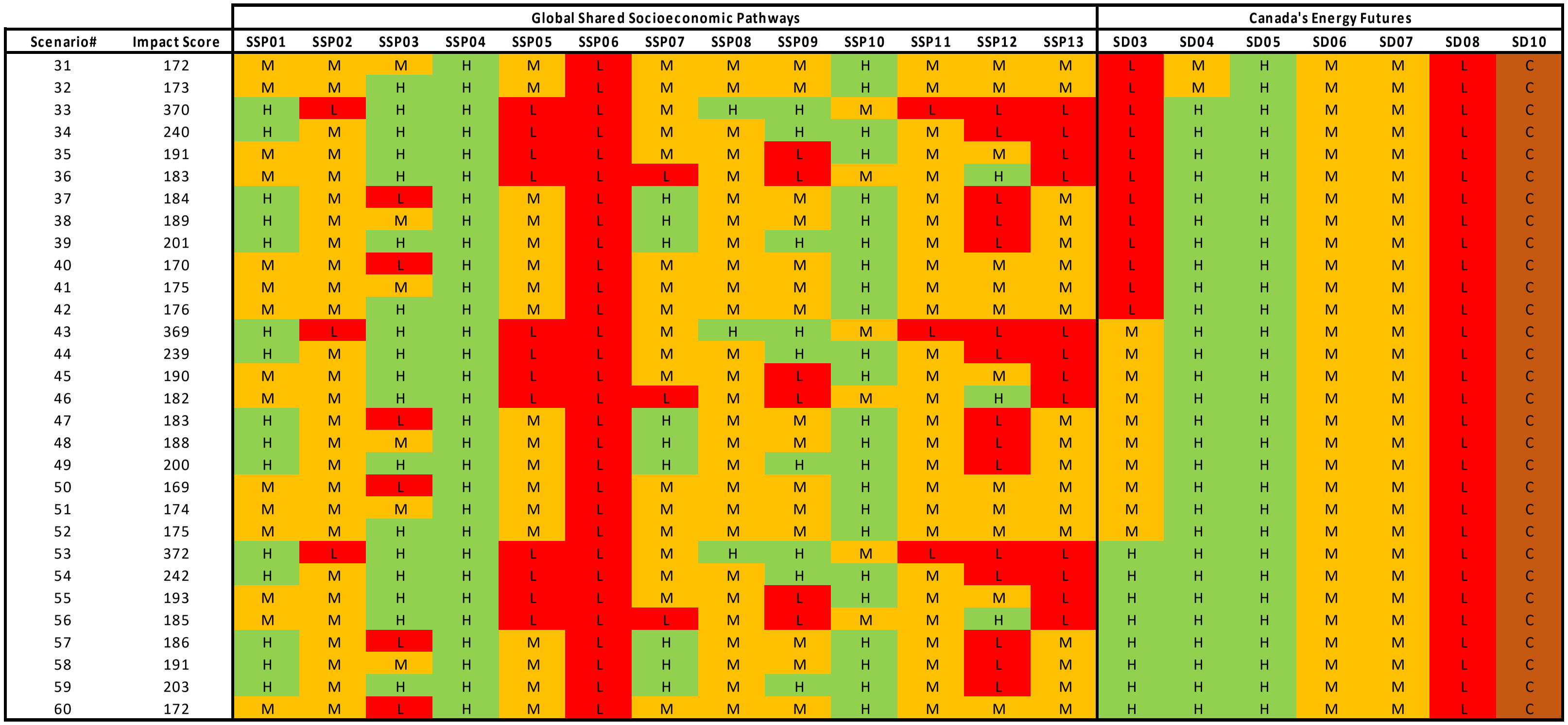
Legend:

H	High Pathway
M	Medium Pathway
L	Low Pathway
C	Coupled with FF
D	Decoupled with FF

Elements:

SSP01 - Population (Global)
SSP02 - Average Income (Global)
SSP03 - Energy Intensity (Global)
SSP04 - Carbon Intensity (Global)
SSP05 - Rate of tech change: Energy (Global)
SSP06 - Agricultural productivity (Global)
SSP07 - Urbanization (Global)
SSP08 - Extreme poverty (Global)
SSP09 - Water scarcity (Global)
SSP10 - Population near coast (Global)
SSP11 - Educational attainment (Global)
SSP12 - Quality of governance (Global)
SSP13 - Innovation capacity (Global)
SD03 - Tech dev in NET (Global)
SD04 - Carbon Intensity (Canada)
SD05 - Income Growth (Canada)
SD06 - Tech dev in green freight (Canada)
SD07 - Tech dev in green transit (Canada)
SD08 - Adoption of EVs (Canada)
SD10 - Decarbonized Economy (Canada)

Figure 23 Results of CIB analysis for the full complete matrix (Part 1 of 3)



		Global Shared Socioeconomic Pathways													Canada's Energy Futures						
Scenario#	Impact Score	SSP01	SSP02	SSP03	SSP04	SSP05	SSP06	SSP07	SSP08	SSP09	SSP10	SSP11	SSP12	SSP13	SD03	SD04	SD05	SD06	SD07	SD08	SD10
31	172	M	M	M	H	M	L	M	M	M	H	M	M	M	L	M	H	M	M	L	C
32	173	M	M	H	H	M	L	M	M	M	H	M	M	M	L	M	H	M	M	L	C
33	370	H	L	H	H	L	L	M	H	H	M	L	L	L	L	H	H	M	M	L	C
34	240	H	M	H	H	L	L	M	M	H	H	M	L	L	L	H	H	M	M	L	C
35	191	M	M	H	H	L	L	M	M	L	H	M	M	L	L	H	H	M	M	L	C
36	183	M	M	H	H	L	L	L	M	L	M	M	H	L	L	H	H	M	M	L	C
37	184	H	M	L	H	M	L	H	M	M	H	M	L	M	L	H	H	M	M	L	C
38	189	H	M	M	H	M	L	H	M	M	H	M	L	M	L	H	H	M	M	L	C
39	201	H	M	H	H	M	L	H	M	H	H	M	L	M	L	H	H	M	M	L	C
40	170	M	M	L	H	M	L	M	M	M	H	M	M	M	L	H	H	M	M	L	C
41	175	M	M	M	H	M	L	M	M	M	H	M	M	M	L	H	H	M	M	L	C
42	176	M	M	H	H	M	L	M	M	M	H	M	M	M	L	H	H	M	M	L	C
43	369	H	L	H	H	L	L	M	H	H	M	L	L	L	M	H	H	M	M	L	C
44	239	H	M	H	H	L	L	M	M	H	H	M	L	L	M	H	H	M	M	L	C
45	190	M	M	H	H	L	L	M	M	L	H	M	M	L	M	H	H	M	M	L	C
46	182	M	M	H	H	L	L	L	M	L	M	M	H	L	M	H	H	M	M	L	C
47	183	H	M	L	H	M	L	H	M	M	H	M	L	M	M	H	H	M	M	L	C
48	188	H	M	M	H	M	L	H	M	M	H	M	L	M	M	H	H	M	M	L	C
49	200	H	M	H	H	M	L	H	M	H	H	M	L	M	M	H	H	M	M	L	C
50	169	M	M	L	H	M	L	M	M	M	H	M	M	M	M	H	H	M	M	L	C
51	174	M	M	M	H	M	L	M	M	M	H	M	M	M	M	H	H	M	M	L	C
52	175	M	M	H	H	M	L	M	M	M	H	M	M	M	M	H	H	M	M	L	C
53	372	H	L	H	H	L	L	M	H	H	M	L	L	L	H	H	H	M	M	L	C
54	242	H	M	H	H	L	L	M	M	H	H	M	L	L	H	H	H	M	M	L	C
55	193	M	M	H	H	L	L	M	M	L	H	M	M	L	H	H	H	M	M	L	C
56	185	M	M	H	H	L	L	L	M	L	M	M	H	L	H	H	H	M	M	L	C
57	186	H	M	L	H	M	L	H	M	M	H	M	L	M	H	H	H	M	M	L	C
58	191	H	M	M	H	M	L	H	M	M	H	M	L	M	H	H	H	M	M	L	C
59	203	H	M	H	H	M	L	H	M	H	H	M	L	M	H	H	H	M	M	L	C
60	172	M	M	L	H	M	L	M	M	M	H	M	M	M	H	H	H	M	M	L	C

Legend:

H	High Pathway
M	Medium Pathway
L	Low Pathway
C	Coupled with FF
D	Decoupled with FF

Elements:

SSP01 - Population (Global)
SSP02 - Average Income (Global)
SSP03 - Energy Intensity (Global)
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SSP07 - Urbanization (Global)
SSP08 - Extreme poverty (Global)
SSP09 - Water scarcity (Global)
SSP10 - Population near coast (Global)
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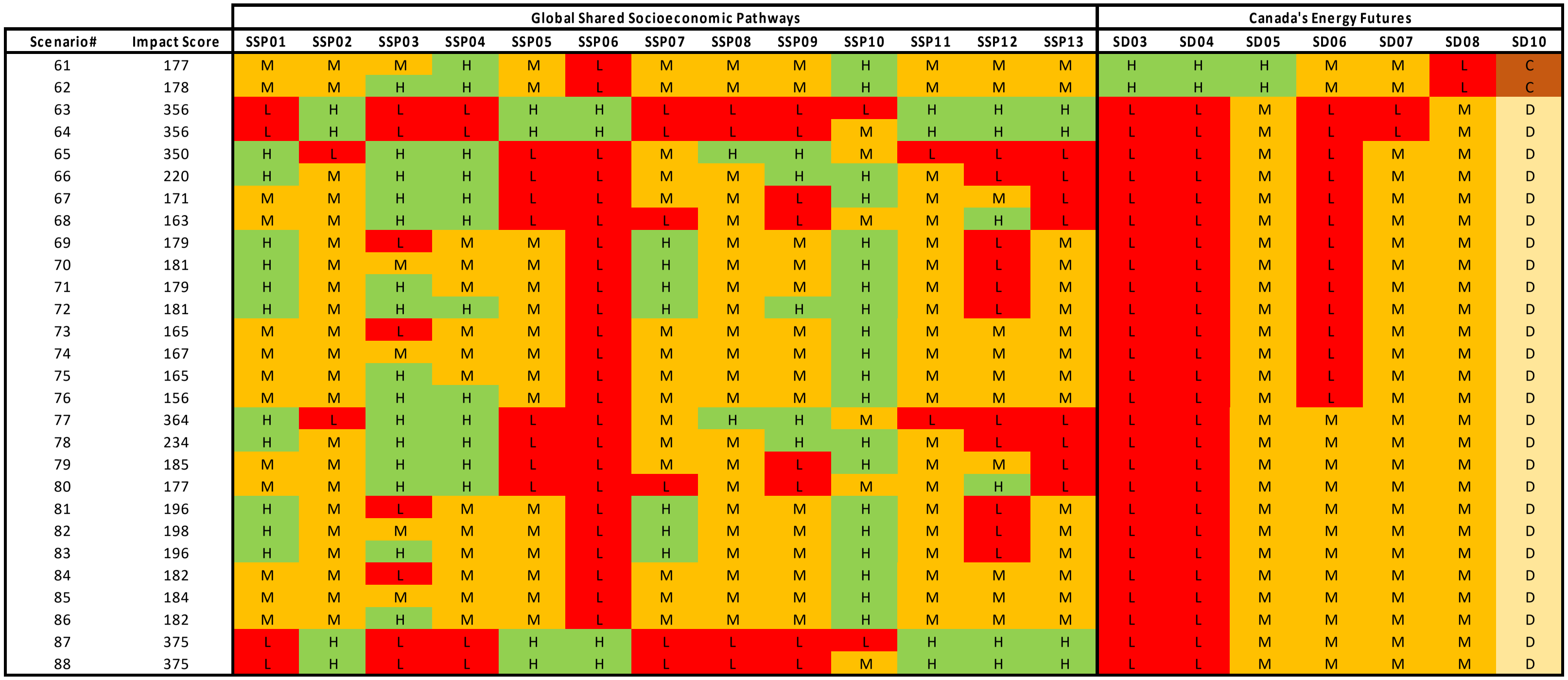
SSP12 - Quality of governance (Global)
SSP13 - Innovation capacity (Global)
SD03 - Tech dev in NET (Global)
SD04 - Carbon Intensity (Canada)
SD05 - Income Growth (Canada)
SD06 - Tech dev in green freight (Canada)
SD07 - Tech dev in green transit (Canada)
SD08 - Adoption of EVs (Canada)
SD10 - Decarbonized Economy (Canada)

Figure 24 Results of CIB analysis for the full complete matrix (Part 2 of 3)



		Global Shared Socioeconomic Pathways													Canada's Energy Futures						
Scenario#	Impact Score	SSP01	SSP02	SSP03	SSP04	SSP05	SSP06	SSP07	SSP08	SSP09	SSP10	SSP11	SSP12	SSP13	SD03	SD04	SD05	SD06	SD07	SD08	SD10
61	177	M	M	M	H	M	L	M	M	M	H	M	M	M	H	H	H	M	M	L	C
62	178	M	M	H	H	M	L	M	M	M	H	M	M	M	H	H	H	M	M	L	C
63	356	L	H	L	L	H	H	L	L	L	L	H	H	H	L	L	M	L	L	M	D
64	356	L	H	L	L	H	H	L	L	L	M	H	H	H	L	L	M	L	L	M	D
65	350	H	L	H	H	L	L	M	H	H	M	L	L	L	L	L	M	L	M	M	D
66	220	H	M	H	H	L	L	M	M	H	H	M	L	L	L	L	M	L	M	M	D
67	171	M	M	H	H	L	L	M	M	L	H	M	M	L	L	L	M	L	M	M	D
68	163	M	M	H	H	L	L	L	M	L	M	M	H	L	L	L	M	L	M	M	D
69	179	H	M	L	M	M	L	H	M	M	H	M	L	M	L	L	M	L	M	M	D
70	181	H	M	M	M	M	L	H	M	M	H	M	L	M	L	L	M	L	M	M	D
71	179	H	M	H	M	M	L	H	M	M	H	M	L	M	L	L	M	L	M	M	D
72	181	H	M	H	H	M	L	H	M	H	H	M	L	M	L	L	M	L	M	M	D
73	165	M	M	L	M	M	L	M	M	M	H	M	M	M	L	L	M	L	M	M	D
74	167	M	M	M	M	M	L	M	M	M	H	M	M	M	L	L	M	L	M	M	D
75	165	M	M	H	M	M	L	M	M	M	H	M	M	M	L	L	M	L	M	M	D
76	156	M	M	H	H	M	L	M	M	M	H	M	M	M	L	L	M	L	M	M	D
77	364	H	L	H	H	L	L	M	H	H	M	L	L	L	L	L	M	M	M	M	D
78	234	H	M	H	H	L	L	M	M	H	H	M	L	L	L	L	M	M	M	M	D
79	185	M	M	H	H	L	L	M	M	L	H	M	M	L	L	L	M	M	M	M	D
80	177	M	M	H	H	L	L	L	M	L	M	M	H	L	L	L	M	M	M	M	D
81	196	H	M	L	M	M	L	H	M	M	H	M	L	M	L	L	M	M	M	M	D
82	198	H	M	M	M	M	L	H	M	M	H	M	L	M	L	L	M	M	M	M	D
83	196	H	M	H	M	M	L	H	M	M	H	M	L	M	L	L	M	M	M	M	D
84	182	M	M	L	M	M	L	M	M	M	H	M	M	M	L	L	M	M	M	M	D
85	184	M	M	M	M	M	L	M	M	M	H	M	M	M	L	L	M	M	M	M	D
86	182	M	M	H	M	M	L	M	M	M	H	M	M	M	L	L	M	M	M	M	D
87	375	L	H	L	L	H	H	L	L	L	L	H	H	H	L	L	M	M	M	M	D
88	375	L	H	L	L	H	H	L	L	L	M	H	H	H	L	L	M	M	M	M	D

Legend:

H	High Pathway
M	Medium Pathway
L	Low Pathway
C	Coupled with FF
D	Decoupled with FF

Elements:

SSP01 - Population (Global)
SSP02 - Average Income (Global)
SSP03 - Energy Intensity (Global)
SSP04 - Carbon Intensity (Global)
SSP05 - Rate of tech change: Energy (Global)
SSP06 - Agricultural productivity (Global)
SSP07 - Urbanization (Global)
SSP08 - Extreme poverty (Global)
SSP09 - Water scarcity (Global)
SSP10 - Population near coast (Global)
SSP11 - Educational attainment (Global)
SSP12 - Quality of governance (Global)
SSP13 - Innovation capacity (Global)
SD03 - Tech dev in NET (Global)
SD04 - Carbon Intensity (Canada)
SD05 - Income Growth (Canada)
SD06 - Tech dev in green freight (Canada)
SD07 - Tech dev in green transit (Canada)
SD08 - Adoption of EVs (Canada)
SD10 - Decarbonized Economy (Canada)

Figure 25 Results of CIB analysis for the full complete matrix (Part 3 of 3)

6.3.1 Consistent Scenarios for Global SSPs

For the global SSPs side, the CIB analysis identifies 18 internally consistent scenarios (Figure 26, 27 & 28). Each internally consistent scenario (labelled GL#) comprises an end-state of the thirteen scenario elements (descriptors SSP01 to SSP13). For example, the scenario configuration for scenario GL01 suggests a 'world' with high development pathways for population (SSP01→H), energy intensity (SSP03→H), carbon intensity (SSP04→H), extreme poverty (SSP08→H), and water scarcity (SSP09→H); and medium development pathways for urbanization (SSP07→M) and coastal population (SSP10→M); but with low development pathways for income (SSP02→L), technological change (SSP05→L), agricultural productivity (SSP06→L), education (SSP11→L), governance (SSP12→L), and innovation capacity (SSP13→L). Examining a group of scenarios as a set can also be useful, for example, the results suggest that the low pathways of global population (SSP01→L), carbon intensity (SSP04→L) and extreme poverty (SSP08→L) are internally consistent with a high pathway of global average income (SSP02→H), a rapid rate of technological change (SSP05→H), a higher increase in agricultural productivity (SSP06→H), educational attainment (SSP11→H) and innovation capacity (SSP13→H)—these conditions fit GL09 and GL10 scenarios. GL09 and GL10 scenario configurations have the same outcome for all of the elements but one, coastal population (SSP10). This means that, by disregarding SSP10, GL09 and GL10 would have the same configuration.

One should note that the situation described herein does not imply causation. Instead, it simply states that should an end-state of an element occur, e.g., a decarbonized world where SSP04→L, it would likely be accompanied by the low pathways of population, extreme poverty, energy intensity and the high pathways of average income, rate of technological change, agricultural productivity, education attainment, and innovation capacity. Subsequently, Chapter 6.3.2 will analyse the consistent scenario configurations for Canada. Chapter 6.3.3 will describe how scenario configurations from the global SSPs and the Canadian side are linked to produce pair-wise combinations that make up the 88 internally consistent scenarios.

			Global Shared Socioeconomic Pathways												
GL-scenario#	Scenario#	Impact Score	SSP01	SSP02	SSP03	SSP04	SSP05	SSP06	SSP07	SSP08	SSP09	SSP10	SSP11	SSP12	SSP13
GL01	1	375	H	L	H	H	L	L	M	H	H	M	L	L	L
	13	368	H	L	H	H	L	L	M	H	H	M	L	L	L
	23	367	H	L	H	H	L	L	M	H	H	M	L	L	L
	33	370	H	L	H	H	L	L	M	H	H	M	L	L	L
	43	369	H	L	H	H	L	L	M	H	H	M	L	L	L
	53	372	H	L	H	H	L	L	M	H	H	M	L	L	L
	65	350	H	L	H	H	L	L	M	H	H	M	L	L	L
	77	364	H	L	H	H	L	L	M	H	H	M	L	L	L
GL02	2	245	H	M	H	H	L	L	M	M	H	H	M	L	L
	14	238	H	M	H	H	L	L	M	M	H	H	M	L	L
	24	237	H	M	H	H	L	L	M	M	H	H	M	L	L
	34	240	H	M	H	H	L	L	M	M	H	H	M	L	L
	44	239	H	M	H	H	L	L	M	M	H	H	M	L	L
	54	242	H	M	H	H	L	L	M	M	H	H	M	L	L
	66	220	H	M	H	H	L	L	M	M	H	H	M	L	L
	78	234	H	M	H	H	L	L	M	M	H	H	M	L	L
GL03	7	206	H	M	H	H	M	L	H	M	H	H	M	L	M
	19	199	H	M	H	H	M	L	H	M	H	H	M	L	M
	29	198	H	M	H	H	M	L	H	M	H	H	M	L	M
	39	201	H	M	H	H	M	L	H	M	H	H	M	L	M
	49	200	H	M	H	H	M	L	H	M	H	H	M	L	M
	59	203	H	M	H	H	M	L	H	M	H	H	M	L	M
	72	181	H	M	H	H	M	L	H	M	H	H	M	L	M
GL04	71	179	H	M	H	M	M	L	H	M	M	H	M	L	M
	83	196	H	M	H	M	M	L	H	M	M	H	M	L	M
GL05	5	189	H	M	L	H	M	L	H	M	M	H	M	L	M
	17	182	H	M	L	H	M	L	H	M	M	H	M	L	M
	27	181	H	M	L	H	M	L	H	M	M	H	M	L	M
	37	184	H	M	L	H	M	L	H	M	M	H	M	L	M
	47	183	H	M	L	H	M	L	H	M	M	H	M	L	M
	57	186	H	M	L	H	M	L	H	M	M	H	M	L	M

Legend:

H	High Pathway
M	Medium Pathway
L	Low Pathway

Elements:

SSP01 - Population (Global)
SSP02 - Average Income (Global)
SSP03 - Energy Intensity (Global)
SSP04 - Carbon Intensity (Global)
SSP05 - Rate of tech change: Energy (Global)
SSP06 - Agricultural productivity (Global)
SSP07 - Urbanization (Global)
SSP08 - Extreme poverty (Global)
SSP09 - Water scarcity (Global)
SSP10 - Population near coast (Global)
SSP11 - Educational attainment (Global)
SSP12 - Quality of governance (Global)
SSP13 - Innovation capacity (Global)

Figure 26 Results of CIB analysis for the global SSP side (part 1 of 3)

GL-scenario#	Scenario#	Impact Score	Global Shared Socioeconomic Pathways												
			SSP01	SSP02	SSP03	SSP04	SSP05	SSP06	SSP07	SSP08	SSP09	SSP10	SSP11	SSP12	SSP13
GL06	69	179	H	M	L	M	M	L	H	M	M	H	M	L	M
	81	196	H	M	L	M	M	L	H	M	M	H	M	L	M
GL07	6	194	H	M	M	H	M	L	H	M	M	H	M	L	M
	18	187	H	M	M	H	M	L	H	M	M	H	M	L	M
	28	186	H	M	M	H	M	L	H	M	M	H	M	L	M
	38	189	H	M	M	H	M	L	H	M	M	H	M	L	M
	48	188	H	M	M	H	M	L	H	M	M	H	M	L	M
	58	191	H	M	M	H	M	L	H	M	M	H	M	L	M
GL08	70	181	H	M	M	M	M	L	H	M	M	H	M	L	M
	82	198	H	M	M	M	M	L	H	M	M	H	M	L	M
GL09	11	343	L	H	L	L	H	H	L	L	L	L	H	H	H
	63	356	L	H	L	L	H	H	L	L	L	L	H	H	H
	87	375	L	H	L	L	H	H	L	L	L	L	H	H	H
GL10	12	343	L	H	L	L	H	H	L	L	L	M	H	H	H
	64	356	L	H	L	L	H	H	L	L	L	M	H	H	H
	88	375	L	H	L	L	H	H	L	L	L	M	H	H	H
GL11	4	188	M	M	H	H	L	L	L	M	L	M	M	H	L
	16	181	M	M	H	H	L	L	L	M	L	M	M	H	L
	26	180	M	M	H	H	L	L	L	M	L	M	M	H	L
	36	183	M	M	H	H	L	L	L	M	L	M	M	H	L
	46	182	M	M	H	H	L	L	L	M	L	M	M	H	L
	56	185	M	M	H	H	L	L	L	M	L	M	M	H	L
	68	163	M	M	H	H	L	L	L	M	L	M	M	H	L
	80	177	M	M	H	H	L	L	L	M	L	M	M	H	L
GL12	3	196	M	M	H	H	L	L	M	M	L	H	M	M	L
	15	189	M	M	H	H	L	L	M	M	L	H	M	M	L
	25	188	M	M	H	H	L	L	M	M	L	H	M	M	L
	35	191	M	M	H	H	L	L	M	M	L	H	M	M	L
	45	190	M	M	H	H	L	L	M	M	L	H	M	M	L
	55	193	M	M	H	H	L	L	M	M	L	H	M	M	L
	67	171	M	M	H	H	L	L	M	M	L	H	M	M	L
	79	185	M	M	H	H	L	L	M	M	L	H	M	M	L

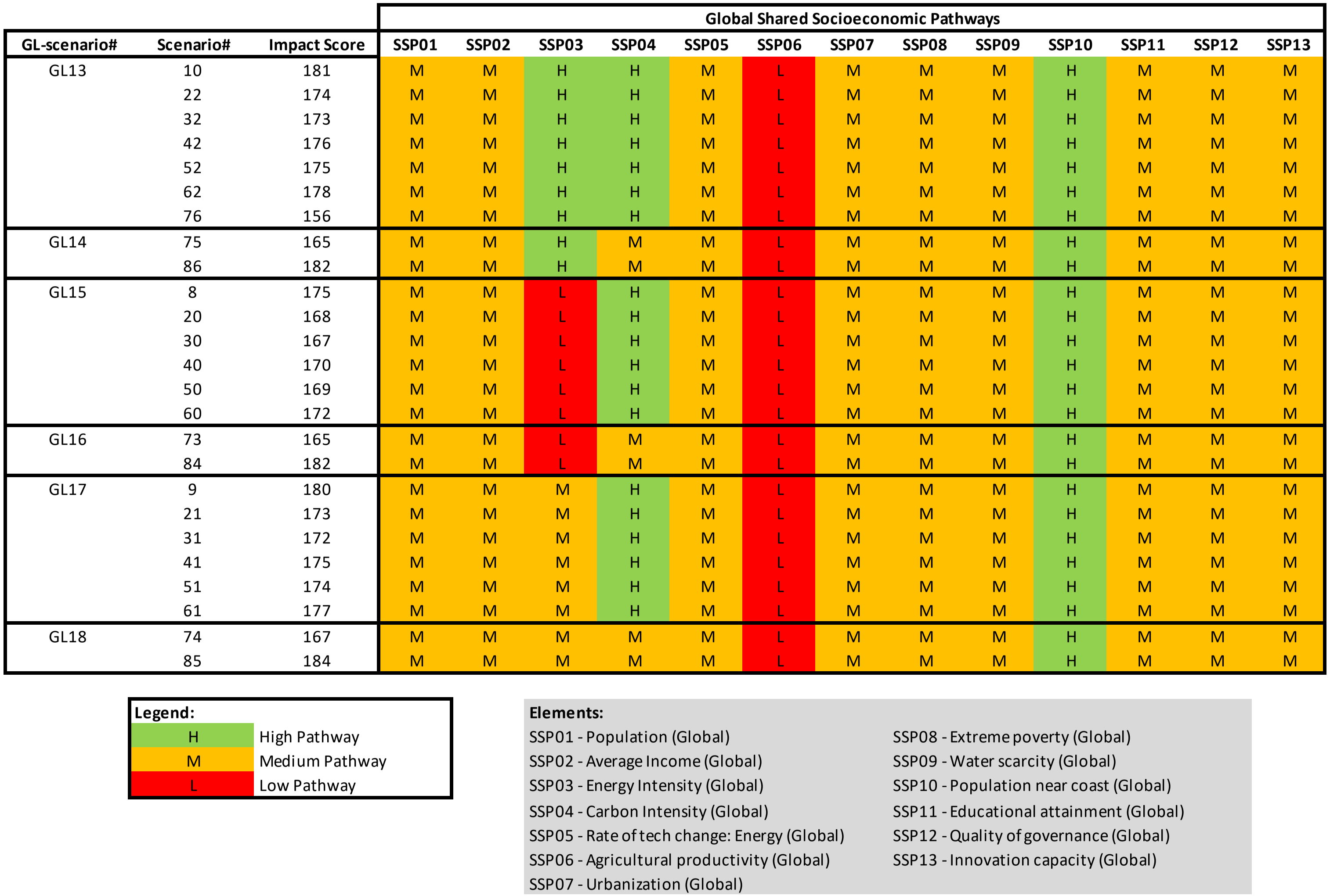
Legend:

H	High Pathway
M	Medium Pathway
L	Low Pathway

Elements:

SSP01 - Population (Global)
SSP02 - Average Income (Global)
SSP03 - Energy Intensity (Global)
SSP04 - Carbon Intensity (Global)
SSP05 - Rate of tech change: Energy (Global)
SSP06 - Agricultural productivity (Global)
SSP07 - Urbanization (Global)
SSP08 - Extreme poverty (Global)
SSP09 - Water scarcity (Global)
SSP10 - Population near coast (Global)
SSP11 - Educational attainment (Global)
SSP12 - Quality of governance (Global)
SSP13 - Innovation capacity (Global)

Figure 27 Results of CIB analysis for the global SSP side (part 2 of 3)



			Global Shared Socioeconomic Pathways												
GL-scenario#	Scenario#	Impact Score	SSP01	SSP02	SSP03	SSP04	SSP05	SSP06	SSP07	SSP08	SSP09	SSP10	SSP11	SSP12	SSP13
GL13	10	181	M	M	H	H	M	L	M	M	M	H	M	M	M
	22	174	M	M	H	H	M	L	M	M	M	H	M	M	M
	32	173	M	M	H	H	M	L	M	M	M	H	M	M	M
	42	176	M	M	H	H	M	L	M	M	M	H	M	M	M
	52	175	M	M	H	H	M	L	M	M	M	H	M	M	M
	62	178	M	M	H	H	M	L	M	M	M	H	M	M	M
	76	156	M	M	H	H	M	L	M	M	M	H	M	M	M
GL14	75	165	M	M	H	M	M	L	M	M	M	H	M	M	M
	86	182	M	M	H	M	M	L	M	M	M	H	M	M	M
GL15	8	175	M	M	L	H	M	L	M	M	M	H	M	M	M
	20	168	M	M	L	H	M	L	M	M	M	H	M	M	M
	30	167	M	M	L	H	M	L	M	M	M	H	M	M	M
	40	170	M	M	L	H	M	L	M	M	M	H	M	M	M
	50	169	M	M	L	H	M	L	M	M	M	H	M	M	M
	60	172	M	M	L	H	M	L	M	M	M	H	M	M	M
GL16	73	165	M	M	L	M	M	L	M	M	M	H	M	M	M
	84	182	M	M	L	M	M	L	M	M	M	H	M	M	M
GL17	9	180	M	M	M	H	M	L	M	M	M	H	M	M	M
	21	173	M	M	M	H	M	L	M	M	M	H	M	M	M
	31	172	M	M	M	H	M	L	M	M	M	H	M	M	M
	41	175	M	M	M	H	M	L	M	M	M	H	M	M	M
	51	174	M	M	M	H	M	L	M	M	M	H	M	M	M
	61	177	M	M	M	H	M	L	M	M	M	H	M	M	M
GL18	74	167	M	M	M	M	M	L	M	M	M	H	M	M	M
	85	184	M	M	M	M	M	L	M	M	M	H	M	M	M

Legend:

H	High Pathway
M	Medium Pathway
L	Low Pathway

Elements:

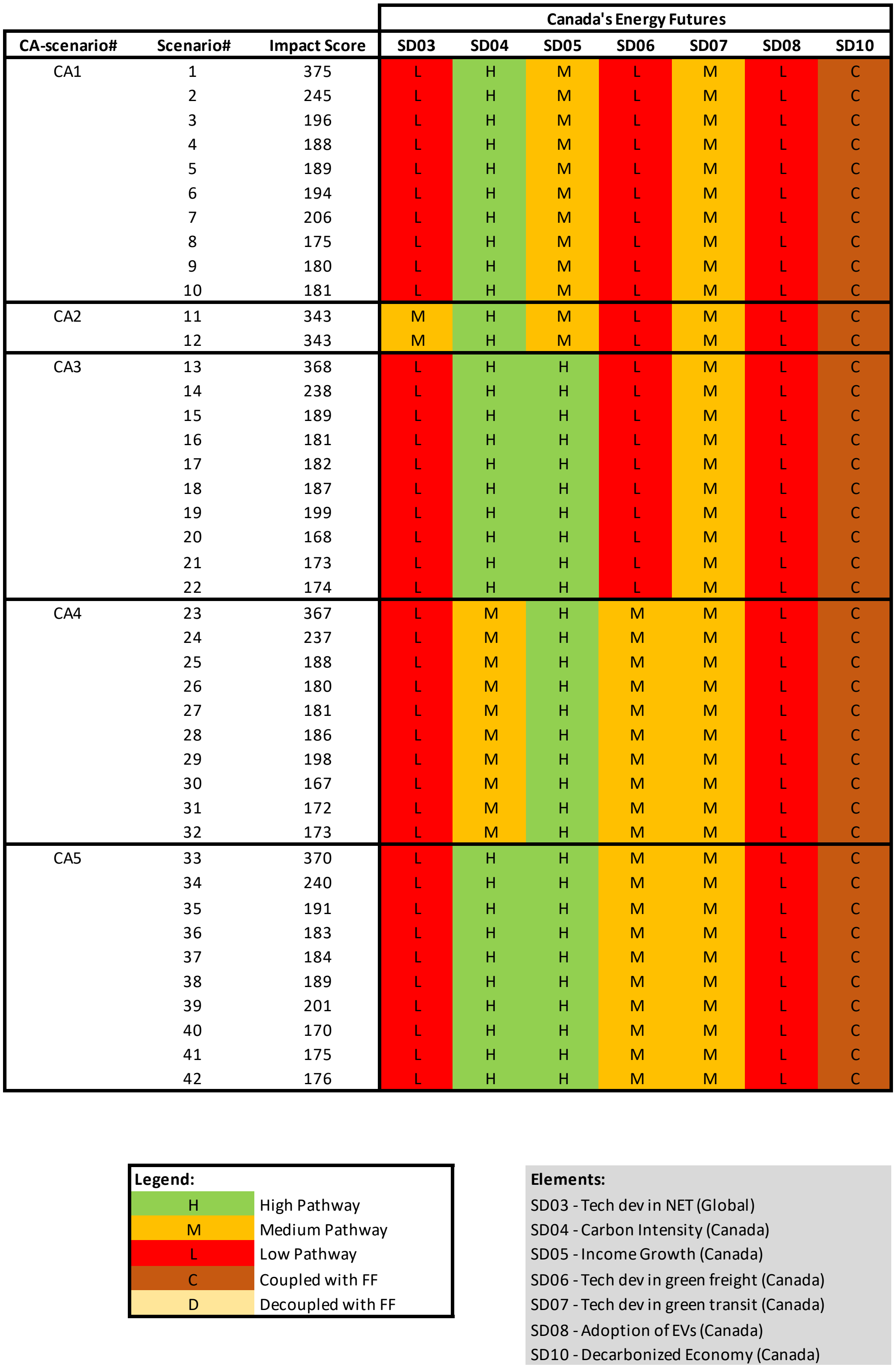
SSP01 - Population (Global)
SSP02 - Average Income (Global)
SSP03 - Energy Intensity (Global)
SSP04 - Carbon Intensity (Global)
SSP05 - Rate of tech change: Energy (Global)
SSP06 - Agricultural productivity (Global)
SSP07 - Urbanization (Global)
SSP08 - Extreme poverty (Global)
SSP09 - Water scarcity (Global)
SSP10 - Population near coast (Global)
SSP11 - Educational attainment (Global)
SSP12 - Quality of governance (Global)
SSP13 - Innovation capacity (Global)

Figure 28 Results of CIB analysis for the global SSP side (part 3 of 3)

6.3.2 Consistent Scenarios for Canada’s Energy Futures

To identify consistent scenario configurations at the Canadian scale, one can visualize only the configurations under Canada’s side as shown in Figure 29 & 30. As previously mentioned, scenario configurations that have the same end-states are ‘collapsed’ as one. There are ten consistent scenarios for the Canadian side. Three scenarios (i.e. scenario CA8, CA9, and CA10) are consistent with Canada’s economy being dependent on the national income of fossil fuel extraction and production (SD10→C). This state (i.e., SD10→C) also corresponds to the state of national carbon intensity being high (SD04→H). Another three scenarios (CA4, CA5 and CA6) present plausible futures in which Canada’s economy is decarbonized (SD10→D). A decarbonized economy (i.e., SD10→D) is consistent with the national carbon intensity being low (SD04→L) and the rate of adoption of EVs being moderate (SD08→M).

An interesting point to note is that technology development in green freight transport is at low or medium development pathways (SD06→L or SD06→M) for all scenario configurations. This finding reflects expert’s comment who stated that the uptake of green technologies in Canada’s freight transport is primarily driven by the cost of technologies and the profit margins of the transport operators. As freight transport is driven by the private sector, there is little public or social pressure on transport operators to act in greening freight unless for commercial reasons. In this respect, technological change in freight transport tends to lag when it comes to adopting green technologies, making the higher development pathway therefore unlikely. Recall that the development pathways for technological development of green freight transport was time bound—for example, full technology adoption (80%) in Canada realized as early as 2070 reflects the higher development pathway. Because of the lag, the development of green freight technologies (SD06) will be equal to or lower than the development of green transit technologies (SD07). In essence, the CIB analysis can integrate interdisciplinary expert judgments and evaluate how similar (or dissimilar) their judgments are in affecting the overall system behaviour. The judgments of the expert participants were elicited anonymously, meaning that judgments were offered by an expert participant who had no access to the judgments of other experts.



CA-scenario#	Scenario#	Impact Score	Canada's Energy Futures						
			SD03	SD04	SD05	SD06	SD07	SD08	SD10
CA1	1	375	L	H	M	L	M	L	C
	2	245	L	H	M	L	M	L	C
	3	196	L	H	M	L	M	L	C
	4	188	L	H	M	L	M	L	C
	5	189	L	H	M	L	M	L	C
	6	194	L	H	M	L	M	L	C
	7	206	L	H	M	L	M	L	C
	8	175	L	H	M	L	M	L	C
	9	180	L	H	M	L	M	L	C
	10	181	L	H	M	L	M	L	C
CA2	11	343	M	H	M	L	M	L	C
	12	343	M	H	M	L	M	L	C
CA3	13	368	L	H	H	L	M	L	C
	14	238	L	H	H	L	M	L	C
	15	189	L	H	H	L	M	L	C
	16	181	L	H	H	L	M	L	C
	17	182	L	H	H	L	M	L	C
	18	187	L	H	H	L	M	L	C
	19	199	L	H	H	L	M	L	C
	20	168	L	H	H	L	M	L	C
	21	173	L	H	H	L	M	L	C
	22	174	L	H	H	L	M	L	C
CA4	23	367	L	M	H	M	M	L	C
	24	237	L	M	H	M	M	L	C
	25	188	L	M	H	M	M	L	C
	26	180	L	M	H	M	M	L	C
	27	181	L	M	H	M	M	L	C
	28	186	L	M	H	M	M	L	C
	29	198	L	M	H	M	M	L	C
	30	167	L	M	H	M	M	L	C
	31	172	L	M	H	M	M	L	C
	32	173	L	M	H	M	M	L	C
CA5	33	370	L	H	H	M	M	L	C
	34	240	L	H	H	M	M	L	C
	35	191	L	H	H	M	M	L	C
	36	183	L	H	H	M	M	L	C
	37	184	L	H	H	M	M	L	C
	38	189	L	H	H	M	M	L	C
	39	201	L	H	H	M	M	L	C
	40	170	L	H	H	M	M	L	C
	41	175	L	H	H	M	M	L	C
	42	176	L	H	H	M	M	L	C

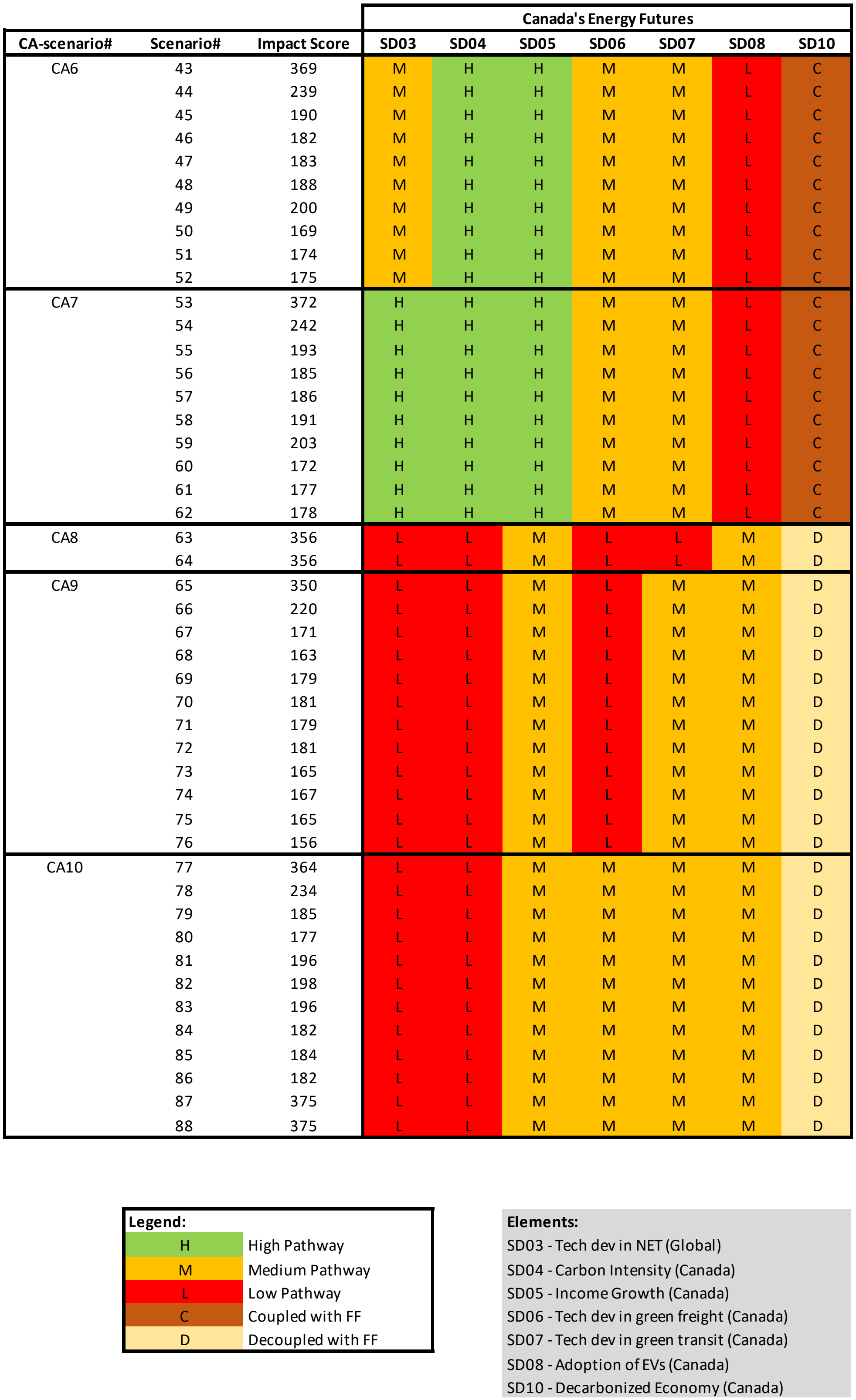
Legend:

H	High Pathway
M	Medium Pathway
L	Low Pathway
C	Coupled with FF
D	Decoupled with FF

Elements:

SD03 - Tech dev in NET (Global)
SD04 - Carbon Intensity (Canada)
SD05 - Income Growth (Canada)
SD06 - Tech dev in green freight (Canada)
SD07 - Tech dev in green transit (Canada)
SD08 - Adoption of EVs (Canada)
SD10 - Decarbonized Economy (Canada)

Figure 29 Results of CIB analysis for CA matrix (part 1 of 2)



CA-scenario#	Scenario#	Impact Score	Canada's Energy Futures						
			SD03	SD04	SD05	SD06	SD07	SD08	SD10
CA6	43	369	M	H	H	M	M	L	C
	44	239	M	H	H	M	M	L	C
	45	190	M	H	H	M	M	L	C
	46	182	M	H	H	M	M	L	C
	47	183	M	H	H	M	M	L	C
	48	188	M	H	H	M	M	L	C
	49	200	M	H	H	M	M	L	C
	50	169	M	H	H	M	M	L	C
	51	174	M	H	H	M	M	L	C
	52	175	M	H	H	M	M	L	C
CA7	53	372	H	H	H	M	M	L	C
	54	242	H	H	H	M	M	L	C
	55	193	H	H	H	M	M	L	C
	56	185	H	H	H	M	M	L	C
	57	186	H	H	H	M	M	L	C
	58	191	H	H	H	M	M	L	C
	59	203	H	H	H	M	M	L	C
	60	172	H	H	H	M	M	L	C
	61	177	H	H	H	M	M	L	C
	62	178	H	H	H	M	M	L	C
CA8	63	356	L	L	M	L	L	M	D
	64	356	L	L	M	L	L	M	D
CA9	65	350	L	L	M	L	M	M	D
	66	220	L	L	M	L	M	M	D
	67	171	L	L	M	L	M	M	D
	68	163	L	L	M	L	M	M	D
	69	179	L	L	M	L	M	M	D
	70	181	L	L	M	L	M	M	D
	71	179	L	L	M	L	M	M	D
	72	181	L	L	M	L	M	M	D
	73	165	L	L	M	L	M	M	D
	74	167	L	L	M	L	M	M	D
	75	165	L	L	M	L	M	M	D
	76	156	L	L	M	L	M	M	D
CA10	77	364	L	L	M	M	M	M	D
	78	234	L	L	M	M	M	M	D
	79	185	L	L	M	M	M	M	D
	80	177	L	L	M	M	M	M	D
	81	196	L	L	M	M	M	M	D
	82	198	L	L	M	M	M	M	D
	83	196	L	L	M	M	M	M	D
	84	182	L	L	M	M	M	M	D
	85	184	L	L	M	M	M	M	D
	86	182	L	L	M	M	M	M	D
	87	375	L	L	M	M	M	M	D
	88	375	L	L	M	M	M	M	D

Legend:

H	High Pathway
M	Medium Pathway
L	Low Pathway
C	Coupled with FF
D	Decoupled with FF

Elements:

SD03 - Tech dev in NET (Global)
SD04 - Carbon Intensity (Canada)
SD05 - Income Growth (Canada)
SD06 - Tech dev in green freight (Canada)
SD07 - Tech dev in green transit (Canada)
SD08 - Adoption of EVs (Canada)
SD10 - Decarbonized Economy (Canada)

Figure 30 Results of CIB analysis for CA matrix (part 2 of 2)

However, having global technology development in NETs being moderate or high (SD03→M or SD03→H) is consistent with the rate of adoption of EVs being low (SD08→L) and Canada's economy being dependent on fossil-fuel income (SD10→C). This finding also resonates with some expert responses. For instance, experts indicated that the rapid adoption of NETs may put less pressure on Canada to decarbonize the economy and transportation systems. In another case, an expert participant also suggested that the rapid adoption of NETs could also potentially reduce the impacts of climate change, provisioning cheaper options for implementing climate change adaptation measures. Cheaper options of adaptation will result in cost-savings and better income (i.e. less spending means higher disposable income). When cross-impact judgments of these experts were analyzed holistically using CIB analysis, it suggests that higher income growth (SD05→H) is consistent with a fossil-fueled economy (SD10→C). Further, high income growth (SD05→H) can also prevail with low development in NETS (SD03→L) under scenarios CA3, CA4, and CA5. The results from this CIB analysis suggest that the socio-economic implications of NETs are crucial to Canada's effort to be decarbonized, prompting the need for further investigation in future research. Moreover, research examining potentially contradicting social impacts due to NETs is still lacking. As Minx et al. (2018) rightly put it, there is a need *"... to explore the broader ethical implications of NETs in the context of global justice and* ***sustainable development****"* (pp.23) [emphasis added]. As expert participants have commented, development of NETs could potentially motivate the persistence of fossil fuel production, meaning that fossil-rich countries may reap benefits from the deployment of NETs.

6.3.3 Consistent Scenarios Across Scales

The consistent cross-scale scenario configurations are the combined configurations derived from the global SSP side and the Canadian side. That means a consistent scenario across scales consists of a pair-wise combination of SSP scenarios and CA scenarios (Figure 31). For instance, GL01-CA1 means that SSP scenario configuration GL01 and CA scenario configuration CA4 are consistent when they are paired. A scenario configuration (take CA1 for example) can be found consistent with several global scenario configurations (meaning CA1 is consistent with SSP scenario configuration GL01, GL02, GL03, GL05, GL07, GL11, GL12, GL13, GL15, and GL17; Figure 31).

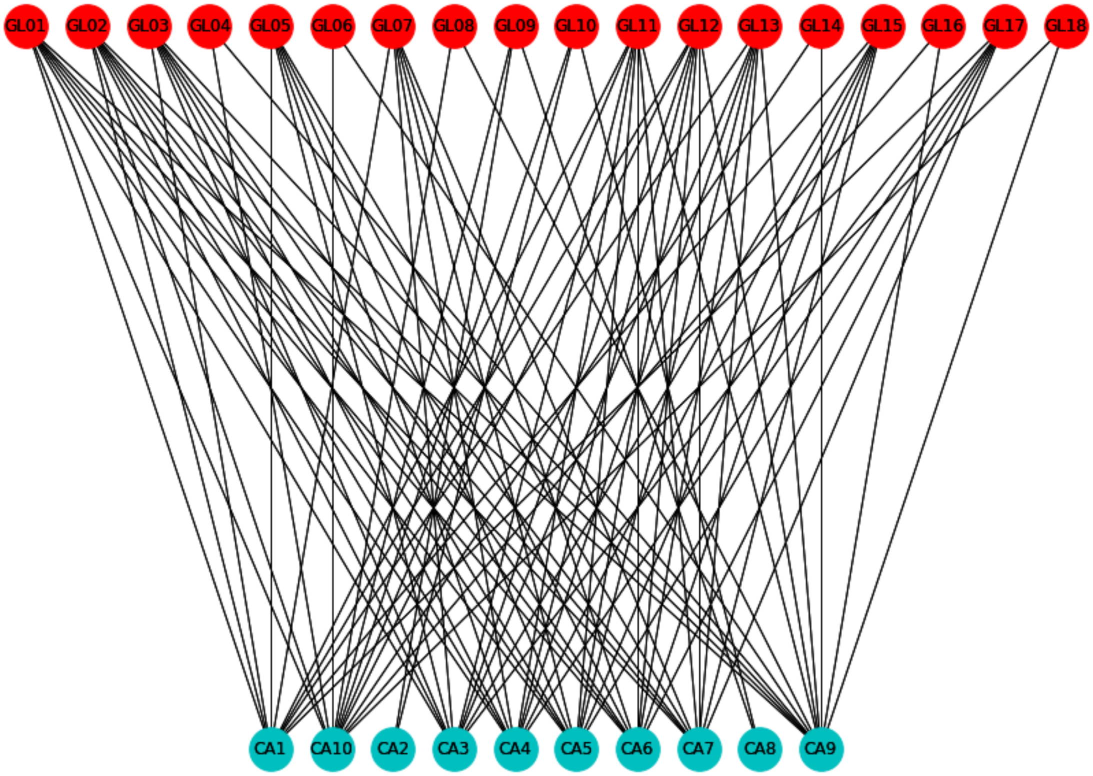


Figure 31 Pair-wise combinations of CA scenarios (cyan) and Global SSP scenarios (red)

6.4 Discussion

In this dissertation, the multi-scale cross-impact (CI) matrix was analyzed wholly using the complete solver function in ScenarioWizard, and it did not necessitate partitioning. The CIB analysis identified a total of 88 scenario combinations. The approach to scenario analysis in this dissertation is multi-scale and it differs from the traditional single-scale perspective. This multi-scale study produced scenarios taking considerations of plausible development pathways at the global level. Although national energy scenarios do consider global elements, these elements tend to be very specific to energy development (e.g., development in Negative Emission Technologies) and plausible socioeconomic situations at the global level tend to be underrepresented. However, energy development at the global level can be influenced by different global socioeconomic conditions; plausible different socioeconomic 'worlds' under climate change are already depicted by the SSP framework. The SSP framework can be extended to develop national energy scenarios since different global socioeconomic developments will have many implications on energy development domestically. Scenario studies conducted at the national level can better incorporate global socioeconomic development pathways by extending the basic or global SSPs. The link between national energy development and global socioeconomic development are usually underrepresented; yet such a multi-scale modelling exercise provides a better understanding of global and local dynamics. Furthermore, national energy development is greatly impacted by global issues. For instance, global oil price drop could be incited potentially by the fall in the demand for oil due to novel virus epidemic as the Chinese economic activities came to a halt and the demand for global air travels fell. In this dissertation, scenario elements under a broader socioeconomic framework, the SSPs, are part of the analysis; by linking to the global SSPs, the cross-influences between global socioeconomic development and national energy development can be better understood.

6.4.1 Analysing the Influence of a Carbonized vs. Decarbonized World

Multi-scale scenario analysis is able to unpack any driving forces operating at the global level that may impact Canada. Scenarios depicting a carbonized world (as indicated by the high pathway of carbon intensity; SSP04→H) are found to be consistent with scenarios where Canada's economy is either dependent or independent of fossil-fuel energy production (SD10→C or SD10→D). In a situation in which the world remains carbonized (SSP04→H), so does Canada (SD04→H and SD10→C) (as shown in the top half for the table labeled A in Figure 32[17]), sixty scenario configurations (e.g., scenario# 13, 14, 15, 16, 17, and so on) are consistent with this condition. Hence, it is plausible that the world including Canada would pursue the continuation of the status quo.

However, the analysis also suggests that a future where the world remains carbonized is not a pre-requisite for Canada to remain carbonized. In fact, it is also plausible for Canada to be decarbonized while the rest of the world is not. This situation is depicted by ten consistent scenario configurations, showing Canada's economy being decoupled from the fossil-fuel sector (SD10→D) (as shown in the bottom half of the table labeled B in Figure 32). This condition is also accompanied by Canada's carbon intensity being low (SD04→L). Additionally, some scenario configurations depicting a decarbonized Canada in a carbonized world have higher total

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[17] Figure 32 shows only scenario configurations meeting the condition SSP04→H. Accordingly, 70 out of 88 scenario configurations (as shown) meet this condition.

impact scores[18] (e.g., CA9-65 and CA10-77), which suggest that these scenario configurations are more likely than certain scenario configurations (that have lower impact scores) depicting a carbonized Canada in a carbonized world. The idea that the world remains carbonized while Canada decarbonizes is counterintuitive, which will be discussed further in Chapter 6.4.2.

Assuming the world is decarbonized, meaning the low development pathway for global carbon intensity (i.e., SSP04→L), a decarbonized world is found to be consistent with scenarios where Canada's economy is either dependent or independent on fossil-fuel production (SD10→C or SD10→D). Only two scenario configurations are consistent (i.e., CA2-11 and CA2-12) with Canada being carbonized (SD10→C and SD04→H) (as shown in the top half of the table labeled A in Figure 33). However, in a decarbonized world, it is highly likely that Canada would also be decarbonized as indicated by four scenario configurations (CA8-63, CA8-64, CA10-87, and CA10-88) (as shown in the bottom half of the table labeled B in Figure 33). Additionally, these configurations have the total impact scores that are higher than the configurations depicting a carbonized Canada in a decarbonized world. Although a decarbonized world may be consistent with either carbonized or decarbonized Canada, the higher impact scores for scenario configurations depicting a decarbonized Canada suggest that a future condition for which Canada must also be decarbonized is more likely. If the world decarbonizes, Canada will have the incentive or be pressured to decarbonize too. However, it would also be possible for Canada to remain carbonized. The latter solution is counterintuitive; this will be discussed in the subsequent section.

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[18] In CIB analysis, total impact score refers the sum of all influences impacting a descriptor outcome. A positive score indicate that the outcome is supported, whereas negative scores indicates that the outcome is contradicted. The higher total impact score, either positive or negative, suggest that the outcome is very 'stable', i.e. this particular outcome is more difficult to change.

			Global Shared Socioeconomic Pathways													Canada's Energy Futures							
CA-scenario#	Scenario#	Impact Score	SSP01	SSP02	SSP03	SSP04	SSP05	SSP06	SSP07	SSP08	SSP09	SSP10	SSP11	SSP12	SSP13	SD03	SD04	SD05	SD06	SD07	SD08	SD10	
CA3	13	368	H	L	H	H	L	L	M	H	H	M	L	L	L	L	H	H	L	M	L	C	A
CA3	14	238	H	M	H	H	L	L	M	M	H	H	M	L	L	L	H	H	L	M	L	C	
CA3	15	189	M	M	H	H	L	L	M	M	L	H	M	M	L	L	H	H	L	M	L	C	
CA3	16	181	M	M	H	H	L	L	L	M	L	M	M	H	L	L	H	H	L	M	L	C	
CA3	17	182	H	M	L	H	M	L	H	M	M	H	M	L	M	L	H	H	L	M	L	C	
CA3	18	187	H	M	M	H	M	L	H	M	M	H	M	L	M	L	H	H	L	M	L	C	
CA3	19	199	H	M	H	H	M	L	H	M	H	H	M	L	M	L	H	H	L	M	L	C	
CA3	20	168	M	M	L	H	M	L	M	M	M	H	M	M	M	L	H	H	L	M	L	C	
CA3	21	173	M	M	M	H	M	L	M	M	M	H	M	M	M	L	H	H	L	M	L	C	
CA3	22	174	M	M	H	H	M	L	M	M	M	H	M	M	M	L	H	H	L	M	L	C	
CA1	1	375	H	L	H	H	L	L	M	H	H	M	L	L	L	L	H	M	L	M	L	C	
CA1	2	245	H	M	H	H	L	L	M	M	H	H	M	L	L	L	H	M	L	M	L	C	
CA1	3	196	M	M	H	H	L	L	M	M	L	H	M	M	L	L	H	M	L	M	L	C	
CA1	4	188	M	M	H	H	L	L	L	M	L	M	M	H	L	L	H	M	L	M	L	C	
CA1	5	189	H	M	L	H	M	L	H	M	M	H	M	L	M	L	H	M	L	M	L	C	
CA1	6	194	H	M	M	H	M	L	H	M	M	H	M	L	M	L	H	M	L	M	L	C	
CA1	7	206	H	M	H	H	M	L	H	M	H	H	M	L	M	L	H	M	L	M	L	C	
CA1	8	175	M	M	L	H	M	L	M	M	M	H	M	M	M	L	H	M	L	M	L	C	
CA1	9	180	M	M	M	H	M	L	M	M	M	H	M	M	M	L	H	M	L	M	L	C	
CA1	10	181	M	M	H	H	M	L	M	M	M	H	M	M	M	L	H	M	L	M	L	C	
CA7	53	372	H	L	H	H	L	L	M	H	H	M	L	L	L	H	H	H	M	M	L	C	
CA7	54	242	H	M	H	H	L	L	M	M	H	H	M	L	L	H	H	H	M	M	L	C	
CA7	55	193	M	M	H	H	L	L	M	M	L	H	M	M	L	H	H	H	M	M	L	C	
CA7	56	185	M	M	H	H	L	L	L	M	L	M	M	H	L	H	H	H	M	M	L	C	
CA7	57	186	H	M	L	H	M	L	H	M	M	H	M	L	M	H	H	H	M	M	L	C	
CA7	58	191	H	M	M	H	M	L	H	M	M	H	M	L	M	H	H	H	M	M	L	C	
CA7	59	203	H	M	H	H	M	L	H	M	H	H	M	L	M	H	H	H	M	M	L	C	
CA7	60	172	M	M	L	H	M	L	M	M	M	H	M	M	M	H	H	H	M	M	L	C	
CA7	61	177	M	M	M	H	M	L	M	M	M	H	M	M	M	H	H	H	M	M	L	C	
CA7	62	178	M	M	H	H	M	L	M	M	M	H	M	M	M	H	H	H	M	M	L	C	
CA5	33	370	H	L	H	H	L	L	M	H	H	M	L	L	L	L	H	H	M	M	L	C	
CA5	34	240	H	M	H	H	L	L	M	M	H	H	M	L	L	L	H	H	M	M	L	C	
CA5	35	191	M	M	H	H	L	L	M	M	L	H	M	M	L	L	H	H	M	M	L	C	
CA5	36	183	M	M	H	H	L	L	L	M	L	M	M	H	L	L	H	H	M	M	L	C	
CA5	37	184	H	M	L	H	M	L	H	M	M	H	M	L	M	L	H	H	M	M	L	C	
CA5	38	189	H	M	M	H	M	L	H	M	M	H	M	L	M	L	H	H	M	M	L	C	
CA5	39	201	H	M	H	H	M	L	H	M	H	H	M	L	M	L	H	H	M	M	L	C	
CA5	40	170	M	M	L	H	M	L	M	M	M	H	M	M	M	L	H	H	M	M	L	C	
CA5	41	175	M	M	M	H	M	L	M	M	M	H	M	M	M	L	H	H	M	M	L	C	
CA5	42	176	M	M	H	H	M	L	M	M	M	H	M	M	M	L	H	H	M	M	L	C	
CA6	43	369	H	L	H	H	L	L	M	H	H	M	L	L	L	M	H	H	M	M	L	C	
CA6	44	239	H	M	H	H	L	L	M	M	H	H	M	L	L	M	H	H	M	M	L	C	
CA6	45	190	M	M	H	H	L	L	M	M	L	H	M	M	L	M	H	H	M	M	L	C	
CA6	46	182	M	M	H	H	L	L	L	M	L	M	M	H	L	M	H	H	M	M	L	C	
CA6	47	183	H	M	L	H	M	L	H	M	M	H	M	L	M	M	H	H	M	M	L	C	
CA6	48	188	H	M	M	H	M	L	H	M	M	H	M	L	M	M	H	H	M	M	L	C	
CA6	49	200	H	M	H	H	M	L	H	M	H	H	M	L	M	M	H	H	M	M	L	C	
CA6	50	169	M	M	L	H	M	L	M	M	M	H	M	M	M	M	H	H	M	M	L	C	
CA6	51	174	M	M	M	H	M	L	M	M	M	H	M	M	M	M	H	H	M	M	L	C	
CA6	52	175	M	M	H	H	M	L	M	M	M	H	M	M	M	M	H	H	M	M	L	C	
CA9*	65	350	H	L	H	H	L	L	M	H	H	M	L	L	L	L	L	M	L	M	M	D	B
CA9	66	220	H	M	H	H	L	L	M	M	H	H	M	L	L	L	L	M	L	M	M	D	
CA9	67	171	M	M	H	H	L	L	M	M	L	H	M	M	L	L	L	M	L	M	M	D	
CA9	68	163	M	M	H	H	L	L	L	M	L	M	M	H	L	L	L	M	L	M	M	D	
CA9	72	181	H	M	H	H	M	L	H	M	H	H	M	L	M	L	L	M	L	M	M	D	
CA9	76	156	M	M	H	H	M	L	M	M	M	H	M	M	M	L	L	M	L	M	M	D	
CA10*	77	364	H	L	H	H	L	L	M	H	H	M	L	L	L	L	L	M	M	M	M	D	
CA10	78	234	H	M	H	H	L	L	M	M	H	H	M	L	L	L	L	M	M	M	M	D	
CA10	79	185	M	M	H	H	L	L	M	M	L	H	M	M	L	L	L	M	M	M	M	D	
CA10	80	177	M	M	H	H	L	L	L	M	L	M	M	H	L	L	L	M	M	M	M	D	

A	World remains carbonized (SSP04->H) and Canada remains carbonized (SD10->C, also SD04->H)
B	World remains carbonized (SSP04->H) and Canada decarbonizes (SD10->D, also SD04->L)

Legend:

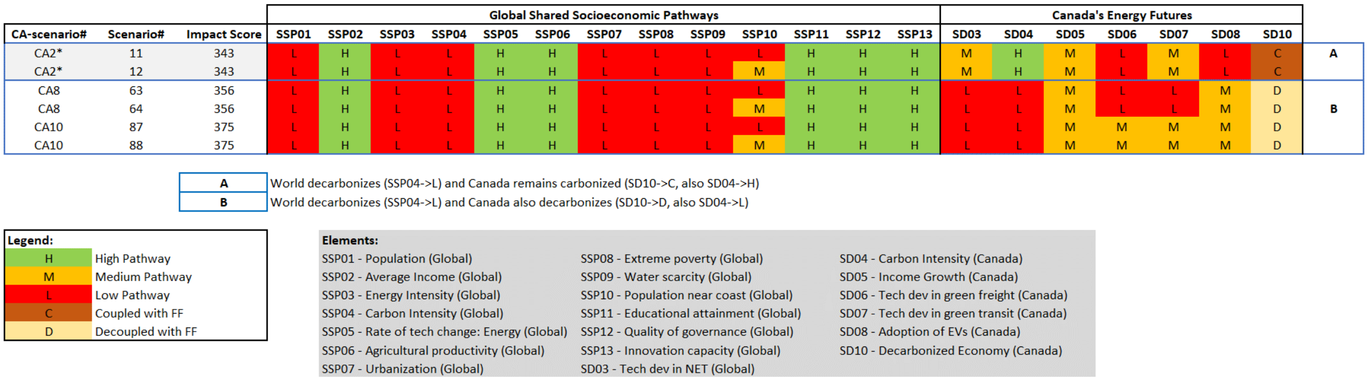
H	High Pathway
M	Medium Pathway
L	Low Pathway
C	Coupled with FF
D	Decoupled with FF

Elements:

SSP01 - Population (Global)
SSP02 - Average Income (Global)
SSP03 - Energy Intensity (Global)
SSP04 - Carbon Intensity (Global)
SSP05 - Rate of tech change: Energy (Global)
SSP06 - Agricultural productivity (Global)
SSP07 - Urbanization (Global)
SSP08 - Extreme poverty (Global)
SSP09 - Water scarcity (Global)
SSP10 - Population near coast (Global)
SSP11 - Educational attainment (Global)
SSP12 - Quality of governance (Global)
SSP13 - Innovation capacity (Global)
SD03 - Tech dev in NET (Global)
SD04 - Carbon Intensity (Canada)
SD05 - Income Growth (Canada)
SD06 - Tech dev in green freight (Canada)
SD07 - Tech dev in green transit (Canada)
SD08 - Adoption of EVs (Canada)
SD10 - Decarbonized Economy (Canada)

* Selected scenario configurations for tracing causal chains, see Section 6.4.2

Figure 32 Scenario configurations showing only for which the world is still carbonized (SSP04→H)



			Global Shared Socioeconomic Pathways													Canada's Energy Futures							
CA-scenario#	Scenario#	Impact Score	SSP01	SSP02	SSP03	SSP04	SSP05	SSP06	SSP07	SSP08	SSP09	SSP10	SSP11	SSP12	SSP13	SD03	SD04	SD05	SD06	SD07	SD08	SD10	
CA2*	11	343	L	H	L	L	H	H	L	L	L	L	H	H	H	M	H	M	L	M	L	C	A
CA2*	12	343	L	H	L	L	H	H	L	L	L	M	H	H	H	M	H	M	L	M	L	C	
CA8	63	356	L	H	L	L	H	H	L	L	L	L	H	H	H	L	L	M	L	L	M	D	B
CA8	64	356	L	H	L	L	H	H	L	L	L	M	H	H	H	L	L	M	L	L	M	D	
CA10	87	375	L	H	L	L	H	H	L	L	L	L	H	H	H	L	L	M	M	M	M	D	
CA10	88	375	L	H	L	L	H	H	L	L	L	M	H	H	H	L	L	M	M	M	M	D	

A	World decarbonizes (SSP04->L) and Canada remains carbonized (SD10->C, also SD04->H)
B	World decarbonizes (SSP04->L) and Canada also decarbonizes (SD10->D, also SD04->L)

Legend:

H	High Pathway
M	Medium Pathway
L	Low Pathway
C	Coupled with FF
D	Decoupled with FF

Elements:

SSP01 - Population (Global)
SSP02 - Average Income (Global)
SSP03 - Energy Intensity (Global)
SSP04 - Carbon Intensity (Global)
SSP05 - Rate of tech change: Energy (Global)
SSP06 - Agricultural productivity (Global)
SSP07 - Urbanization (Global)
SSP08 - Extreme poverty (Global)
SSP09 - Water scarcity (Global)
SSP10 - Population near coast (Global)
SSP11 - Educational attainment (Global)
SSP12 - Quality of governance (Global)
SSP13 - Innovation capacity (Global)
SD03 - Tech dev in NET (Global)
SD04 - Carbon Intensity (Canada)
SD05 - Income Growth (Canada)
SD06 - Tech dev in green freight (Canada)
SD07 - Tech dev in green transit (Canada)
SD08 - Adoption of EVs (Canada)
SD10 - Decarbonized Economy (Canada)

* Selected scenario configurations for tracing causal chains, see Section 6.4.2

Figure 33 Scenario configurations showing only decarbonized worlds (SSP04→L)

6.4.2 Tracing Causal Chains of Decarbonization

Traceability of scenarios refers to the transparency for how certain scenario outcomes were justified (Kosow, 2015). As mentioned, scenarios produced by Intuitive Logics approaches tend to conceal the assumptions and mental models of the storyline contributors. However, the CIB analysis can provide a full disclosure of why such scenario outcomes were produced, which scenario elements support certain outcomes to be internally consistent and which elements do not. For this discussion, scenarios with high total impact scores that are counterintuitive were selected for further elaboration (i.e. the shaded scenario configurations shown in Figure 32 and Figure 33). These scenarios, CA2-11 and CA2-12, depict a future where the world decarbonizes, yet Canada remains carbonized. Also, scenario CA9-65 and CA10-77 depict futures where the world remains carbonized, yet Canada decarbonizes.

6.4.2.1 A case for which the world decarbonizes & Canada remains carbonized

In the case for scenario CA2-11 and CA2-12, the outcome for the low development pathway of global carbon intensity (SSP04→L) (Figure 34-A) is supported by the following elements.

- high global innovation capacity (SSP13→H): +9
- high rate of global energy technology change (SSP05→H): +9
- high global agricultural productivity (SSP06→H): +6
- high global average income (SSP02→H): +3
- low global energy intensity (SSP03→L): +3
- moderate technology development in green transit (SD07→L): +1

This outcome is also contradicted by:

- high carbon intensity in Canada (SD04→H): -9
- moderate technology development in NETs (SD03→M): -4
- carbonized economy of Canada (SD10→C): -3

The outcome for the low development pathway of global carbon intensity (SSP04→L) is considered stable (impact score = +15). This is because the supporting scenario elements are more 'influential' than the contradicting elements in promoting such an outcome. In other words, destabilizing this outcome would require the supporting elements to be less promoting (e.g., innovation capacity, or SSP13, could be medium instead of high) and/or the contradicting elements to be more intensified (e.g., global technology development in NETs, or SD03, could be high instead of medium).

Moving on, the configuration for which Canada remains carbonized is based on Canada's carbon intensity being high (SD04→H) and Canada's economy being coupled with fossil fuel production (SD10→C). The outcome for high carbon intensity is supported by the following (Figure 34-B).

- carbonized economy of Canada (SD10→C): +9
- moderate global technology development in NETs (SD03→M): +6
- medium income growth in Canada (SD05→M): +3

This outcome is contradicted by:

- medium technology development in green transit in Canada (SD07→M): -6
- low technology development in green freight in Canada (SD06→L): -3
- low adoption of EVs in Canada (SD08→L): -3

The outcome of high carbon intensity in Canada is consistent (impact score = +6). However, the impact score is not as stable as the world being decarbonized described earlier. Potentially, the outcome of high carbon intensity in Canada can be destabilized when some elements change their state. For instance, lower technology development in NETs will destabilize this outcome.

The outcome for which the Canadian economy remains coupled with fossil fuel production (SD10→C) is supported by the following elements (Figure 34-C).

- high carbon intensity in Canada (SD04→H): +9

- low technology development in green freight in Canada (SD06→C): +3
- low adoption of EVs in Canada (SD08→L): +3
- low global carbon intensity (SSP04→L): +3

Further, this outcome is contradicted by:

- moderate global technology development in NETs (SD03→M): -6
- medium technology development in green transit in Canada (SD07→M): -3

The outcome for SD10→C is consistent, but this outcome is not as stable as the SSP04→L outcome described earlier by virtue of having a lower impact score (impact score = +9). This means that it could be easier to change the state of scenario elements to destabilize such an outcome.

Should global developments move toward decarbonization, a carbonized Canada would not be able to significantly alter global momentum towards decarbonization. From the national-scale perspective, a carbonized Canada can potentially be destabilized through certain elements changing their end-states. Moderate technology development in green transit (SD07→M) is a driving force that destabilizes the scenario configuration for a carbonized Canada since SD07 contradicts both assumptions: SD04→H and SD10→C.

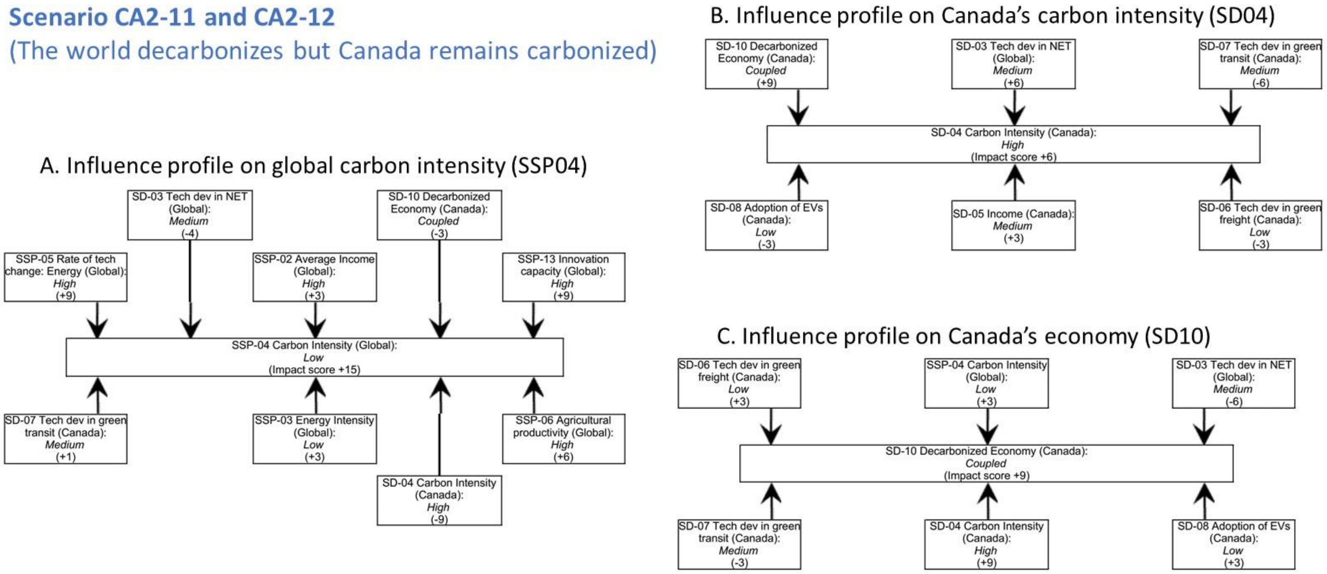


Figure 34 Causal chains for carbonized Canada in a decarbonized world

6.4.2.2 A case for which the world remains carbonized & Canada decarbonizes

The outcome for high global carbon intensity is supported by the following (Figure 35-A).

- low rate of global energy technological change (SSP05→L): +9

- low rate of global agricultural productivity (SSP06→L): +7
- low global innovation capacity (SSP13→L): +5
- low global average income (SSP02→L): +3
- high global energy intensity (SSP03→H): +3
- low carbon intensity in Canada (SD04-L): +3
- medium technology development in green transit in Canada (SD07→M): +1

And, this outcome is contradicted by:

- decarbonized economy of Canada (SD10→D): -6

This outcome (SSP04→H) has a very high impact score (impact score = +25), supported by several scenario elements. Most elements supporting this outcome are elements at the global level. Although there are elements related to Canada's energy futures (e.g., carbon intensity and technology development in green transit), these elements have relatively lower net influence to support this global outcome.

Even though Canada's carbon intensity is already low in this scenario (because Canada is decarbonized), it will still support high global carbon intensity. This can be viewed as an issue since low carbon intensity in Canada should not be directly supporting high carbon intensity globally. The expert who provided the influence judgements for the SD-04 descriptor stated that "[The] uncertainty of the magnitude of CA intensity relative to global intensity but [I] feel there is a direct connection given the relative carbon footprint of Canada and the rest of the world." According to the expert, the 'low' carbon intensity in Canada could be considered 'high' from the global perspective. Therefore, the judgement scores do suggest that regardless of the level of carbon intensity in Canada, there is always the support for high carbon intensity globally. However, such an interrelationship is hardly supported by empirical evidence and therefore contentious. The situation here raises an important issue on the importance of the quality of the raw judgment scores.

The only contradicting element is the decarbonized economy of Canada (SD10→D), but its influence does little to destabilize this global outcome. Therefore, the analysis suggests that a decarbonized Canada might have little impact to destabilize the condition of a carbonized world.

For the Canadian side, the outcome of Canada's carbon intensity being low is supported by the following elements (Figure 35-B).

- decarbonized economy of Canada (SD10→D): +9

- medium adoption of EVs in Canada (SD08→M): +3
- low technology development in green freight in Canada (SD06→L): +3
- medium technology development in green transit in Canada (SD07→M): +3

This outcome is also contradicted by:

- low development in NETs (SD03→L): -3
- medium income growth in Canada (SD05→M): -3

The outcome of Canada's low carbon intensity has a fairly high impact score (impact score = +12), which suggests that minor changes in the states of these elements are unlikely to destabilize this outcome. Not being reliant on fossil fuel production is key to supporting low carbon intensity in Canada. Furthermore, green transport technologies are likely to support low carbon intensity even though their outcomes are only at the medium or low level. As discussed in Chapter 3, technology development in green freight is driven by the private sector and, therefore, lags behind the technology development in green transit. Nevertheless, greening the transportation sector is crucial to reducing Canada's GHG emissions since the sector is one of the major contributors of GHG emissions in Canada (see Chapter 3).

The outcome for which Canada's economy is decoupled from fossil fuel production (SD10→D) is supported by the following elements (Figure 35-C).

- low carbon intensity in Canada (SD04→L): +9
- medium adoption of EVs in Canada (SD08→M): +3
- medium technology development in green transit in Canada (SD07→M): +3

And, it is contradicted by:

- high global carbon intensity (SSP04→H): -9
- low development in NETs (SD03→L): -3
- low technology development in green freight in Canada (SD06→L): -3

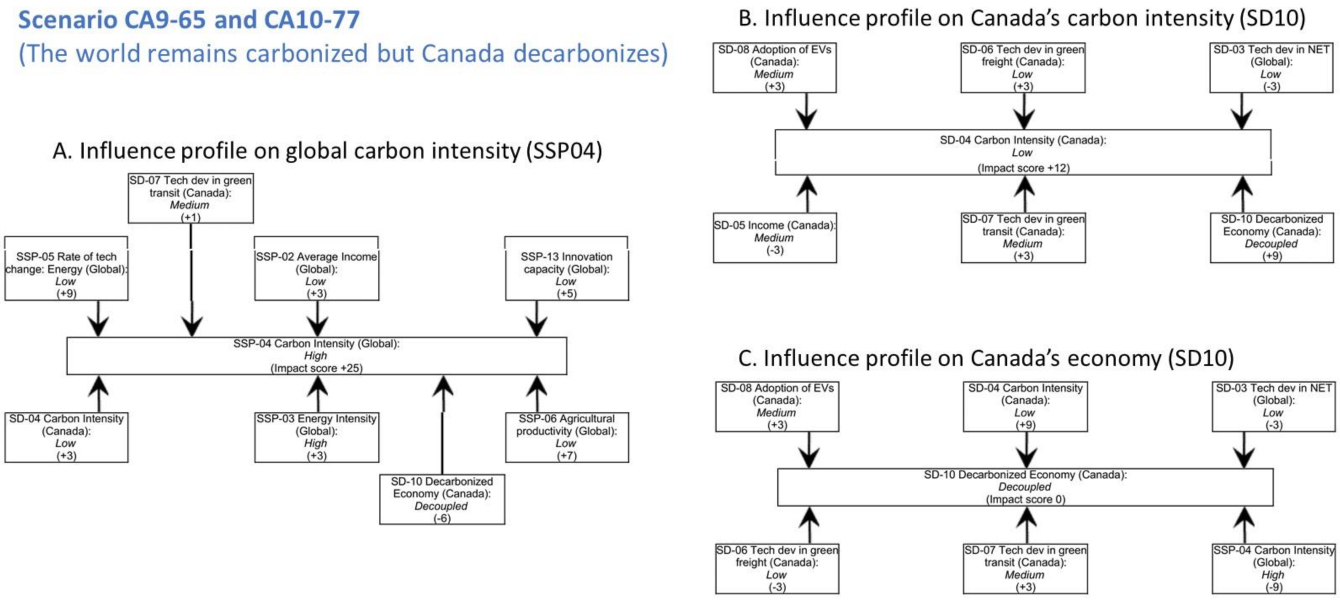


Figure 35 Causal chains for decarbonized Canada in a carbonized world

The outcome that Canada's economy is decoupled from fossil fuel production (SD10→D) while global trends support high carbon intensity (SSP04→H) is consistent, but it has a low impact score (impact score = 0). This suggests that any change in the state of elements could potentially destabilize this outcome. A contradicting element, high global carbon intensity (SSP04→H), acts as a strong driving force that could destabilize this outcome; however, global carbon intensity is already at its highest state—it cannot change further to destabilize the outcome. Other contradicting descriptors such as low development in NETs (SD03→L) and low technology development in green freight in Canada (SD06→L) can become medium or high that will change this scenario outcome.

The analysis suggests that when the global carbon intensity trend is high, it would be anticipated to be stable. Even if Canada were to decarbonize under such a scenario, it may have little influence on the global development. However, it would be plausible for Canada to be decarbonized in a carbonized world because most driving forces that support Canada's decarbonization are elements that are 'local' to Canada. The major global factor that could potentially influence (or destabilize) Canada's decarbonization is the persistence of high carbon intensity in the global development pathway.

6.3.2.3 Implications of boundary conditions

A multi-scale analysis such as this can provide clues for understanding the operation of boundary conditions in a multi-scale system. Within the scientific community, the operation of boundary conditions is often referred to as imposing restriction, meaning global developments should dictate what would be the plausible developments at the regional/national levels (Alcamo, 2008; Dermawan et al., 2013; Zurek and Henrichs, 2007). Conventionally, it is believed that a carbonized world would likely influence Canada to remain carbonized as well. However, that may not be the case as Canada can still be decarbonized even when the world is not. When the world is decarbonized, Canada can either be decarbonized or remain status quo (carbonized). The analysis raises an important issue for consideration, challenging the assumption that developments across scales must be lockstep due to the transfer of boundary conditions. However, in this study, the boundary conditions are found to be non-restrictive. Through this thesis, the CIB analysis shows that local context has its own dynamics, and local development pathways may not necessarily coincide with the development pathways at the global level. In other words, the analysis shows that local dynamics are key for a decarbonized Canada. Actually, understanding local dynamics resonates with the aim of the SSP framework, which is to allow more detailed analyses at a more localized scale (Ebi et al., 2014; O'Neill et al., 2014; van Ruijven et al., 2014). In essence, this is good, as internally consistent multi-scale studies can highlight the dynamic driving forces operating at more regional, local, sectoral scales.

6.4 Conclusion

This chapter demonstrates the development of an SSP extension study using CIB analysis for more detailed national and sectoral analyses and applied them to Canada's energy futures as a case. According to the cross-impact judgments of expert participants in this study, the analysis found 88 scenario configurations that are internally consistent across scales. From unpacking these 88 configurations, 18 unique configurations for the global SSPs and ten configurations for Canada's energy futures were found. Scenario analysis suggests that pathways to decarbonization in Canada are likely promoted by domestic effort regardless of global development pathways (carbonized or decarbonized) that unfold. In a decarbonized world, it is plausible that Canada remains carbonized because factors encouraging high carbon intensity are mostly local. Alternatively, when the world remains carbonized, it is plausible that Canada may be motivated to continue producing and exporting fossil-fuel. However, CIB analysis also finds that when global trends are carbonized, it remains plausible that Canada can take a different stance and be decarbonized. Whether Canada can or cannot be decarbonized does not entirely depend on the prevailing development pathways at the global level. This signals an important opportunity for Canada to demonstrate global leadership towards decarbonization. The analysis of 88 scenario combinations can reveal the plausible development pathways for Canada associated with decarbonization.

In scenario research, ‘scenario consistency’ is often vaguely defined. Such a concept can be treated as a mechanism to restrict the development of regional/national scenarios (Zurek and Henrichs, 2007), but it can also refer to the content of the scenarios developed for regional and sectoral analyses (or the extended SSPs) that do not deviate from the global development pathways (van Ruijven et al., 2014). Nonetheless, a question remains about how one can understand the term scenario consistency. This study unpacks this concept to reveal interesting characteristics of what is meant by scenario consistency. Within the context of this research, the characteristic of consistent scenarios can mean restricting scenario outcomes at regional/national levels that are not compatible with the global development. For instance, when the rest of the world is decarbonized, a restriction may be imposed as such that Canada must also be decarbonized, though it is not always the case. However, scenario consistency does not necessarily require that regional/national scenarios match global outcomes. Scenario outcomes at the regional/national level could show more detailed local dynamics. For example, when the world remains carbonized, Canada can decarbonize as this research has shown. The underlying logics of scenario elements of energy scenarios for Canada may determine whether the scenario outcomes will align exactly with the global development pathways, or they can also deviate from the global development pathways. Yet, this study has shown that both conditions are consistent. The result suggesting that Canada can be decarbonized in a carbonized world is good for the SSPs since the main objective of developing extended SSPs is to explore local dynamics more deeply (O’Neill et al., 2014). Nonetheless, such a result is counterintuitive that should be subjected to further scrutiny.

The CIB analysis provides a means to trace back why scenario outcomes are produced this way and which scenario elements can be modified to make scenario outcomes less undesirable or more desirable (Kosow, 2015; Lloyd and Schweizer, 2014; Scheele et al., 2018). When tracing back counterintuitive scenarios (i.e., a carbonized Canada in a decarbonized world and decarbonized Canada in a carbonized world), to be decarbonized or not is entirely based on

Canada’s efforts. This is because elements that support or discourage efforts toward decarbonization are mostly local driving forces such as whether the Canadian economy is dependent on fossil fuel production and technology development in green transport. Although a depiction of the future whereby Canada decarbonizes and the world remains carbonized is internally consistent, the CIB analysis indicates this depiction is less stable. A global influence exerted by high global carbon intensity can contradict Canada’s decarbonization since the consistent descriptor state had an impact score = 0; however, the analysis suggests that greening the transportation sector is needed to stabilize Canada’s decarbonization effort. Tracing the causal chain of counterintuitive scenarios found that these scenarios have no internal logic problem; thus, these scenarios are internally *consistent*. Scenarios that have internal logic problem should be considered *inconsistent*.

Chapter 7: Summary Conclusion and Contributions

This chapter summarizes research contributions and the conclusion of this dissertation. The next Chapter 7.1 revisits the multiple definitions of scenario consistency, which have contributed to the confusion of what consistency across scales means in multi-scale scenario research. In fact, the term ‘inconsistency’ is more useful to avoid any pitfall in producing multi-scale scenarios that are implausible. Subsequently, Chapter 7.2 explains how the research goal and questions have been addressed in different chapters in this dissertation. Chapter 7.3 highlight the contribution of this dissertation to multi-scale scenario research, and finally closes by explaining the study limitation and future research direction in Chapter 7.4.

7.1 Scenario Consistency Across Scales

The conventional belief or assumption that global and local outcomes must match across scales to be ‘consistent’ was tested in this research. First, the multiple definitions of scenario consistency across scales is detailed in Chapter 2, which addresses research goal 1, assessing multiple interpretations and applications of ‘consistency’ in order to clarify the definition of scenario consistency across scales (Biggs et al., 2007; van Ruijven et al., 2014; Wiek et al., 2013; Zurek and Henrichs, 2007). In multi-scale scenario research, the definition of consistent scenario across scales is often rooted on the linking categories as defined by Zurek and Henrich (2007). For the existing studies on Canada’s energy futures, the outcomes for which Canada would be decarbonized in a decarbonized world and Canada remains carbonized in carbonized world are matched across scales. However, the results of CIB analysis in this dissertation also reveal internally consistent scenarios where global and local outcomes do not match. That means the scenarios depicting Canada be decarbonized in a carbonized world or that Canada remains carbonized in a decarbonized world are also consistent. But such depictions may be mistakenly classified as ‘inconsistent’ when using the cross-scale consistency definition by Zurek and Henrichs (2007) and Biggs et al. (2007).

Due to confusion about what cross-scale consistency means, there is also the need to revise the operational definition of consistency across scales, which addresses research goal 2: To reinterpret Zurek and Henrichs (2007) concept of linking strategies to identify the missing threshold of inconsistency. We can do this by making use of the consistency definition provided by CIB analysis, which points to which global and local outcomes are internally logically consistent (Weimer-Jehle, 2006). That means the global and local outcomes should be non-conflicting (Wiek et al., 2013) or realistic (Tietje, 2005). Hence, performing internal consistency checks in multi-scale scenario analysis is necessary (Kok et al., 2019; Kosow, 2015; Wiek et al., 2013; Zandersen et al., 2019).

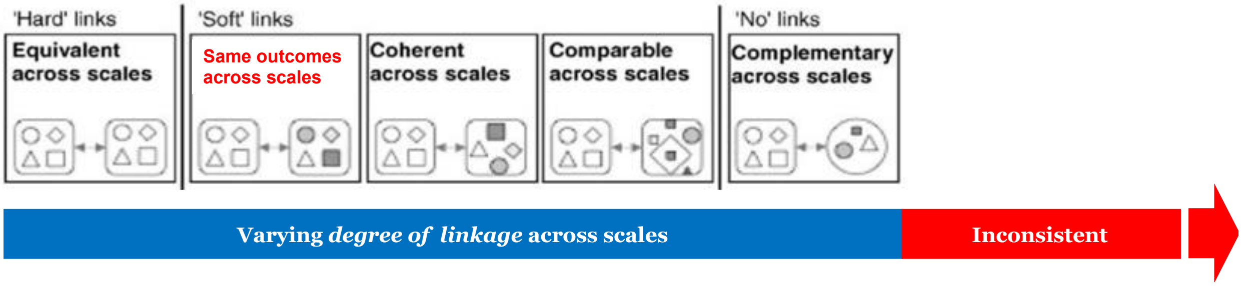


Figure 36 Re-interpreting consistent and inconsistent scenario across scales

We should not confuse the consistency of scenarios across scales with their degree of linkages (i.e., more or fewer links). The confusion arises because Zurek and Henrichs (2007) use the term ‘consistent’ to describe one of the soft links. Instead, the description could be replaced with ‘Same outcomes’ (Figure 36). The varying degree of linkages across scales is important to measure and assess how different studies can be linked or coupled. Also, equally important is that these linking categories can provide the threshold for which scenarios across scales can be considered inconsistent. Rather than focus on the extent to which scenarios are consistent across scales, it may be more useful to define the term ‘inconsistent’ (Figure 36). In Chapter 6.4, I traced the causal chains of decarbonization to investigate which elements bear influences on domestic decarbonization effort for Canada. The scenario configurations that are counterintuitive (i.e. global and national developments are not lockstep) were analysed and found that there are no internal logic problems. The analysis shows that it would be plausible for Canada to be decarbonized in a carbonized world because most driving forces that support Canada’s decarbonization are elements that are ‘local’ to Canada. The major global factor that could potentially influence (or destabilize) Canada’s decarbonization is the persistence of high carbon intensity in the global development pathway. CIB scenarios are consistent across scales, but such scenarios cannot be classified *consistent* under Zurek and Henrichs linking strategies. Rightfully, people may think that, since CIB scenarios are not classified as consistent, these scenarios should be considered *inconsistent.* Such confusion is prevalent and can be better avoided by better defining what inconsistent scenarios are. The term *inconsistent* should be reserved for scenarios that are found to have internal logic problems (scenarios that, for good reasons, would be dismissed as implausible).

7.2 Extending SSPs to a National Level Analysis

The Shared Socioeconomic Pathways (SSPs) framework is flexible, allowing the research community to develop more detailed regional/local and sectoral analyses by extending the SSPs. In this thesis, the capability of the SSP framework was demonstrated, which also addresses research goal 3: To demonstrate the flexibility of the SSP framework. Many SSP extension studies require socioeconomic driving forces operating at a more localized scale. The scope of the global SSPs is meant to be generic, but sometimes the scope is too generic to extend to lower scales usefully. Consequently, this presents a challenge for studies whose scopes are vastly different. However, the scope of the SSPs is not a limitation by any means because the SSP framework is meant to be flexible to allow driving forces operating at a more regional or national scale to be incorporated in the extended SSPs. This capability is further demonstrated in this dissertation—extending the SSPs to develop energy scenarios for Canada. The Canadian energy sector interacts with global developments, and Canada is already playing a key role in driving climate change, both as a high carbon emitter and as a major exporter of fossil fuels. To understand the broader implications of global influences on Canada's low-carbon energy transition, a multi-scale scenario analysis was deployed. Chapter 2, which also addresses research question 1 (i.e. How can globally linked, internally consistent multi-scale scenarios for Canadian energy futures under the SSP framework be developed?) identify different modes of entry for extension studies to be linked to the global SSPs. For this study, the chosen entry mode is re-specifying SSP elements—this is the mode of entry for which the extended SSP studies can be linked to the global SSPs (Phase 1). Because many elements necessary for developing energy scenarios are not part of the scope of the global SSPs, linking such an extended SSP study to the global SSPs through quantitative and narrative downscaling as recommended by the prevailing guidance note (van Ruijven et al., 2014) is challenging. Moreover, this sentiment has also been expressed by other researchers (see e.g., Frame et al., 2018). Yet they have managed to navigate this challenging situation by linking their studies to the global SSPs through the SSP elements or the SSP archetypes. The availability of a global SSP CI matrix presents a means for studies to link to the global SSPs by expanding the CI matrix to include scenario elements relevant for detailed regional or national analyses. This capability was demonstrated in this dissertation by using a scenario analysis technique called cross-impact balance (CIB) analysis (Weimer-Jehle, 2006) in a multi-scale manner. The analytical approach was detailed in Chapter 6, which addresses research question 2.2 (i.e. How can one utilize the cross-impact (CI) matrix of the SSPs for extending the SSPs for more detailed regional or national analyses?), and how new scenario elements can be re-specified and incorporated to the existing CI matrix developed earlier by Schweizer and O'Neill (2014).

This brings up the second phase, which is to identify and prioritize candidate elements necessary for developing energy scenarios for Canada—this was discussed in Chapter 5, which also addresses research question 2.1 (i.e. How can one identify and select elements for developing energy scenarios for Canada under the SSP framework?) Most often, identifying and prioritizing candidate elements are done through expert or stakeholders elicitation. The selection process is usually conducted in a workshop setting, where participants discuss and choose scenario elements they consider important. But selecting scenario elements based on popularity can misguide scenario users to think that popular elements would also be influential. In this dissertation, I have taken an unconventional approach. Instead of eliciting opinions of the stakeholders on what they considered important elements, I have demonstrated a novel approach of using network analysis to empirically determine which elements are influential in a causal network. The potential elements were first extracted from published scenario studies on Canada's energy futures. Network analysis is a systematic approach that increases the transparency of the scenario development process, which would otherwise be left to a subjective interpretation (Lloyd and Schweizer, 2014). Since independent studies on Canada's energy scenarios exist, the relevant scenario elements can be extracted from these studies by subjecting individual studies' documents or reports to a content analysis. As there are interrelationships among these elements, network analysis can integrate all elements extracted from different studies to produce a large multi-study network. Subsequently, node centrality measures can be calculated to determine which elements are more central (or influential in a causal network) that these studies have agreed on.

In the third phase, important candidate elements identified by network analysis were used to develop globally linked internally consistent energy scenarios for Canada under the SSP framework. Chapter 6 discusses the findings—this also addresses research question 3 (i.e. What are the implications of global developments on Canada's low-carbon energy transition?). In this dissertation, I have pioneered an original research approach in multi-scale scenario analysis using CIB and developed an extended SSPs (i.e. energy scenarios) for Canada. One can visualize a multi-scale CI matrix as two CI matrices for different studies 'pasted' together. Already, there is a CI matrix for the global SSPs produced by Schweizer and O'Neill (2014); the CI matrix can be expanded to include descriptors (elements or factors) related to Canada's energy futures. First, I constructed a CI matrix using elements drawn from the network analysis described in Chapter 5. Then, the judgments for how scenario elements interact were elicited by a panel of experts. According to the cross-impact judgments of the expert participants in this study, the CIB analysis further identified 88 scenario combinations that are consistent across scales. These findings suggest that, for instance, when the world is decarbonized, Canada can remain carbonized, meaning that the global developments do not set the agenda whether Canada can be decarbonized or not. In a carbonized world, global influence (e.g., demand for fossil fuel) would have some negative impacts but not strong enough to destabilize Canada's effort towards decarbonization; nonetheless, domestic efforts to decarbonize must be strong. Despite global dependence on fossil-fuel, it is plausible that Canada can be decarbonized, deviating from the global development pathway. Decarbonization requires the will to change and purposeful strategic planning. This study suggests that there is an important opportunity for Canada to demonstrate global leadership towards decarbonization.

7.3 Theoretical, Empirical, and Methodological Contributions

Firstly, the dissertation contributes to the scholarship on extending the SSPs to regional/local and sectoral contexts. Approaches to extending the SSPs have not been comprehensive in addressing what to do when the scope of the global SSP is not broad enough to be extended usefully. As described in Chapter 2, the two other novel modes of entry for which SSP extension studies can be linked to the global SSPs. First, studies can utilize the SSP elements as well as re-specifying the elements of the extended SSPs. Second, studies can adapt the SSP archetypes by developing a compatible framework such as the Representative Agricultural Pathways and Oceanic System Pathways (Maury et al., 2017; Palazzo et al., 2017). This development showcases the flexibility of the SSP framework that is intended to appeal to a broader research community to adopt the SSP-based assessments and help those who find it challenging at first to link their studies to the global SSPs by quantitative or narrative downscaling.

Second, this dissertation examines plausible energy development pathways for Canada that are consistent with different global developments as depicted by the SSPs. The analytical approach used is multi-scale scenario analysis as explained in Chapter 6. The emergence of global developments leading to a decarbonized world could promote the development of the Canadian energy sector to decarbonize aligning with the rest of the world. However, decarbonization at the global scale is not prescriptive for Canada to be decarbonized because Canada could choose to remain status quo and still be carbonized. Conversely, when the world remains carbonized, Canada could follow like the rest of the world to remain dependent on fossil-fuel. But it is also possible for Canada to deviate to become a decarbonized nation regardless which global development unfold. One critical notion revealed in this analysis is the implication of the deployment of NETs. There are two different views on NETs: (1) the development of NETs can motivate fossil fuel production and (2) the development of NETs is good for the economy due to reduced cost of adapting to climate change and reduced residual damages. NETs can play a significant role in Canada’s low-carbon transition, at least in the beginning. Some expert respondents commented that the development of NETs can potentially lift social pressure on Canada to decarbonize the economy. Knowing that technologies can safely remove carbon dioxide from the atmosphere, there is no motivation to reduce fossil-fuel based energy consumption. But there is also a different take on the development of NETs. For instance, one expert participant indicated that a successful deployment of NET could potentially reduce the impact of climate change, and it may translate into cost-savings for the national economy since climate change adaptation would not require costly measures. This study found that there is no consensus, in terms of expert’s opinions, for how the deployment of NETs could influence the pathways towards decarbonization in Canada. However, through CIB analysis, which integrates all expert judgments in this study, results lean in favour of the idea that NETs may encourage the production and consumption of fossil fuel. Nonetheless, more research is needed to advance the understanding of the broader socioeconomic implications of NETs.

As Canada decarbonizes, there is a consistency in which the development of NETs can destabilize decarbonization. When the technology development in NETs is medium or high, Canada would be motivated to continue fossil-fuel production activities since the national GHG emissions can be reduced. With the persistence of fossil-fuel production activities, however, Canada's efforts toward decarbonization remain challenging. These notions are important for energy policy decisions—to be or not to be decarbonized. Policy measures that support fossil-fuel production activities would be too risky when the global development eventually leans toward decarbonization. Resources invested to support the carbonized development pathway(s) domestically (e.g., infrastructure development related to oil and gas production) would be an irrevocable future loss (Bataille et al., 2015). Canadians would be the unfortunate ones to bear the brunt. Alternatively, Canada can assume a leadership role in decarbonization. Should global decarbonization become an eventuality, Canada would have positioned itself as a pioneer in technology associated with a low-carbon transition such as green transport technologies (Potvin et al., 2016).

Third, the methodological contributions of this dissertation have addressed two areas of research on scenario analysis. First, there is a need to integrate scenario studies by different developer teams to account for uncertainties more broadly. Integrating quantitative scenarios is easy because numerical values add up, whereas integrating qualitative scenarios is problematic because storylines (scenario narratives) do not necessarily add up. Hence, this lack of comparability among qualitative scenarios remains an obstacle that is worthy of further investigation. Presented in this thesis, the method for integrating qualitative scenarios using network analysis is a novel approach that can fill this gap (Chapter 5). Additionally, when the scenario elements are assessed as a network (i.e., examining the interconnections among scenario elements), different node centrality scores can be computed to identify which nodes (i.e., scenario elements) are more 'central' in the network. Nodes with high centrality scores tend to be highly connected, which can suggest a general consensus across multiple qualitative studies that these nodes are influential in affecting the overall system behaviour. Conventionally, selecting which scenario elements to incorporate into a model or scenario development process is done subjectively by getting participants in a scenario planning workshop to vote. However, there is an alternative method using network analysis that is more objective than a voting process as demonstrated in this dissertation.

The second methodological area addressed by this dissertation is multi-scale scenario analysis using CIB (Chapter 6). Many scenario frameworks addressing global environmental change require techniques for developing multi-scale scenarios that are consistent across scales.

Multi-scale scenario analysis is not only critical in climate change research, and by extension the SSPs, but also is also in other sectors such as agriculture and food security (i.e., the Representative Agricultural Pathways) and oceanic biodiversity and marine fisheries (i.e., the Oceanic System Pathways). The CIB analysis can be a versatile instrument in a 'scenario toolbox' that can be utilized by the research community to develop internally consistent scenarios across scales, to check the consistency of multi-scale scenarios, and to model the complex interactions of socioeconomic driving forces at different levels. The capability of CIB in multi-scale scenario analysis is demonstrated in Chapter 6.

7.4 Study Limitations

One of the limitations of this study is the lack of conjoint descriptors. For instance, when asked how the first variable influences the second variable, participants have expressed that the direction of the influence (either promoting or discouraging) may depend on an outcome of a third variable. For example, one participant in an interview indicated that the average income in Canada could be influenced by the development state of the Canadian economy (either decarbonized or not) and the global carbon intensity (either high or low). To elaborate, the fossil-fuelled Canadian economy in a world with a high level of carbon intensity could influence the national average income to be high. However, with all else being equal, the opposite effect (i.e., decreasing national average income) could be motivated in a world with a low level of carbon intensity instead. Currently, there is no clear guideline how to handle such a complex interdependent interaction. Further guidance is required on how to represent conjoint descriptors for CIB analysis; this could be future research.

Another challenge faced by the study participants is internalizing the different pathways of the scenario elements. For example, one participant commented that technology variables are too aggregated (too generalized) to usefully elicit impact judgment arising from (and impacting on) such variables. Not all technologies can influence other scenario elements in the same manner. As the scenario elements such as technology development in green freight transport are 'aggregated,' it forces participants to make heuristic guesses about what aggregated technology actually means. As a result, participants' interpretation of development pathways can differ. Nonetheless, this challenge is associated with the scenario development process in general. This study employs expert elicitation as a means to obtain cross-impact judgments for CIB analysis; each expert participant responds to a specific portion of the cross-impact matrix related to their respective expert domain, having no knowledge whatsoever of who the other expert participants are or what their responses were. Like the Delphi mode of inquiry, the process of eliciting impact judgments is designed to maintain the anonymity of the expert participants; therefore, the individual expert is not compelled to align his or her judgments with the others. While such a process of scenario development is preferred for compartmentalizing experts' judgement (i.e., no one expert can dominate the 'conversation'), there was an instance where one of the expert participants thought that the low development pathway for NETs is 'too high' by his or her standard, while others did not think so. This is despite the fact that all expert participants were provided with the same definitions and visualizations for mental 'calibration.' Although these expert's judgments were skewed to a particular scenario outcome, this issue was mitigated by CIB analysis using the bias correction feature as described in Chapter 6.

Evidently, the bias correction feature alone cannot mitigate issues regarding inaccurate raw judgements. As discussed in Chapter 6.4.2.2, regardless of any levels of carbon intensity in Canada, it will support high carbon intensity globally no matter what. The logic underlying such an interrelationship can be subjective and therefore contentious. Being human themselves, expert participants could mistakenly provide incorrect judgment scores, or they might be confused when internalizing what it meant by how a variable (or a factor) could be either 'promoting' or 'discouraging' another variable. Although expert participants also provided written comments that corroborated their judgment scores, the written comments could also be lost-in-translation. This challenging situation can be overcome by having two or more experts to respond to the same set of questionnaires. Alternatively, like the study by Schweizer and O'Neill (2014), two or more panels of expert participants could be sought. Schweizer and O'Neill obtained judgment scores of the global SSP matrix from two panels of expert (i.e. Panel A and Panel B). The objective of having multiple responses for the same set of influence judgments is to allow for comparison to identify the areas of conceptual agreement and disagreements among experts. This could be an improvement in future research.

7.5 Future Research Directions

The SSPs are a scenario framework for developing multi-scale scenarios for climate change research. The importance of multi-scale scenario analysis goes beyond global/regional/national analyses, as it is also critical for national/sub-national analyses where the developments at the sub-national level tend to vary quite significantly in large countries like Canada. Unfortunately, scenario studies in the Canadian context rarely examine the dynamic interplay between national and provincial development pathways. As Chapter 6 describes, the CI matrix is flexible and can be expanded to include elements relevant at the provincial levels. These can, in turn, be utilized to search for scenario configurations at the provincial level that are consistent with the national and global development pathways. For the future, this dissertation on developing globally linked internally consistent energy scenarios for Canada provides a framework for more detailed sub-national/sub-sectoral analyses. Incorporating socioeconomic and socio-technical driving forces operating at the provincial levels can offer more detailed analyses. For instance, provinces that are 'heavy' on mining, oil and gas operations may consider delving deeper into the economic viability of this sector under different global or national development pathways. Analyses at the provincial level could take different directions. For instance, a more populated province like Ontario may be more concerned with transportation, an important sub-sector of the energy system in Ontario.

7.6 Concluding Remarks

Overall, this dissertation underscores the usefulness of multi-scale scenario analysis in climate change research. In multi-scale scenario analysis, it is critical that scenarios developed for regional/local analyses be consistent across scales. But the definition of 'consistent' is contested, yet it is also been taken for granted. The disagreements over the meaning of cross-scale consistency distract from defining what should be the concern for the scientific community, which is cross-scale *inconsistency*. As this study has demonstrated, the CIB analysis can assess the consistency of scenarios across scales more systematically. The term 'consistent' as defined by Zurek and Henrichs (2007) can be reinterpreted as 'same outcomes across scales.' Additionally, the term 'consistent' as defined in Zurek and Henrichs (2007) should not be confused with the term scenario consistency across scales which describes the interrelationships among scenarios at different scales. More importantly, the definition of 'inconsistent' scenarios must be reserved for distinguishing 'bad' or implausible scenarios.

Methodological innovations for scenario analysis were developed and applied to complete this study. First, network analysis was deployed to construct a multi-study network to examine how different scenario studies on Canada's energy futures interface. Even though these studies were conducted by different author teams and sometimes in parallel, these studies have scenario elements that are common. Although the study scopes might be different, they also overlap in some respects. Visualizing how different scenario elements are interconnected in a multi-study network presents the opportunity to select candidate scenario elements for CIB analysis more objectively. Second, scenarios for Canada's energy futures were developed in the context of global SSPs. This study was an example of using a CIB technique for multi-scale scenario analysis by connecting Canadian extensions to global SSPs. The Canadian extension study can be linked to the global SSPs by re-specifying a new set of elements that are relevant for national level analysis. The extension study also makes use of and expands the global SSP CI matrix developed by Schweizer and O'Neill (2014). Two counterintuitive assumptions for which Canada decarbonizes in a carbonized world and Canada remains carbonized in a decarbonized world were tested for internal consistency; the findings show particular counterintuitive cases that are consistent across scales and do not have internal logic problems. These counterintuitive scenarios suggest that global carbon intensity outcomes do not set the agenda for Canada to be decarbonized or to remain carbonized.

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Appendix A: SSP Scenario Narratives

Source: O’Neill et al. (2017)

SSP1: Sustainability—Taking the green road

The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries. Increasing evidence of and accounting for the social, cultural, and economic costs of environmental degradation and inequality drive this shift. Management of the global commons slowly improves, facilitated by increasingly effective and persistent cooperation and collaboration of local, national, and international organizations and institutions, the private sector, and civil society. Educational and health investments accelerate the demographic transition, leading to a relatively low population. Beginning with current high-income countries, the emphasis on economic growth shifts toward a broader emphasis on human well-being, even at the expense of somewhat slower economic growth over the longer term. Driven by an increasing commitment to achieving development goals, inequality is reduced both across and within countries. Investment in environmental technology and changes in tax structures lead to improved resource efficiency, reducing overall energy and resource use and improving environmental conditions over the longer term. Increased investment, financial incentives and changing perceptions make renewable energy more attractive. Consumption is oriented toward low material growth and lower resource and energy intensity. The combination of directed development of environmentally friendly technologies, a favorable outlook for renewable energy, institutions that can facilitate international cooperation, and relatively low energy demand results in relatively low challenges to mitigation. At the same time, the improvements in human well-being, along with strong and flexible global, regional, and national institutions imply low challenges to adaptation.

SSP2: Middle of the road

The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceeds unevenly, with some countries making relatively good progress while others fall short of expectations. Most economies are politically stable. Globally connected markets function imperfectly. Global and national institutions work toward but make slow progress in achieving sustainable development goals, including improved living conditions and access to education, safe water, and health care. Technological development proceeds apace, but without fundamental breakthroughs. Environmental systems experience degradation, although there are some improvements and overall the intensity of resource and energy use declines. Even though fossil fuel dependency decreases slowly, there is no reluctance to use unconventional fossil resources. Global population growth is moderate and levels off in the second half of the century as a consequence of completion of the demographic transition. However, education investments are not high enough to accelerate the transition to low fertility rates in low-income countries and to rapidly slow population growth. This growth, along with income inequality that persists or improves only slowly, continuing societal stratification, and limited social cohesion, maintain challenges to reducing vulnerability to societal and environmental changes and constrain significant advances in sustainable development. These moderate development trends leave the world, on average, facing moderate challenges to mitigation and adaptation, but with significant heterogeneities across and within countries.

SSP3: Regional rivalry—A rocky road

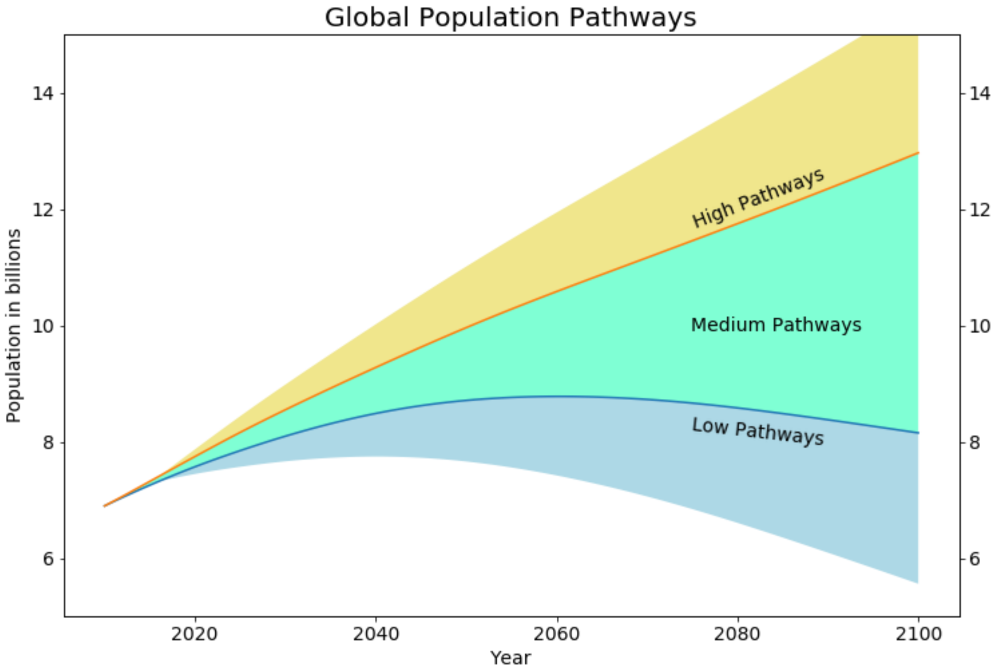
A resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or, at most, regional issues. This trend is reinforced by the limited number of comparatively weak global institutions, with uneven coordination and cooperation for addressing environmental and other global concerns. Policies shift over time to become increasingly oriented toward national and regional security issues, including barriers to trade, particularly in the energy resource and agricultural markets. Countries focus on achieving energy and food security goals within their own regions at the expense of broader-based development, and in several regions move toward more authoritarian forms of government with highly regulated economies. Investments in education and technological development decline. Economic development is slow, consumption is material-intensive, and inequalities persist or worsen over time, especially in developing countries. There are pockets of extreme poverty alongside pockets of moderate wealth, with many countries struggling to maintain living standards and provide access to safe water, improved sanitation, and health care for disadvantaged populations. A low international priority for addressing environmental concerns leads to strong environmental degradation in some regions. The combination of impeded development and limited environmental concern results in poor progress toward sustainability. Population growth is low in industrialized and high in developing countries. Growing resource *intensity and fossil fuel dependency along with difficulty in achieving international cooperation and slow technological change imply high challenges to mitigation. The limited progress on human development, slow income growth, and lack of effective institutions, especially those that can act across regions, implies high challenges to adaptation for many groups in all regions.*

SSP4: Inequality—A road divided
Highly unequal investments in human capital, combined with increasing disparities in economic opportunity and political power, lead to increasing inequalities and stratification both across and within countries. Over time, a gap widens between an internationally connected society that is well educated and contributes to knowledge- and capital-intensive sectors of the global economy, and a fragmented collection of lower-income, poorly educated societies that work in a labor intensive, low-tech economy. Power becomes more concentrated in a relatively small political and business elite, even in democratic societies, while vulnerable groups have little representation in national and global institutions. Economic growth is moderate in industrialized and middle-income countries, while low income countries lag behind, in many cases struggling to provide adequate access to water, sanitation and health care for the poor. Social cohesion degrades and conflict and unrest become increasingly common. Technology development is high in the high-tech economy and sectors. Uncertainty in the fossil fuel markets lead to underinvestment in new resources in many regions of the world. Energy companies hedge against price fluctuations partly through diversifying their energy sources, with investments in both carbon-intensive fuels like coal and unconventional oil, but also low-carbon energy sources. Environmental policies focus on local issues around middle and high income areas. The combination of some development of low carbon supply options and expertise, and a well-integrated international political and business class capable of acting quickly and decisively, implies low challenges to mitigation. Challenges to adaptation are high for the substantial proportions of populations at low levels of development and with limited access to effective institutions for coping with economic or environmental stresses.

SSP5: Fossil-fueled development—Taking the highway
Driven by the economic success of industrialized and emerging economies, this world places increasing faith in competitive markets, innovation and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development. Global markets are increasingly integrated, with interventions focused on maintaining competition and removing institutional barriers to the participation of disadvantaged population groups. There are also strong investments in health, education, and institutions to enhance human and social capital. At the same time, the push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy intensive lifestyles around the world. All these factors lead to rapid growth of the global economy. There is faith in the ability to effectively manage social and ecological systems, including by geo-engineering if necessary. While local environmental impacts are addressed effectively by technological solutions, there is relatively little effort to avoid potential global environmental impacts due to a perceived tradeoff with progress on economic development. Global population peaks and declines in the 21st century. Though fertility declines rapidly in developing countries, fertility levels in high income countries are relatively high (at or above replacement level) due to optimistic economic outlooks. International mobility is increased by gradually opening up labor markets as income disparities decrease. The strong reliance on fossil fuels and the lack of global environmental concern result in potentially high challenges to mitigation. The attainment of human development goals, robust economic growth, and highly engineered infrastructure results in relatively low challenges to adaptation to any potential climate change for all but a few.

Appendix B: Development Pathways

SD-01 Population (Global)



Global population is defined as the total number of people living in the world. The range of pathways through 2100 is as follows[19]:

A: High Pathways	Population > 13 billion people by 2100
B: Medium Pathways	Population 8-13 billion people by 2100
C: Low Pathways	Population < 8 billion people by 2100

Note: When providing the answer about how these pathways may be influenced, feel free to consider pathways of related but not explicitly provided variables. For example, each pathway for global population may contain implications for the pathway of average global fertility.

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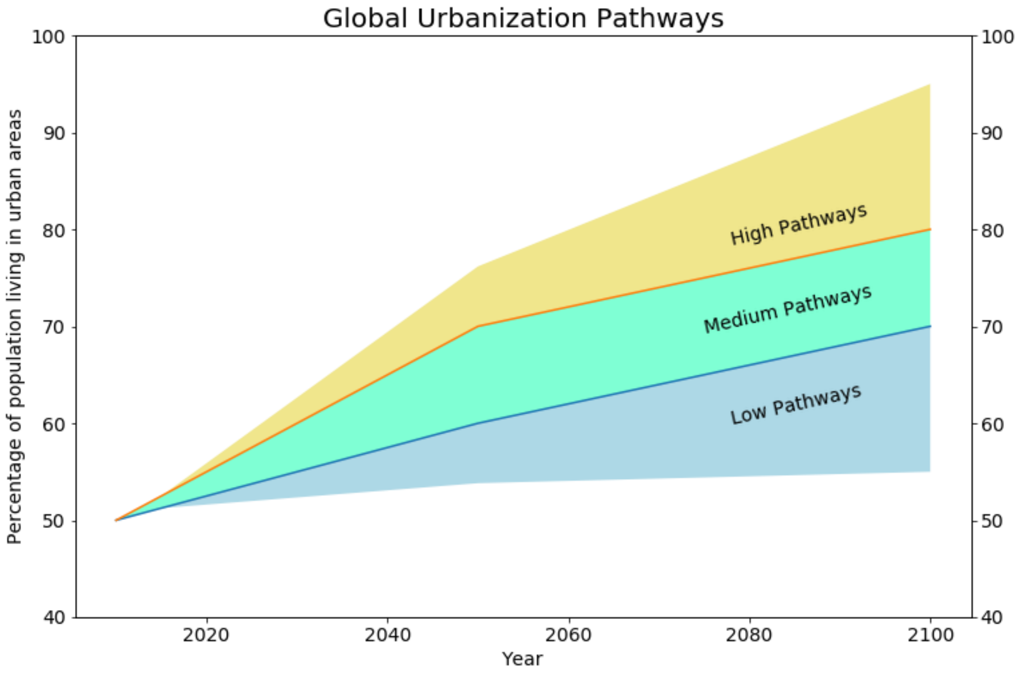
[19] The description of these pathways is based upon UN projections in the study by Schweizer and O'Neill (2014), Systematic construction of global socioeconomic pathways using internally consistent element combinations. Climatic Change, 122(3), 431-445

SD-02 Urbanization (Global)



Urbanization is defined as the percentage of global population living in urban areas. Currently, about 50% of global population is urban. The description of pathways through 2100 is as follows[20]:

A: High Pathways	Urbanization occurs rapidly, reaching > 70% by 2050 and > 80% by 2100
B: Medium Pathways	Urbanization occurs at a moderate pace, reaching 60% - 70% by 2050 and 70% - 80% by 2100
C: Low Pathways	Urbanization occurs slowly and could stall or reverse in some regions, reaching < 60% by 2050 and < 70% by 2100

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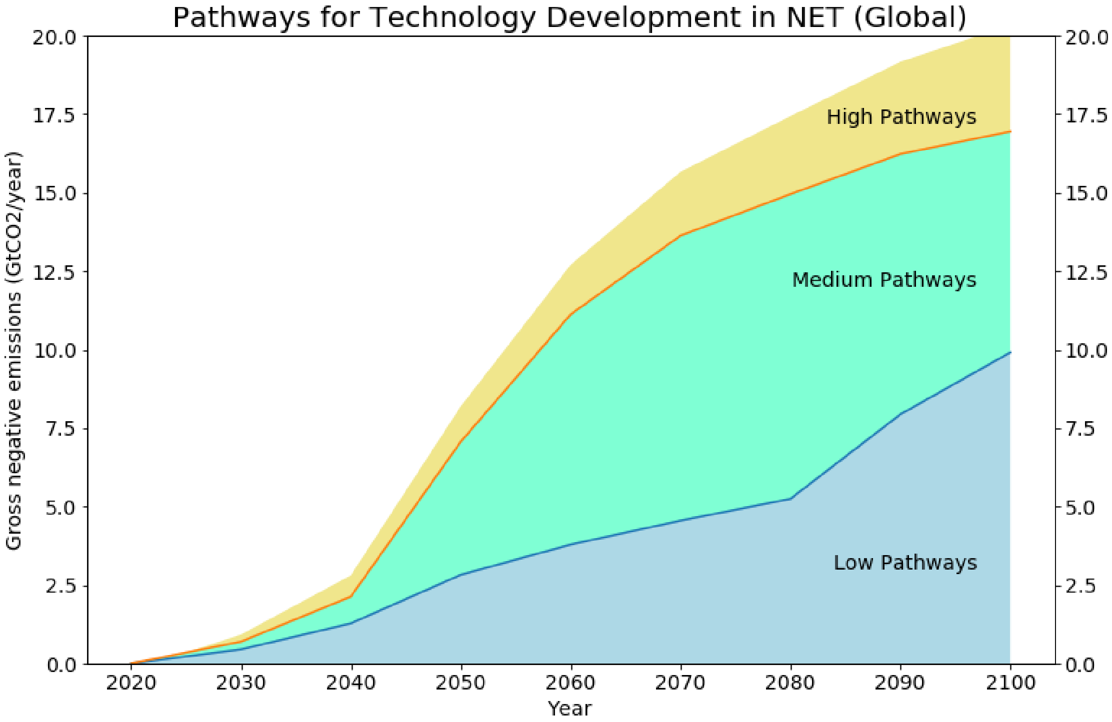
[20] The description of these pathways was informed by projections by the UN and IIASA and are taken from Schweizer and O'Neill (2014), Systematic construction of global socioeconomic pathways using internally consistent element combinations. Climatic Change, 122(3), 431-445.

SD-03 Tech Development in Negative Emissions Technologies (NET) (Global)



Negative emissions are defined as “intentional human efforts to remove CO2 emissions from the atmosphere” (Minx et al. 2018)[21]. Negative emissions technologies (NET) facilitate this effort. The range of pathways is as follows.

A: High Pathways	Negative emissions are > 15 GtCO2 per year by 2100, which is approximately 50% of the world emissions in 2015 (World emission total: 32.3GtCO2/year[22])
B: Medium Pathways	Negative emissions are 10-15 GtCO2 per year by 2100
C: Low Pathways	Negative emissions are < 10 GtCO2 per year by 2100, which is approximately double the amount of emissions from the USA and Canada in 2015 (Annex II North America emissions totaled 5.5GtCO2/year)

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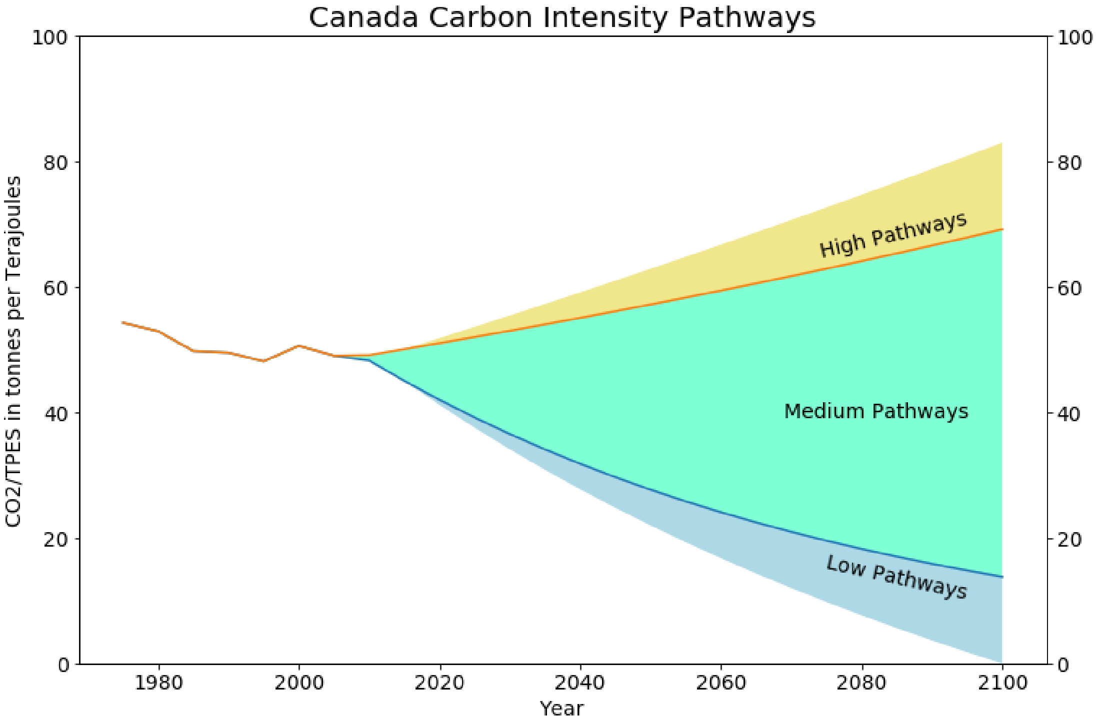
[21] Increases in gross negative emissions would mean more deployment of NET. Hence gross negative emissions are a proxy measure for technology development in NET. Gross negative emissions pathways are adapted from Minx et al. (2018). Negative emissions—Part 1: Research landscape and synthesis. Environmental Research Letters, 13(6), 063001.

[22] Source: IEA (2017) CO2 Emissions from fuel combustion – Highlights. Retrieved from https://www.iea.org/publications/freepublications/publication/CO2EmissionsfromFuelCombustionHighlights2017.pdf

SD-04 Carbon Intensity (Canada)



Average carbon intensity is defined as the ratio of CO2 emissions (metric tons) to total primary energy consumed (TJ). The range for pathways through 2100 for Canada is defined as follows.

A: High Pathways	Increasing exponentially by more than 0.38% per year[23]. High pathways reverse historical reductions observed since the late 1970s.
B: Medium Pathways	In line with historical trends, carbon intensity fluctuates between +0.38% (growth) and -1.4% (decrease) per year. The overall long-term trend is decreasing slightly.
C: Low Pathways	Decreasing exponentially by more than 1.4% per year. Low pathways decrease carbon intensity faster than the historical trend.

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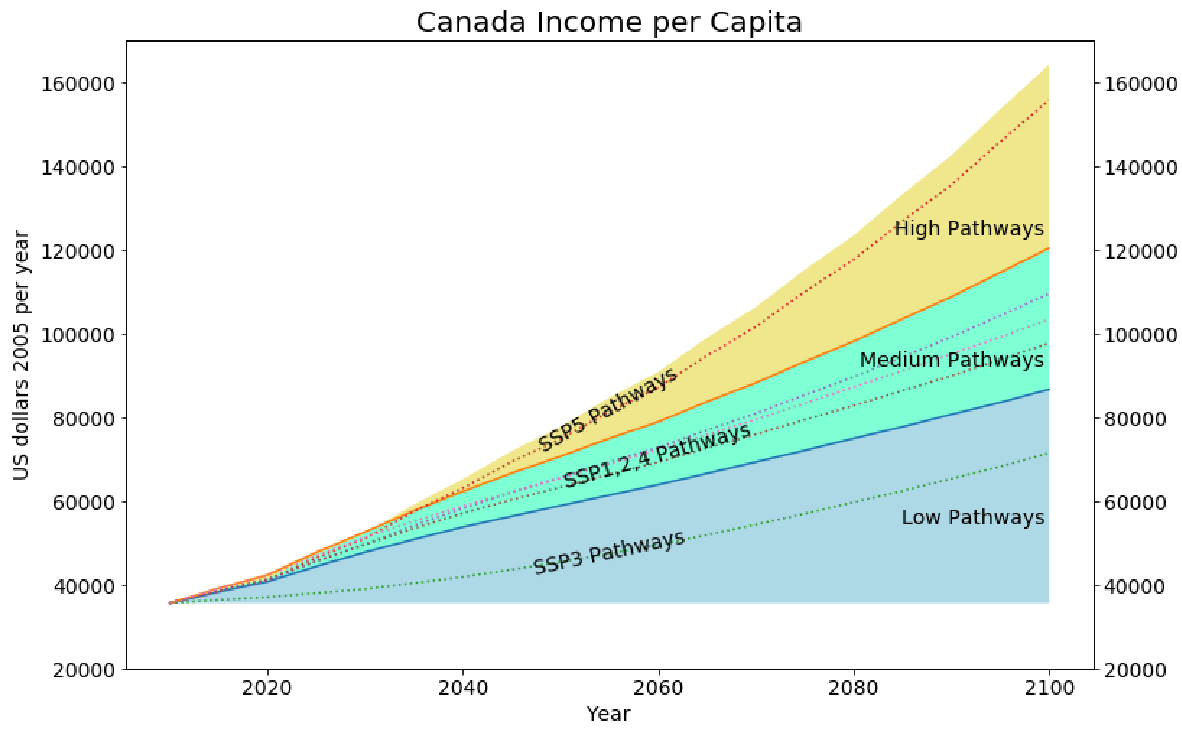
[23] Ranges for these pathways are based upon minimum and maximum annualized growth rates observed over 10 – 20 year periods. Country data was retrieved originally from IEA; pathways are informed by Schweizer and O'Neill (2014), Systematic construction of global socioeconomic pathways using internally consistent element combinations. Climatic Change, 122(3), 431-445.

SD-05 Income per capita (Canada)



The income per capita is the ratio of GDP and the total projected population in Canada. Alternative pathways[24] for the income per capita are described as follows.

A: High Pathways	Increasing exponentially reaching more US$ 120,000/year by 2100 (or equivalent to a rate of increase of 2.4% per year).
B: Medium Pathways	Increasing moderately reaching between US$ 86,000/year to US$120,000/year by 2100 (or equivalent to a rate of increase between 1.6% - 2.4% per year)
C: Low Pathways	Increasing weakly reaching at best less than US$86,000/year by 2100 (or equivalent to the rate of increase of 1.6% per year)

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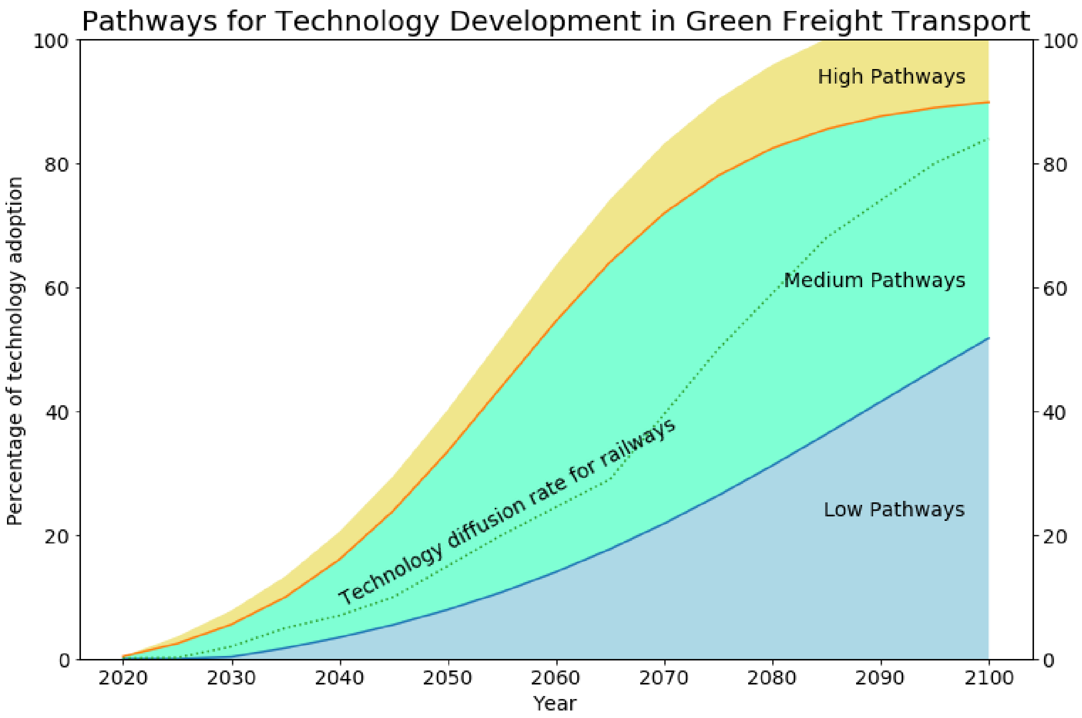
[24] Pathways are informed by GDP and Population projections for Canada from the Shared Socioeconomic Pathways (SSP) database hosted by IIASA. Boundaries between high, medium, and low pathways respectively were set by midpoints between SSP5 (“Fossil-fueled development”), SSP2 (“Middle of the Road”), and SSP3 (“Regional Rivalry”) respectively. For more information about SSPs, see Riahi et al. (2017) The Shared Socioeconomic Pathways and their energy, land-use, and greenhouse gas emissions implications: An overview. Global Environmental Change, 42, 153-168. The SSP database can be accessed from https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about.

SD-06 Technology Development in Green Freight Transport (Canada)



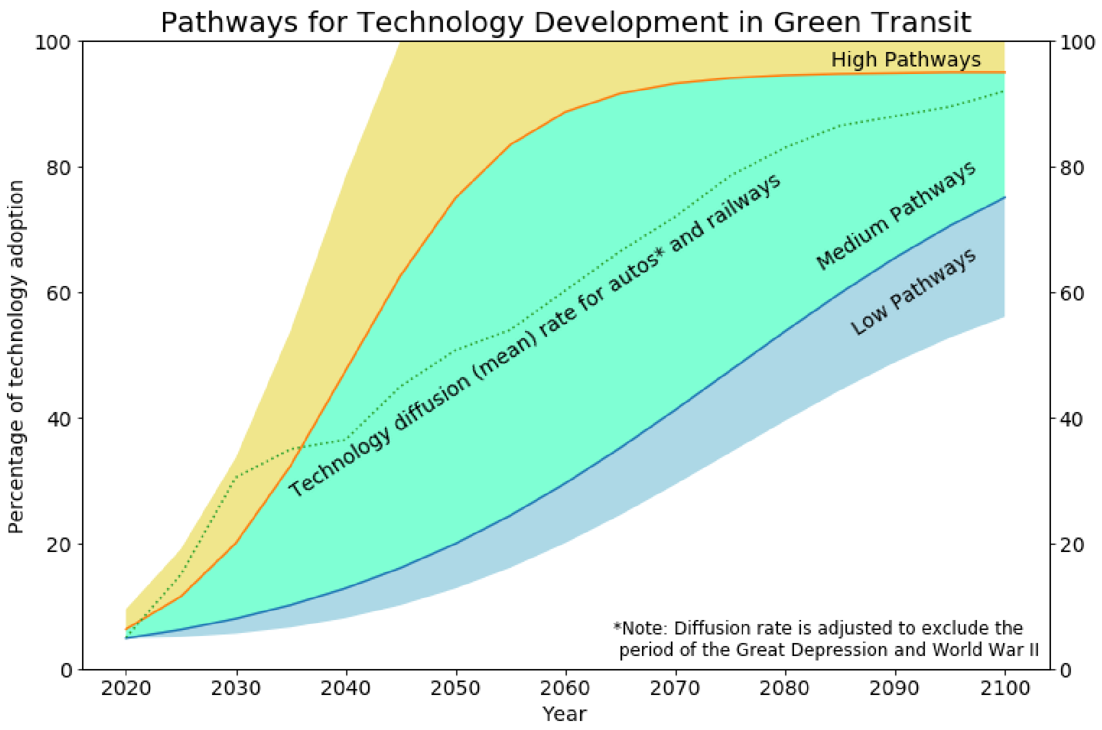
Technology development refers to how quickly technology is innovated, diffused and eventually adopted. Technology in green freight transport refers to low carbon means for transporting freight from producers to consumers. Examples include alternative fuels (e.g. hydrogen, natural gas) for heavy freight, electric trains, and electric trucks. Technology development could be represented by technology diffusion rate S-curves—for example, railways took about 100 years to be fully adopted in the US (Sovacool, 2016)[25]. Alternative pathways for technology development in green freight transport are as follows.

A: High pathways	Technology innovation starts immediately, with full technology adoption in Canada realized as early as 2070. Technology is adopted at a rate faster than the historical trend for railways, possibly due to fuel switching.
B: Medium pathways	Technology innovation is modest or delayed until 2030, and uptake is at the historical diffusion rate for railways. By 2100, half or more of freight transport in Canada is green.
C: Low pathways	Technology innovation is delayed after 2030, and uptake is slower than the historical diffusion rate for railways. By 2100, less than half of freight transport in Canada is green.

---

[25] Sovacool, B. K. (2016). How long will it take? Conceptualizing the temporal dynamics of energy transitions. Energy Research & Social Science, 13, 202-215. Railways chosen for comparison, since investments in infrastructure for electric trains may be comparable to historical investments in new railways. The high and low development pathways were developed through consultation with the in-house expert.

SD-07 Technology Development in Green Transit (Canada)



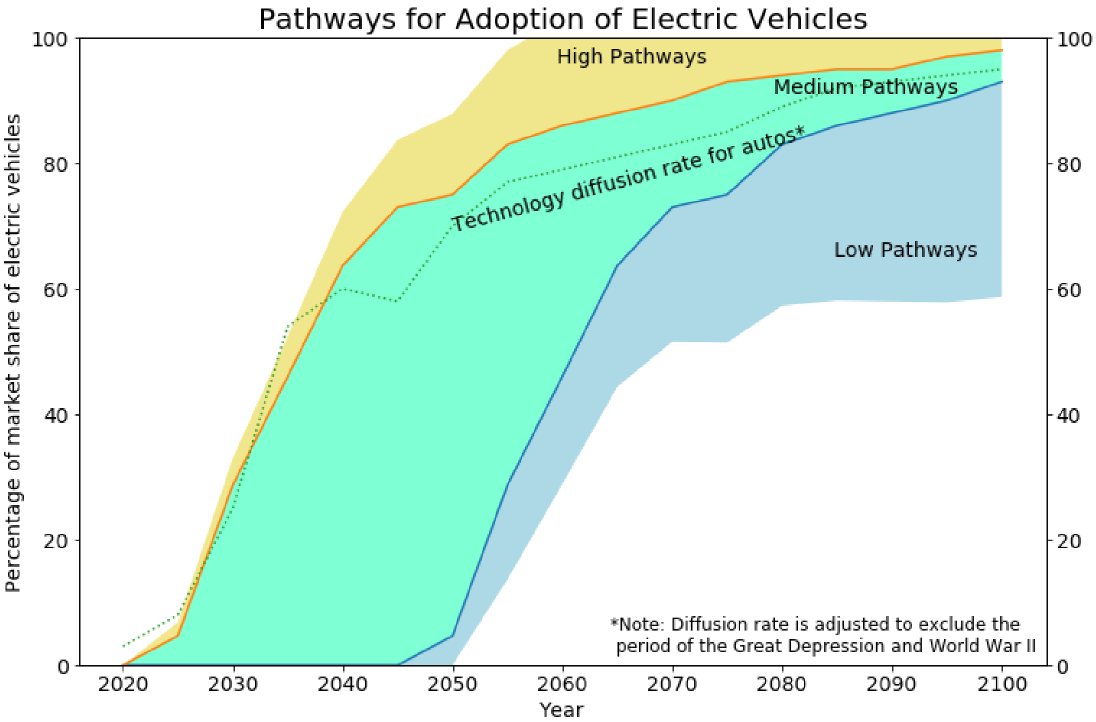
Green transit refers to low-carbon and efficient public transportation modes (e.g. electric buses and trains). Alternative pathways[26] for technology development in green transit are as follows.

A: High pathways	Technology uptake through 2050 is very fast, consistent with a sustained take-up rate of early adopters. Full technology adoption could materialize in Canada before 2060.
B: Medium pathways	Technology uptake corresponds with the historical diffusion rate of autos and railways. By 2080, more than half of Canadian transit systems are green.
C: Low pathways	Technology uptake is slower than the historical diffusion rate of autos and railways. By 2100, at best, 75% of Canadian transit systems are green.

---

[26] In the figure, the reference pathway is the average of the technology diffusion rate for railways and personal automobiles. These technologies were chosen for comparison because some communities may need to simply green existing fleets, while others may need to build new infrastructure, such as light rail. The railway diffusion rate is from Sovacool, B.K. (2016). How long will it take? Conceptualizing the temporal dynamics of energy transitions. Energy Research & Social Science, 13, 202-215. The automobile diffusion rate rate has been adjusted to exclude the Great Depression and World War II, as these events flattened household consumption of automobiles.

SD-08 Adoption of Electric Vehicles (EVs) (Canada)



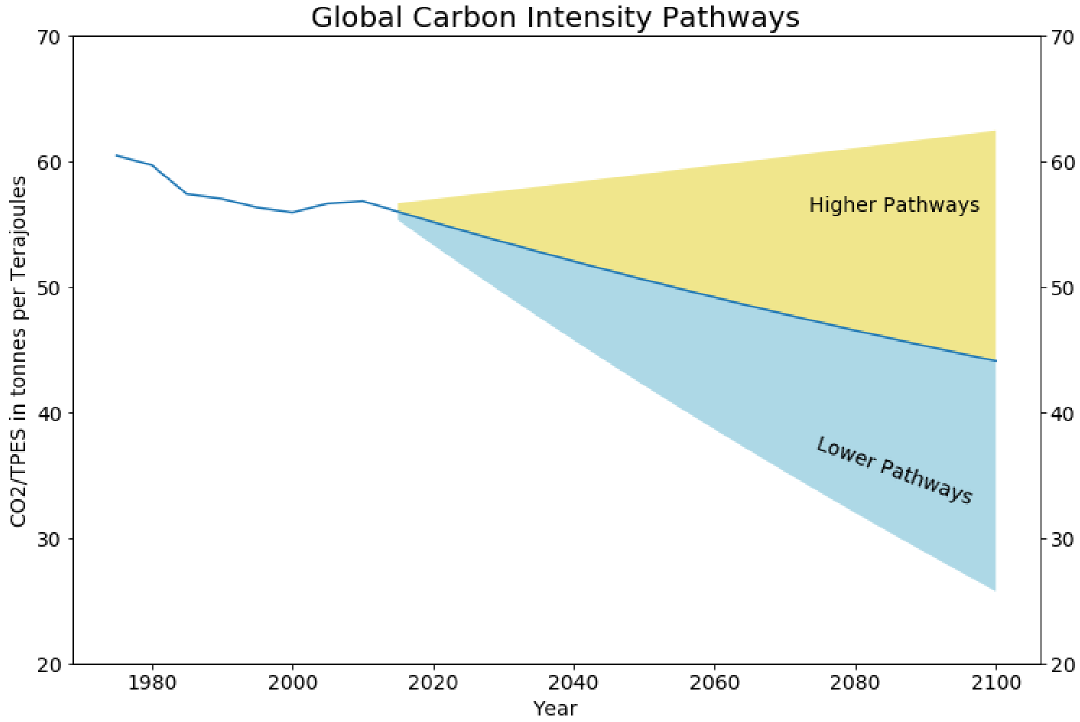
The adoption of electric vehicles (EVs) refers to both privately owned vehicles and fleets. It is measured by the percentage of market share of electric-powered light-duty passenger vehicles and excludes public transit (buses, trams, etc.). Alternative pathways[27] through 2100 for Canada are defined as follows.

A: High Pathways	Market shares of EVs increase drastically from 2020. Market penetration of 80% would be achieved **by 2050**. High pathways reflect slightly faster diffusion rates than historically observed for auto technology.
B: Medium Pathways	Market shares of EVs increase at a rate consistent with the historical trend for auto technology diffusion from 2020 – 2050. Market penetration of 80% would be achieved **after 2050 but before 2075**.
C: Low Pathways	Low pathways maintain the historical diffusion rate of automobiles, but uptake is significantly delayed, possibly because conventional autos are perceived as more convenient or cost-effective. Market shares of EVs do not increase until after 2050, with market penetration of 80% **after 2075**.

---

[27] Pathways are informed by EV demand projections and historical diffusion rates for automobiles. Demand projections are adapted from the report, Pathways to Deep Decarbonization in Canada (Bataille et al. 2015). Diffusion rates for automobiles are adapted from Cox and Alm (2008), where adjustments were made to exclude the Great Depression and World War II. See Bataille, C., Sawyer, D., & Melton, N. (2015). Pathways to deep decarbonization in Canada. Sustainable Development Solutions Network.

SD-09 Carbon Intensity (Global)



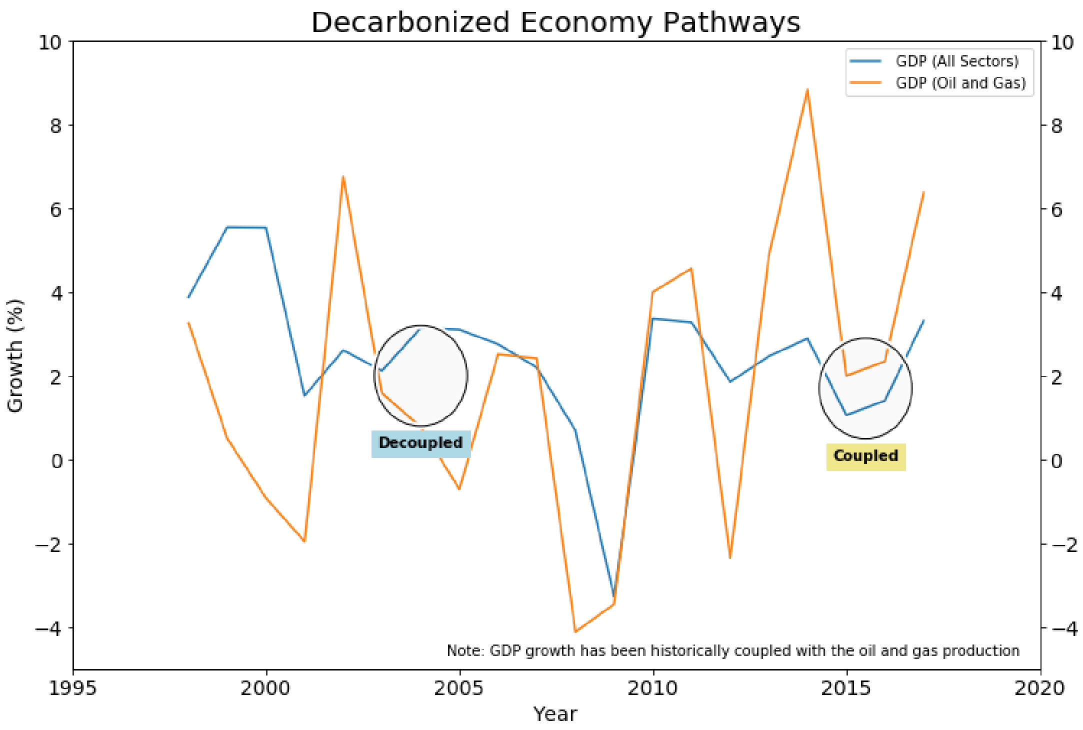
Average carbon intensity is defined as the ratio of CO2 emissions (metric tons) to total primary energy consumed (TJ). The range of pathways through 2100 is as follows[28]:

A: High Pathways	Decreasing exponentially by < 0.3%
B: Low Pathways	Decreasing exponentially by > 0.3%

---

[28] Ranges for these pathways are based upon minimum and maximum annualized growth rates observed over 10 – 20-year periods. The description of these pathways is informed by Schweizer and O'Neill (2014), Systematic construction of global socioeconomic pathways using internally consistent element combinations. Climatic Change, 122(3), 431-445.

SD-10 Decarbonized Economy (Canada)



The decarbonized economy refers to how "coupled" the Canadian economy is to the fossil fuel sector. The figure shows the historical (1997-2017) GDP[29] growth trend in all sectors and in the oil and gas sector (excluding mining and quarrying). Whether Canada's economy is decarbonized or not is represented in the pathways qualitatively as follows.

A: The economy is 'coupled' to the fossil fuel sector	Canadian GDP growth moves in tandem with the fossil fuel sector, which indicates that Canadian GDP is 'coupled' to the growth in the fossil fuel (oil and gas) sector. This trend has been observed since 2006.
B: The economy is 'decoupled' from the fossil fuel sector	Canadian GDP growth is independent from the fossil fuel sector, which indicates that Canadian GDP is 'decoupled' from growth in the fossil fuel sector. Canadian GDP may continue to grow despite reversals in the fossil fuel sector. Based on data available, such trends were observed over the periods 1997-2000 and 2003-2006.

---

[29] Data on GDP by industrial sector were retrieved from Statistics Canada (https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3610043402). The oil and gas sector alone contributed to 6% of total GDP in 2017. Together with mining and quarrying, this industrial sector is the third largest industrial sector in Canada since 1997 (8.4% of total GDP) behind real estate (13% of total GDP) and manufacturing (10.3% of total GDP).

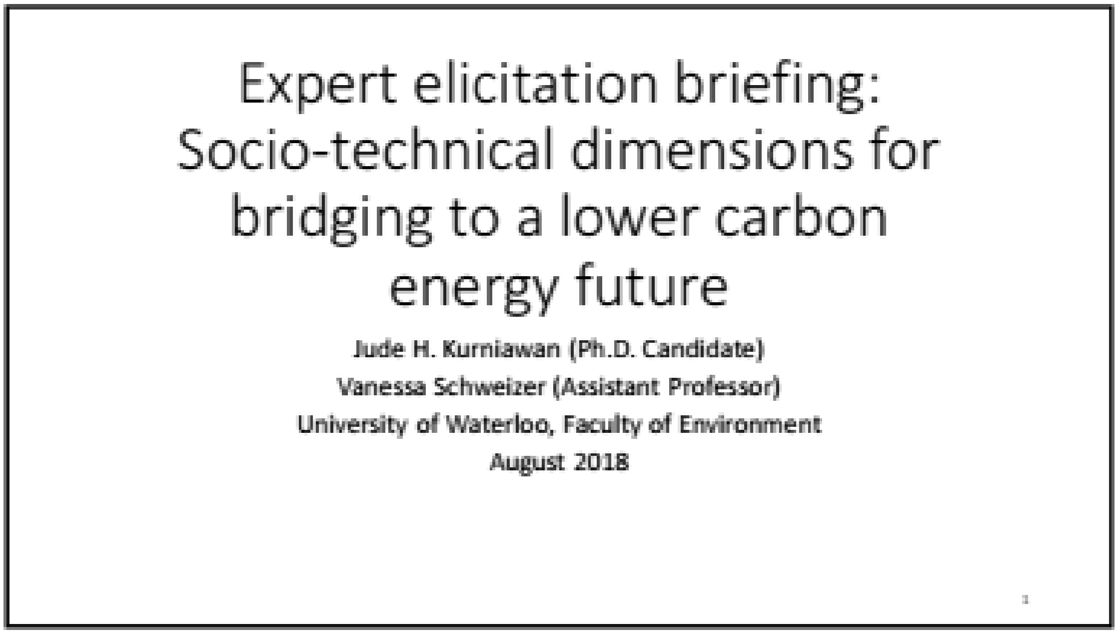
Appendix C: Narrative Interpretations for CIB Analysis

PART 1: List of Expert Participants

An invitation email was sent to individual expert participant at least two weeks before the survey. They were given a choice to complete the questionnaire on their own or in an interview setting (face-to-face or via Skype). All participants chose to complete the questionnaire in an interview setting.

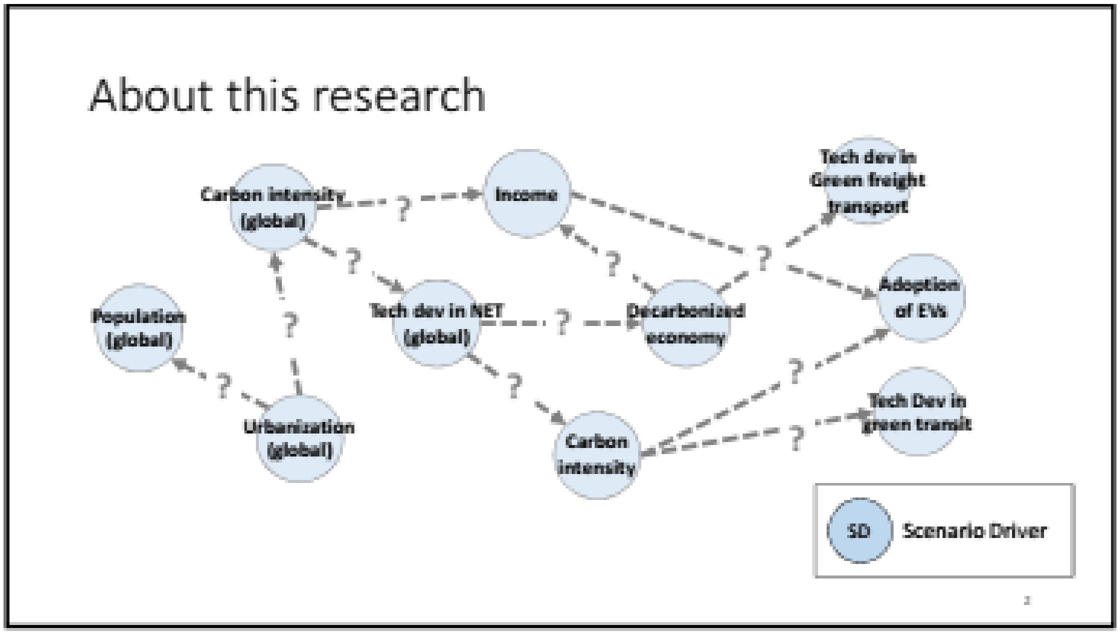
Ideally an aggregate list of all expert participants and their affiliations would be disclosed in this type of study. However, due to the small number of participants, participant names will not be disclosed to preserve confidentiality

Within the interview, experts were first briefed about the project. The purpose of the briefing is to provide information for how they can distinguish direct and indirect influences. The slide used in the briefing is shown below:



Expert elicitation briefing:
Socio-technical dimensions for bridging to a lower carbon energy future

Jude H. Kurniawan (Ph.D. Candidate)
Vanessa Schweizer (Assistant Professor)
University of Waterloo, Faculty of Environment
August 2018



About this research

Carbon intensity (global)

Income

Tech dev in Green freight transport

Population (global)

Tech dev in NET (global)

Decarbonized economy

Adoption of EVs

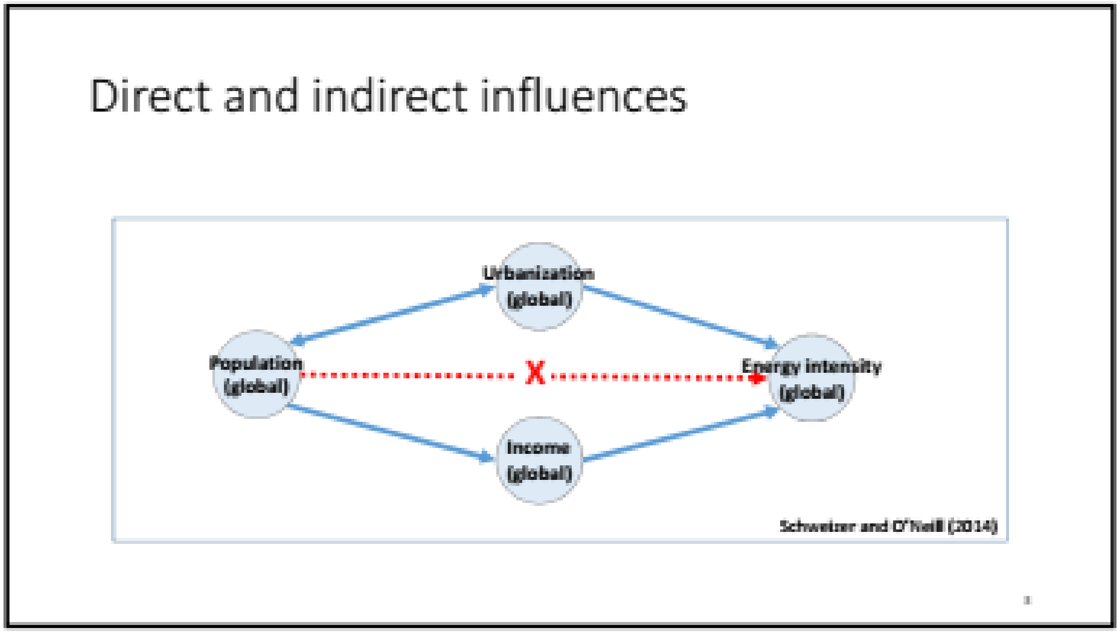
Urbanization (global)

Carbon intensity

Tech Dev in green transit

?

SD Scenario Driver



Direct and indirect influences

Urbanization (global)

Population (global)

X

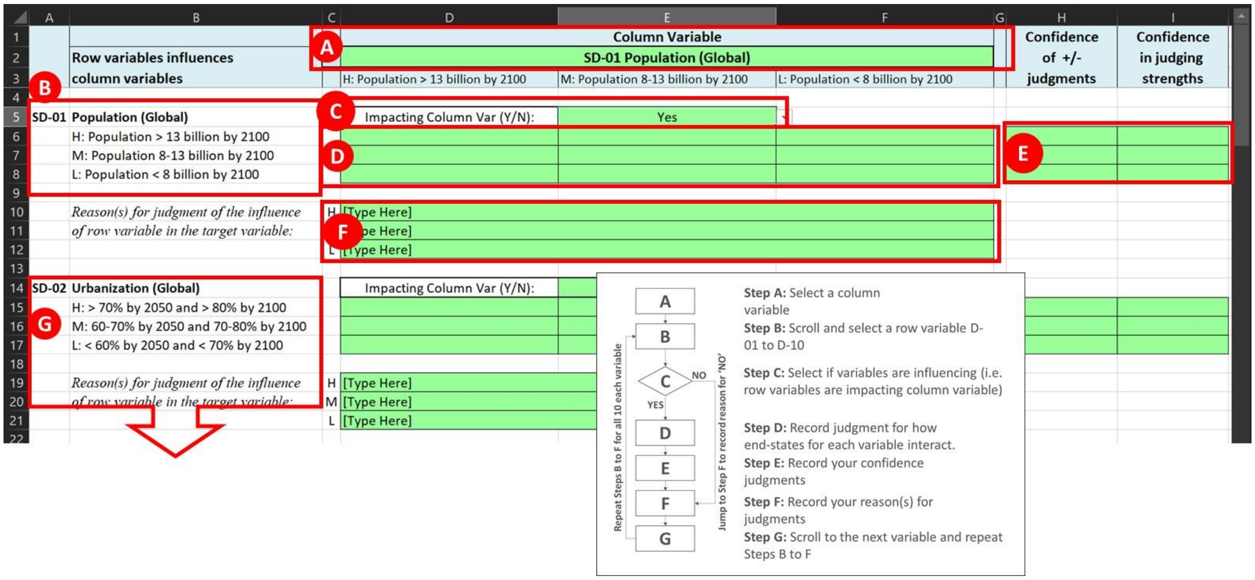
Energy intensity (global)

Income (global)

Schweizer and O'Neill (2014)

PART 2: Elicitation Instruments and Protocols

The task of completing the questionnaire is divided into 7 Steps (A to G) as shown below.


Row variables influences column variables

Column Variable

SD-01 Population (Global)

H: Population > 13 billion by 2100

M: Population 8-13 billion by 2100

L: Population < 8 billion by 2100

Confidence of +/- judgments

Confidence in judging strengths

SD-01 Population (Global)
H: Population > 13 billion by 2100
M: Population 8-13 billion by 2100
L: Population < 8 billion by 2100

Impacting Column Var (Y/N): Yes

Reason(s) for judgment of the influence of row variable in the target variable:
H [Type Here]
M [Type Here]
L [Type Here]

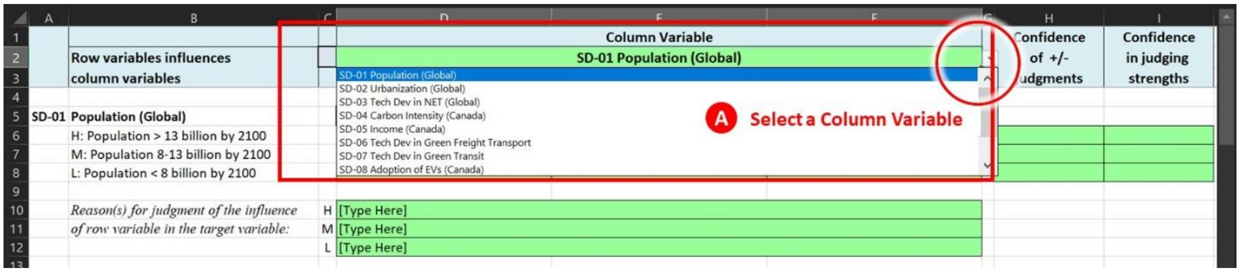
SD-02 Urbanization (Global)
H: > 70% by 2050 and > 80% by 2100
M: 60-70% by 2050 and 70-80% by 2100
L: < 60% by 2050 and < 70% by 2100

Impacting Column Var (Y/N):

Reason(s) for judgment of the influence of row variable in the target variable:
H [Type Here]
M [Type Here]
L [Type Here]

Step A: Select a column variable
Step B: Scroll and select a row variable D-01 to D-10
Step C: Select if variables are influencing (i.e. row variables are impacting column variable)
Step D: Record judgment for how end-states for each variable interact.
Step E: Record your confidence judgments
Step F: Record your reason(s) for judgments
Step G: Scroll to the next variable and repeat Steps B to F

A column variable (Step A) would already be assigned to the individual expert based on their expertise. Here, they were asked if they were comfortable to provide the response of the state variable.


Row variables influences column variables

Column Variable

SD-01 Population (Global)

SD-01 Population (Global)
SD-02 Urbanization (Global)
SD-03 Tech Dev in NET (Global)
SD-04 Carbon Intensity (Canada)
SD-05 Income (Canada)
SD-06 Tech Dev in Green Freight Transport
SD-07 Tech Dev in Green Transit
SD-08 Adoption of EVs (Canada)

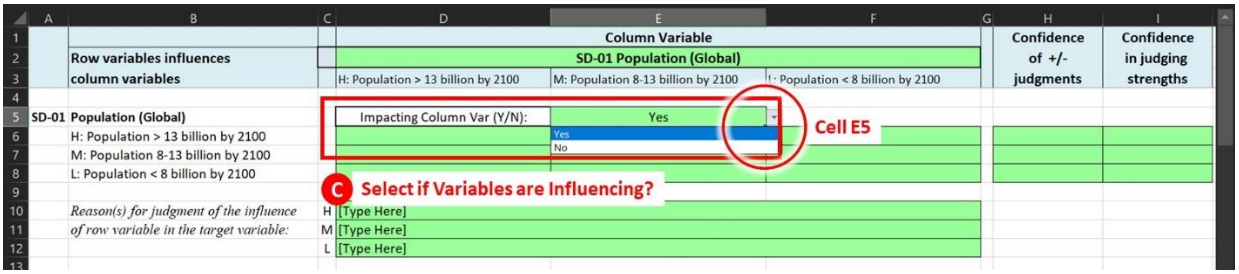
Confidence of +/- judgments

Confidence in judging strengths

SD-01 Population (Global)
H: Population > 13 billion by 2100
M: Population 8-13 billion by 2100
L: Population < 8 billion by 2100

Reason(s) for judgment of the influence of row variable in the target variable:
H [Type Here]
M [Type Here]
L [Type Here]

Row variables are labelled as SD-01 to SD-10 (Step B). For each variable, there are 2 or 3 end-states indicating low, medium and high pathways. The first question asked would be their opinion about how the row variable could be impacting SD-01 as the column variable (see below). This is indicated by selecting YES or NO answer (Step C). For NO answers, the participants were asked to move on to the next row variable.


Row variables influences column variables

Column Variable

SD-01 Population (Global)

H: Population > 13 billion by 2100

M: Population 8-13 billion by 2100

L: Population < 8 billion by 2100

Confidence of +/- judgments

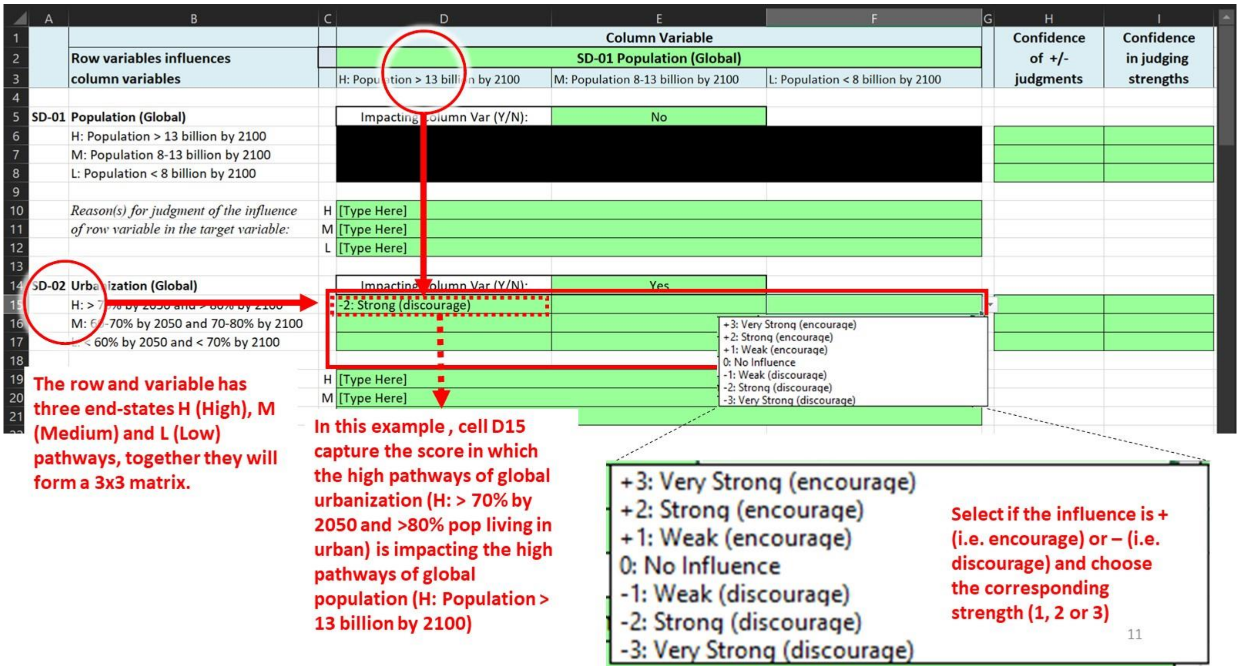
Confidence in judging strengths

SD-01 Population (Global)
H: Population > 13 billion by 2100
M: Population 8-13 billion by 2100
L: Population < 8 billion by 2100

Impacting Column Var (Y/N): Yes
Yes
No

Reason(s) for judgment of the influence of row variable in the target variable:
H [Type Here]
M [Type Here]
L [Type Here]

If the answer is YES, the participants would consider the end-states of the row variable one at a time (e.g. H, M, L). They were asked how each end-state of the row variable directly influence the respective end-states of the column variable (Step D).



Row variables influences column variables

Column Variable

SD-01 Population (Global)

H: Popu tion > 13 bill n by 2100 | M: Population 8-13 billion by 2100 | L: Population < 8 billion by 2100

Confidence of +/- judgments

Confidence in judging strengths

SD-01 Population (Global)

H: Population > 13 billion by 2100

M: Population 8-13 billion by 2100

L: Population < 8 billion by 2100

Impacting olumn Var (Y/N): No

Reason(s) for judgment of the influence of row variable in the target variable:

H [Type Here]

M [Type Here]

L [Type Here]

SD-02 Urba ization (Global)

H: > 7

M: 6 -70% by 2050 and 70-80% by 2100

< 60% by 2050 and < 70% by 2100

Impacting olumn Var (Y/N): Yes

-2: Strong (discourage)

+3: Very Strong (encourage)
+2: Strong (encourage)
+1: Weak (encourage)
0: No Influence
-1: Weak (discourage)
-2: Strong (discourage)
-3: Very Strong (discourage)

H [Type Here]

M [Type Here]

The row and variable has three end-states H (High), M (Medium) and L (Low) pathways, together they will form a 3x3 matrix.

In this example , cell D15 capture the score in which the high pathways of global urbanization (H: > 70% by 2050 and >80% pop living in urban) is impacting the high pathways of global population (H: Population > 13 billion by 2100)

+3: Very Strong (encourage)
+2: Strong (encourage)
+1: Weak (encourage)
0: No Influence
-1: Weak (discourage)
-2: Strong (discourage)
-3: Very Strong (discourage)

Select if the influence is + (i.e. encourage) or – (i.e. discourage) and choose the corresponding strength (1, 2 or 3)

Definition of + and – (Encouraging, No Influence, Discouraging)

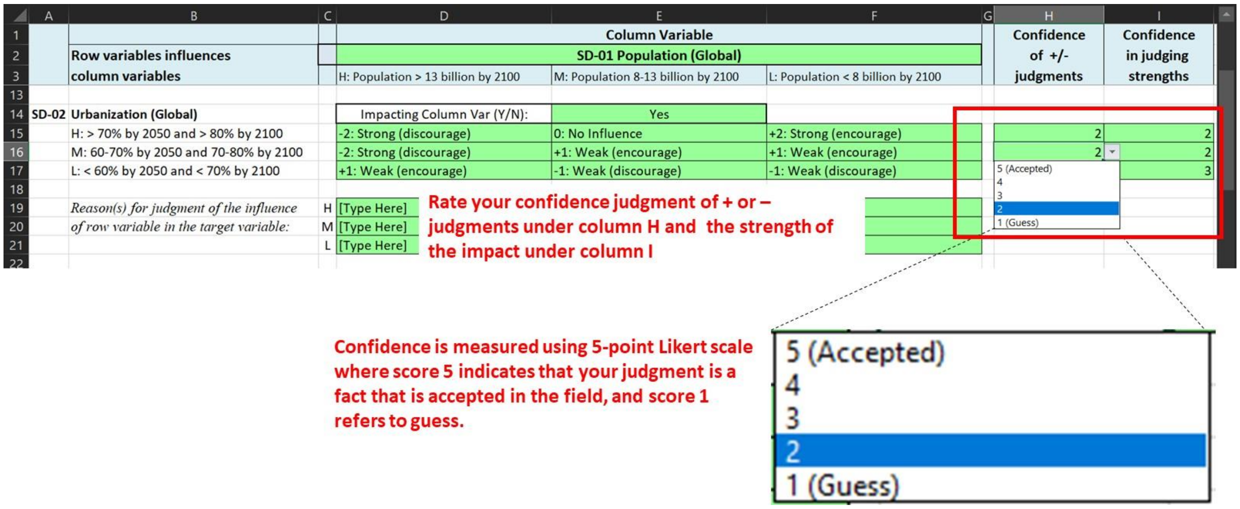
- Positive score (+) indicates that the end-state from the row variable is encouraging (or promoting or supporting) the end-state from the column variable.
- Negative score (-) indicates that the end-state from the row variable is discouraging (or inhibiting or hindering) the end-state from the column variable.
- ’Zero’ score (0) means the end-state is neither encouraging nor discouraging; in other words, the end-state in the row variable has no influence directly on the end-state in the column variable.

Definition of Weak, Strong and Very Strong influences (Ordinal value: +/- 1, 2, or 3)

- Weak (Ordinal value: +/- 1): The change in your likelihood judgment for the pathway of the column variable is > 0% but < 10% (for a regression model of the two variables, similar to r2 > 0 but r2 < 0.1)
- Strong (Ordinal value: +/- 2): The change in your likelihood judgment for the pathway of the column variable is between 10% - 30% (for a regression model of the two variables, similar to r2 > 0.1 but r2 < 0.3)
- Very Strong (Ordinal value: +/- 3): The change in your likelihood judgment for the pathway of the column variable is > 30% (for a regression model of the two variables, similar to r2 > 0.3)

The example above shows the Row variable SD-02 Urbanization (Global) is impacted by the Column variable SD-01, Population (Global). Each cell indicates how one end-state from the row variable is expected to directly impact one end-state of the target variable. For example, cell D15 is the influence score of -2, which suggests the high pathways for Urbanization (Global) (i.e. H: >70% by 2050 and >80% by 2100) would strongly discourage the high pathways of Population (Global) (i.e. H: Population > 13 billion by 2100).

After they recorded their influence judgments, they would record the confidence about their answers (Step E). There are two confidence scores shown on column H and I. Column H refers to the confidence in the direction or sign (+ or -) of direct influence judgements on the same row. Column I refers to the confidence in the strength or magnitude (score 0, 1, 2 or 3) of direct influence judgments on the same row.

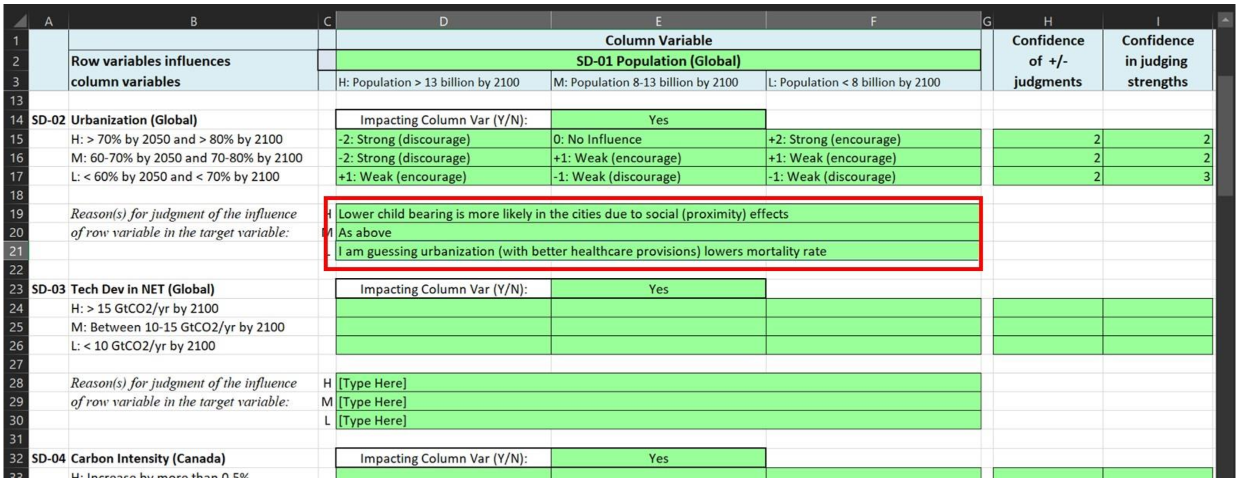


	A	B	C	D	E	F	G	H	I
1				**Column Variable**				**Confidence of +/- judgments**	**Confidence in judging strengths**
2		**Row variables influences column variables**		**SD-01 Population (Global)**					
3				H: Population > 13 billion by 2100	M: Population 8-13 billion by 2100	L: Population < 8 billion by 2100			
13									
14	**SD-02**	**Urbanization (Global)**		Impacting Column Var (Y/N):	Yes				
15		H: > 70% by 2050 and > 80% by 2100		-2: Strong (discourage)	0: No Influence	+2: Strong (encourage)		2	2
16		M: 60-70% by 2050 and 70-80% by 2100		-2: Strong (discourage)	+1: Weak (encourage)	+1: Weak (encourage)		2	2
17		L: < 60% by 2050 and < 70% by 2100		+1: Weak (encourage)	-1: Weak (discourage)	-1: Weak (discourage)			3
18									
19		*Reason(s) for judgment of the influence*	H	[Type Here]					
20		*of row variable in the target variable:*	M	[Type Here]					
21			L	[Type Here]					

Rate your confidence judgment of + or – judgments under column H and the strength of the impact under column I

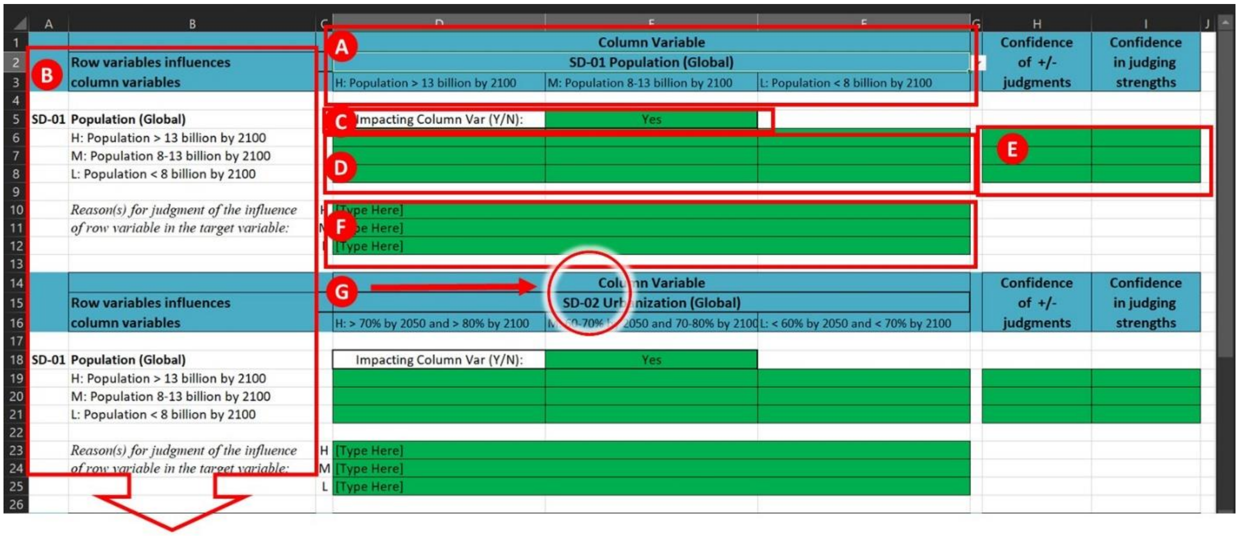
Confidence is measured using 5-point Likert scale where score 5 indicates that your judgment is a fact that is accepted in the field, and score 1 refers to guess.

After answering steps B through E, the participants were asked to provide their reasons for judgments. Reasoning can be based on the consensus of their field, theory, empirical findings, logical conclusion, or individual personally justified belief. After participants articulated their reasons, it means that they have completed inputting their judgment for one variable (Step F). Then, the participants would repeat steps B to G (Step G).



	A	B	C	D	E	F	G	H	I
1				**Column Variable**				**Confidence of +/- judgments**	**Confidence in judging strengths**
2		**Row variables influences column variables**		**SD-01 Population (Global)**					
3				H: Population > 13 billion by 2100	M: Population 8-13 billion by 2100	L: Population < 8 billion by 2100			
13									
14	**SD-02**	**Urbanization (Global)**		Impacting Column Var (Y/N):	Yes				
15		H: > 70% by 2050 and > 80% by 2100		-2: Strong (discourage)	0: No Influence	+2: Strong (encourage)		2	2
16		M: 60-70% by 2050 and 70-80% by 2100		-2: Strong (discourage)	+1: Weak (encourage)	+1: Weak (encourage)		2	2
17		L: < 60% by 2050 and < 70% by 2100		+1: Weak (encourage)	-1: Weak (discourage)	-1: Weak (discourage)		2	3
18									
19		*Reason(s) for judgment of the influence*	H	Lower child bearing is more likely in the cities due to social (proximity) effects					
20		*of row variable in the target variable:*	M	As above					
21			L	I am guessing urbanization (with better healthcare provisions) lowers mortality rate					
22									
23	**SD-03**	**Tech Dev in NET (Global)**		Impacting Column Var (Y/N):	Yes				
24		H: > 15 GtCO2/yr by 2100							
25		M: Between 10-15 GtCO2/yr by 2100							
26		L: < 10 GtCO2/yr by 2100							
27									
28		*Reason(s) for judgment of the influence*	H	[Type Here]					
29		*of row variable in the target variable:*	M	[Type Here]					
30			L	[Type Here]					
31									
32	**SD-04**	**Carbon Intensity (Canada)**		Impacting Column Var (Y/N):	Yes				

In the second part of the questionnaire, experts were asked to provide judgments of direct influences upon global scenario elements (specifically population, carbon intensity and urbanization). The procedure to their judgment is the same with an exception that the row variable (their area of expertise) now acts as the source of direct influences on the column variables, which are the global variables (SD-01: Population (Global), SD-02: Urbanization (Global), SD-09: Carbon Intensity (Global)).



	A	B	C	D	E	F	H	I
1				Column Variable			Confidence of +/- judgments	Confidence in judging strengths
2		Row variables influences column variables		SD-01 Population (Global)				
3				H: Population > 13 billion by 2100	M: Population 8-13 billion by 2100	L: Population < 8 billion by 2100		
4								
5	SD-01	Population (Global)		mpacting Column Var (Y/N):	Yes			
6		H: Population > 13 billion by 2100						
7		M: Population 8-13 billion by 2100						
8		L: Population < 8 billion by 2100						
9								
10		*Reason(s) for judgment of the influence of row variable in the target variable:*	H	Type Here]				
11				pe Here]				
12				[Type Here]				
13								
14				Colu n Variable			Confidence of +/- judgments	Confidence in judging strengths
15		Row variables influences column variables		SD-02 Ur nization (Global)				
16				H: > 70% by 2050 and > 80% by 2100	2050 and 70-80% by 2100	L: < 60% by 2050 and < 70% by 2100		
17								
18	SD-01	Population (Global)		Impacting Column Var (Y/N):	Yes			
19		H: Population > 13 billion by 2100						
20		M: Population 8-13 billion by 2100						
21		L: Population < 8 billion by 2100						
22								
23		*Reason(s) for judgment of the influence of row variable in the target variable:*	H	[Type Here]				
24			M	[Type Here]				
25			L	[Type Here]				
26								

Part 3: Judgment Quality Adjustments

After expert judgments were collected, they were examined for quality. The written comments (on the reasons for judgments) would take precedence over the judgment scores. At times, experts could have misrepresented direct and indirect influences when inputting judgment scores. Written comments for the judgment scores referred to indirect influences were disregarded. There were judgment scores that contradicted written comments; in this case, the judgment scores were modified to reflect experts' reasons. The detail of the adjustments performed is as follows.

SD-04 Carbon Intensity

	SD-04 Carbon Intensity (Canada) Low (>1.4% decrease/yr) Medium (+0.38% to -1.4% change/yr) High (>0.38% increase/yr)					
	Raw Judgments			Adjusted Judgments		
	L	M	H	L	M	H
SD-01/SSP-01 Population (Global)						
Low (<8 billion)	1	0	-1	0	0	0
Medium (8-13 billion)	2	-2	-2	0	0	0
High (>13 billion)	3	-2	-3	0	0	0
SD-05 Income Growth (Canada)						
Low (<US$86K per yr by 2100)	1	0	0	0	0	0
Medium (US$86K to US$120K /yr by 2100)	1	0	1	-1	0	1
High (>US$120K per yr by 2100)	2	0	2	-1	-1	2
SD-06 Tech dev in green freight (Canada)						
Low (Uptake after 2030, <50% by 2100)	1	0	-1	1	0	-1
Medium (50% uptake by 2100)	2	0	-2	1	1	-2
High (Fully adopted by 2070)	3	0	-3	2	1	-3
SD-07 Tech dev in green transit (Canada)						
Low (<75% by 2100)	1	0	-1	1	0	-1
Medium (>50% uptake by 2080)	2	0	-2	1	1	-2
High (Fully adopted by 2060)	3	0	-3	2	1	-3
SD-08 Adoption of EVs (Canada)						
Low (>80% uptake after 2075)	1	0	-1	1	0	-1
Medium (>80% after 2050 but before 2075)	2	0	-2	1	1	-2
High (>80% uptake by 2050)	3	0	-3	2	1	-3

Interpretation:

- For SSP-01 (global population), expert commented that the high development pathway of global population could pressure Canadian government to take action to reduce domestic carbon intensity. The reason provides show 'indirect' influence; hence, judgment was adjusted to show no direct influences.
- For SD-05 (income growth) low pathway, expert commented that the relationship is a status quo. Hence, the low pathway judgment was adjusted as such it has no influence on carbon intensity.
- For SD-05 (income growth) medium and high pathways, expert commented that income can influence carbon intensity in two directions. People can be sustainable, and therefore better income could promote lower carbon intensity. Also, people can remain in the same ('current') situation, meaning that higher income will increase carbon intensity. The judgments were adjusted to reflect the 'current' condition.
- For SD-06 (technology development in green freight), SD-07 (tech development in green transit), and SD-08 (adoption of EVs), expert commented that there is a correlation between carbon

emissions and various technologies. The judgments were adjusted to add a minimum value for the medium pathways. The adjustments nonetheless maintain the relationships but less optimistic.

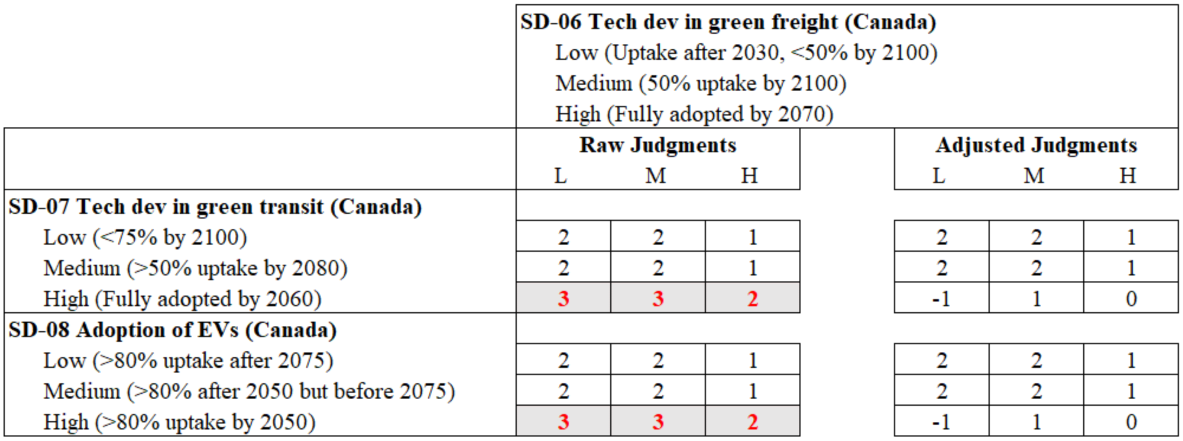
SD-05 Income Growth

	SD-05 Income Growth (Canada) Low (<US$86K per yr by 2100) Medium (US$86K to US$120K /yr by 2100) High (>US$120K per yr by 2100)					
	Raw Judgments			**Adjusted Judgments**		
	L	M	H	L	M	H
SD-06 Tech dev in green freight (Canada)						
Low (Uptake after 2030, <50% by 2100)	-1	0	1	-1	1	0
Medium (50% uptake by 2100)	-2	0	2	-2	1	1
High (Fully adopted by 2070)	-3	0	3	-3	1	2
SD-07 Tech dev in green transit (Canada)						
Low (<75% by 2100)	-1	0	1	-1	1	0
Medium (>50% uptake by 2080)	-2	0	2	-2	1	1
High (Fully adopted by 2060)	-3	0	3	-3	1	2
SD-08 Adoption of EVs (Canada)						
Low (>80% uptake after 2075)	-1	0	1	-1	1	0
Medium (>80% after 2050 but before 2075)	-2	0	2	-2	1	1
High (>80% uptake by 2050)	-3	0	3	-3	1	2
SD-10 Decarbonized Economy (Canada)						
Coupled (Econ coupled with fossil fuel income)	-2	0	2	-2	0	2
Decoupled (Econ decoupled with fossil fuel inc)	2	0	-2	1	1	-2

Interpretation:

- For SD-06 (technology development in green freight), SD-07 (tech development in green transit), and SD-08 (adoption of EVs), expert commented that greener mode of transport would be significant that could result in reducing the cost of mitigation and adaptation. The judgments were adjusted to add a minimum value for the medium pathways. The adjustments nonetheless maintain the relationships but less optimistic.
- For SD-10 (decarbonized economy), expert indicated that the increase in productivity (efficient use of energy) may not support high pathways of income growth. The judgments for low and medium pathways were adjusted to reflect an opposite effect.

SD-06 Technology Development in Green Freight

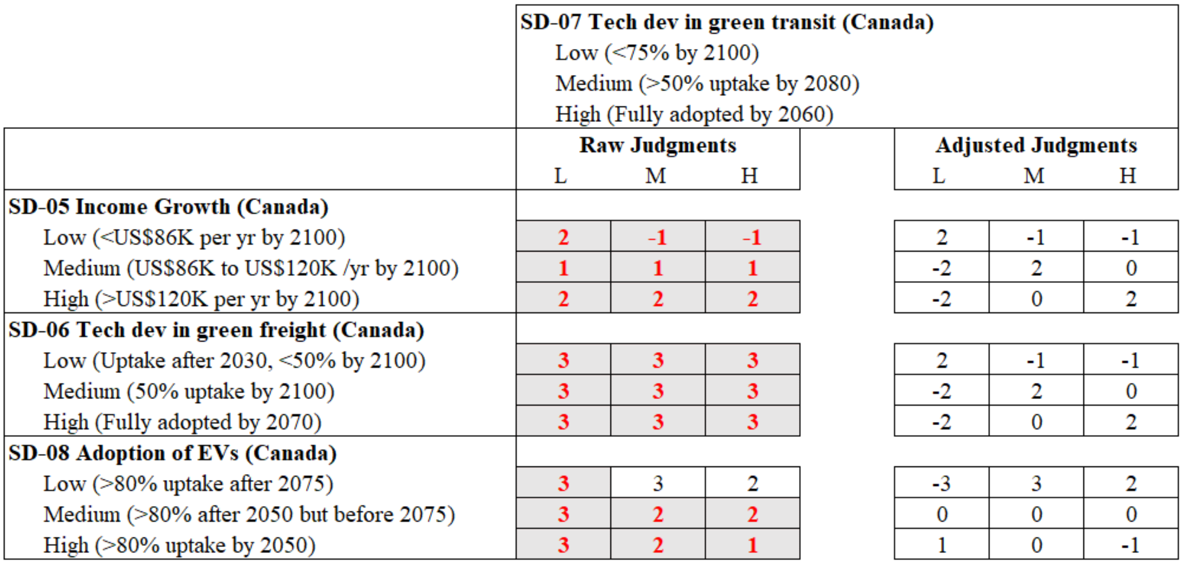


	SD-06 Tech dev in green freight (Canada) Low (Uptake after 2030, <50% by 2100) Medium (50% uptake by 2100) High (Fully adopted by 2070)					
	Raw Judgments			Adjusted Judgments		
	L	M	H	L	M	H
SD-07 Tech dev in green transit (Canada)						
Low (<75% by 2100)	2	2	1	2	2	1
Medium (>50% uptake by 2080)	2	2	1	2	2	1
High (Fully adopted by 2060)	3	3	2	-1	1	0
SD-08 Adoption of EVs (Canada)						
Low (>80% uptake after 2075)	2	2	1	2	2	1
Medium (>80% after 2050 but before 2075)	2	2	1	2	2	1
High (>80% uptake by 2050)	3	3	2	-1	1	0

Interpretation:

- For SD-07 (tech development in green transit) and SD-08 (adoption of EVs), expert commented that passenger and freight have more or less same technologies, but technology development in freight transport lags behind as it is driven by private sector (i.e., profit consideration). The judgments for high pathways of SD-07 and SD-08 were adjusted to reflect the verbal reason correctly.

SD-07 Technology Development in Green Transit



	SD-07 Tech dev in green transit (Canada) Low (<75% by 2100) Medium (>50% uptake by 2080) High (Fully adopted by 2060)					
	Raw Judgments			Adjusted Judgments		
	L	M	H	L	M	H
SD-05 Income Growth (Canada)						
Low (<US$86K per yr by 2100)	2	-1	-1	2	-1	-1
Medium (US$86K to US$120K /yr by 2100)	1	1	1	-2	2	0
High (>US$120K per yr by 2100)	2	2	2	-2	0	2
SD-06 Tech dev in green freight (Canada)						
Low (Uptake after 2030, <50% by 2100)	3	3	3	2	-1	-1
Medium (50% uptake by 2100)	3	3	3	-2	2	0
High (Fully adopted by 2070)	3	3	3	-2	0	2
SD-08 Adoption of EVs (Canada)						
Low (>80% uptake after 2075)	3	3	2	-3	3	2
Medium (>80% after 2050 but before 2075)	3	2	2	0	0	0
High (>80% uptake by 2050)	3	2	1	1	0	-1

Interpretation:

- For SD-05 (income growth) and SD-06 (technology development in green freight), expert commented that these two elements and SD-07 (technology development in green transit) co-vary. These judgments were adjusted to show co-variance relationship.
- For SD-08 (adoption of EVs), expert explained that the relationship is likely determined by the consumer choice. The higher adoption rate of EVs means a weaker support for green transit; however, expert added that this link is not a 'strong' link. The judgment for the low pathway was corrected (flipped sign) to depict a weaker correlation.

SD-08 Adoption of Electric Vehicles

	SD-08 Adoption of EVs (Canada) Low (>80% uptake after 2075) Medium (>80% after 2050 but before 2075) High (>80% uptake by 2050)					
	Raw Judgments			**Adjusted Judgments**		
	L	M	H	L	M	H
SD-04 Carbon Intensity (Canada)						
Low (>1.4% decrease/yr)	-1	2	1	-1	2	1
Medium (+0.38% to -1.4% change/yr)	1	-1	-1	0	-1	-1
High (>0.38% increase/yr)	1	-2	-2	0	1	1
SD-07 Tech dev in green transit (Canada)						
Low (<75% by 2100)	0	1	1	0	-1	-1
Medium (>50% uptake by 2080)	0	1	1	0	1	1
High (Fully adopted by 2060)	0	2	2	0	2	2

Interpretation:

- For SD-04 (carbon intensity), expert explained that higher carbon intensity could discourage higher adoption of EVs. Judgments were adjusted to reflect expert's comment correctly.
- For SD-07 (technology development in green transit), expert commented that better technology development presents a strong encouragement for the adoption of EVs because of shared infrastructure. Judgments for the low pathways were adjusted for to contrast the M and H pathways.

SD-10 Decarbonized Economy

	SD-10 Decarbonized Economy (Canada) Coupled (Econ coupled with fossil fuel income) Decoupled (Econ decoupled with fossil fuel inc)			
	Raw Judgments		**Adjusted Judgments**	
	C	D	C	D
SD-03 Tech dev in NET (Global)				
Low (remove <10 GtCO2/yr by 2100)	0	0	1	-1
Medium (10-15 GtCO2/yr removal by 2100)	-2	2	-2	2
High (remove >15 GtCO2/yr by 2100)	-3	3	-3	3
SD-06 Tech dev in green freight (Canada)				
Low (Uptake after 2030, <50% by 2100)	0	0	1	-1
Medium (50% uptake by 2100)	-1	1	-1	1
High (Fully adopted by 2070)	-3	3	-3	3
SD-07 Tech dev in green transit (Canada)				
Low (<75% by 2100)	0	0	1	-1
Medium (>50% uptake by 2080)	-1	1	-1	1
High (Fully adopted by 2060)	-3	3	-3	3
SD-08 Adoption of EVs (Canada)				
Low (>80% uptake after 2075)	0	0	1	-1
Medium (>80% after 2050 but before 2075)	-1	1	-1	1
High (>80% uptake by 2050)	-3	3	-3	3

Interpretation:

- For SD-03 (technology development in negative emission technologies), SD-06 (technology development in green freight), SD-07 (technology development in green transit), and SD-08 (adoption of EVs), expert explained that better technology and higher adoption of EVs will reduce oil prices, therefore the dependence on fossil fuel extraction. Judgments for low pathways were adjusted to show the opposite effect, contrasting medium and high pathways.

Appendix D: Complete Cross-impact Matrix with Raw Influence Judgments

	SSP01 Pop			SSP02 Income			SSP03 E Intensity			SSP04 C Intensity			SSP05 E Tech Chg			SSP06 Agri			SSP07 Urban			SSP08 Poverty			SSP09 Water			SSP10 Pop coast			SSP11 Edu att			SSP12 Governance			SSP13 Innovation			SD03 GL Tech NET			SD04 CA C Intensity			SD05 CA Income			SD06 CA Tech Freight			SD07 CA Tech Transit			SD08 CA EV			SD10 CA Economy	
	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	C	D
SD-01/SSP-01 Population (Global)																																																											
Low (<8 billion)				-1	-1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	-3	3	0	-3	0	0	0	-2	2	3	-1	0	1	0	0	0	0	0	0	1	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Medium (8-13 billion)				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-2	0	2	0	0	0	0	0	0	-2	0	3	0	0	0	0	0	0	0	0	0	2	-2	-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
High (>13 billion)				1	1	-1	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	1	-3	0	3	-3	0	3	0	0	0	3	2	-3	1	0	-1	0	0	0	0	0	0	3	-2	-3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SSP-02 Average Income (Global)																																																										
Low (annual growth <1.5%)	-1	0	1				-2	0	2	-1	0	1	3	-1	-3	0	0	0	1	1	-2	-3	2	3	2	0	-2	-1	0	-1	3	2	-3	3	0	-3	1	-2	-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Medium (1.5% - 2.0% growth/yr)	0	0	0				0	0	0	0	0	0	-1	1	-1	0	0	0	0	1	-1	2	2	2	0	1	0	-1	1	1	-2	2	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
High (annual growth >2.0%)	1	0	-1				2	0	-2	1	0	-1	-3	-1	3	0	0	0	-1	-1	2	3	2	-3	-2	0	2	0	1	1	-3	2	3	-3	0	3	-2	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SSP-03 Energy Intensity (Global)																																																										
Low (>1.0% decrease/yr)	0	0	0	0	0	0				1	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Medium (0.5% - 1.0% decrease/yr)	0	0	0	0	0	0				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
High (<0.5% decrease/yr)	0	0	0	0	0	0				-1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SD-09/SSP-04 Carbon Intensity (Global)																																																										
Low (>0.5% decrease/yr)	0	0	0	0	0	0	0	0	0				0	0	0	0	0	0	0	0	0	0	0	0	1	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	-1	-1	-2	0	0	0	2	0	-2	2	2	2	3	1	1	0	0	0	1	-1
Medium (0.1% - 0.5% decrease/yr)	0	0	0	0	0	0	0	0	0				0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
High (<0.1% decrease/yr)	0	0	0	0	0	0	0	0	0				0	0	0	0	0	0	0	0	0	0	0	0	-1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	-1	0	0	0	-2	0	2	1	1	1	-3	-2	-1	0	0	0	3	-3
SSP-05 Rate of tech change: Energy (Global)																																																										
Low (AEEI~0.5% per yr)	0	0	0	1	-1	-1	-3	0	3	-3	0	3				1	0	-1	0	0	0	0	0	0	-1	0	1	0	0	0	1	1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Medium (AEEI~1.0% per yr)	0	0	0	0	0	0	0	0	0	-1	1	-1				0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
High (AEEI~1.5% per yr)	0	0	0	-1	1	1	3	0	-3	3	0	-3				-1	0	1	0	0	0	0	0	0	1	0	-1	0	0	0	-3	-2	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SSP-06 Agricultural productivity (Global)																																																										
Low (<0.75% improvement/yr)	0	0	0	2	0	-2	0	0	0	-2	-1	2	0	0	0				1	0	-1	-3	2	3	3	0	-3	0	0	0	1	1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Medium (0.75%-1.25% improvement/yr)	0	0	0	0	1	0	0	0	0	-1	1	-1	0	0	0				-1	1	0	2	2	-1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
High (>1.25% improvement/yr)	0	0	0	-2	1	2	0	0	0	2	0	-2	0	0	0				-1	0	1	3	0	-3	-3	0	3	0	0	0	-3	-2	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SD-02/SSP-07 Urbanization (Global)																																																										
Low (<70% by 2100)	-1	0	1	0	0	0	-1	0	1	0	0	0	1	0	-1	0	0	0				0	0	0	0	0	0	2	1	-3	0	0	0	-2	0	2	1	-1	-1	0	0	0	0	0	0	0	0	0	2	2	1	1	1	1	0	0	0	0	0
Medium (70% - 80% by 2100)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				0	0	0	0	0	0	-1	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	1	1	3	3	0	0	0	0	0
High (>80% by 2100)	1	0	-1	0	0	0	1	0	-1	0	0	0	-1	0	1	0	0	0				0	0	0	0	0	0	-3	0	3	-1	0	0	2	0	-2	-1	1	1	0	0	0	0	0	0	0	0	0	2	2	1	1	3	3	0	0	0	0	0
SSP-08 Extreme poverty (Global)																																																										
Low (>4% decrease/yr)	1	0	-1	-3	-2	3	0	0	0	0	0	0	0	0	0	0	0	0	1	0	-1				0	0	0	0	0	0	-3	2	3	-1	0	1	-1	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Medium (1% - 4% decrease/yr)	0	0	0	-2	3	-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				0	0	0	0	0	0	2	2	-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
High (<1% decrease/yr)	-1	0	1	3	-2	-3	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	1				0	0	0	0	1	0	3	2	-3	1	0	-1	1	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SSP-09 Water scarcity (Global)																																																										
Low (<10% global population)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-2	0	2	0	0	0	1	1	-1				0	0	0	0	0	0	-1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Medium (10% - 20% global population)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	-1	-2	0	0	0	1	1	1				-1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
High (>20% global population)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	-2	-3	0	0	0	-1	1	1				-1	1	1	0	0	0	1	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SSP-10 Population near coast (Global)																																																										
Low (<40% global population)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Medium (40%-50% global population)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
High (>50% global population)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SSP-11 Educational attainment (Global)																																																										
Low (<65% global population)	-1	0	1	3	-2	-3	0	0	0	0	0	0	0	0	0	1	0	-1	0	0	0	3	0	3	0	0	0	0	0	0				3	0	-3	2	1	-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Medium (65% - 75% global population)	0	0	0	-2	3	-2	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	1	3	3	-3	0	0	0	0	0	0				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
High (>75% global population)	1	0	-1	-3	-2	3	0	0	0	0	0	0	0	0	0	-1	0	1	1	0	-1	3	0	-3	0	0	0	0	0	0				-3	0	3	-2	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SSP-12 Quality of governance (Global)																																																										
Low (>20% governments fail)	-1	0	1	2	-1	-2	-1	0	1	0	0	0	2	-1	-2	1	0	-1	-1	0	1	-2	1	2	-2	0	2	0	0	0	3	2	-3				1	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Medium (10% - 20% governments fail)	0	0	0	-1	2	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	-1	0	1	0	0	0	0	2	2	-2				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
High (<10% governments fail)	1	0	-1	-2	-1	2	1	0	-1	0	0	0	-2	1	2	-1	0	1	1	0	-1	3	0	-2	2	0	-2	0	0	0	-3	2	3				-1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SSP-13 Innovation capacity (Global)																																																										
Low (deterioration)	0	0	0	2	-1	-1	-2	0	2	-3	0	1	3	-2	-3	3	-2	-3	0	0	0	0	0	0	2	0	-2	0	0	0	3	2	-3	1	0	-1				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Medium (no/modest improvement)	0	0	0	-1	2	-1	0	0	0	-1	1	0	-2	2	-2	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	2	2	-2	0	0	0				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
High (substantial improvement)	0	0	0	-3	-1	2	2	0	-2	3	-1	-2	-3	-1	3	-1	1	2	0	0	0	0	0	0	-2	0	2	0	0	0	-3	0	3	-1	0	1				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SD-03 Tech dev in NET (Global)																																																										
Low (remove <10 GtCO2/yr by 2100)	0	0	0	0	0	0	0	0	0	-2	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				-1	0	1	-1	0	1	-1	-1	-1	2	2	1	1	1	-1	0	0
Medium (10-15 GtCO2/yr removal by 2100)	0	0	0	0	0	0	0	0	0	-3	0	-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				-2	0	2	-2	0	2	-1	-1	-1	1	1	1	1	-2	-2	-2	2
High (remove >15 GtCO2/yr by 2100)	0	0	0	0	0	0	0	0	0	-3	0	-3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				-3	0	3	-3	0	3	-1	-1	-1	1	1	1	1	-3	-3	-3	3
SD-04 Carbon Intensity (Canada)																																																										
Low (>1.4% decrease/yr)	0	0	0	0	0	0	0	0	0	-1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	-1				1	0	-1	2	2	2	1	1	0	-1	2	1	-3	3
Medium (+0.38% to -1.4% change/yr)	0	0	0	0	0	0	0	0	0	-2	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1				2	0	-2	1	1	1	1	1	1	1	-1	-1	1	-1
High (>0.38% increase/yr)	0	0	0	0	0	0	0	0	0	-3	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	2				3	0	-3	-1	-1	-1	2	2	1	1	-2	-2	3	-3
SD-05 Income Growth (Canada)																																																										
Low (<US$86K per yr by 2100)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0				0	0	0	2	-1	-1	0	-2	-2	0	0
Medium (US$86K to US$120K /yr by 2100)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1				0	0	0	1	1	1	0	-1	-1	0	0
High (>US$120K per yr by 2100)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	2				0	0	0	2	2	2	0	1	1	0	0
SD-06 Tech dev in green freight (Canada)																																																										
Low (Uptake after 2030, <50% by 2100)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	-1	-1	0	1				3	3	3	0	0	0	0	0
Medium (50% uptake by 2100)	0	0	0	0	0	0	0	0	0	-1	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	-2	-2	0	2				3	3	3	0	0	0	-1	1
High (Fully adopted by 2070)	0	0	0	0	0	0	0	0	0	-1	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	-3	-3	0	3				3	3	3	0	0	0	-3	3
SD-07 Tech dev in green transit (Canada)																																																										
Low (<75% by 2100)	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	-1	-1	0	1	2	2	1				0	1	1	0	0
Medium (>50% uptake by 2080)	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	-2	-2	0	2	2	2	1				0	1	1	-1	1
High (Fully adopted by 2060)	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	-3	-3	0	3	3	3	2				0	2	2	-3	3
SD-08 Adoption of EVs (Canada)																																																										
Low (>80% uptake after 2075)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	-1	-1	0	1	2	2	1	3	3	2				0	0
Medium (>80% after 2050 but before 2075)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	-2	-2	0	2	2	2	1	3	2	2				-1	1
High (>80% uptake by 2050)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	-3	-3	0	3	3	3	2	3	2	1				-3	3
SD-10 Decarbonized Economy (Canada)																																																										
Coupled (Econ coupled with fossil fuel income)	0	0	0	0	0	0	0	0	0	-1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	3	-3	0	3	-2	0	2	-2	-2	-2	0	0	0	1	-2	-3		
Decoupled (Econ decoupled with fossil fuel inc)	0	0	0	0	0	0	0	0	0	2	0	-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	-2	-3	3	0	-3	2	0	-2	0	0	0	0	0	0	0	3	3		

Appendix E: Complete Cross-impact Matrix after Bias Correction and Standardization

	SSP01 Pop			SSP02 Income			SSP03 E Intensity			SSP04 C Intensity			SSP05 E Tech Chg			SSP06 Agri			SSP07 Urban			SSP08 Poverty			SSP09 Water			SSP10 Pop coast			SSP11 Edu att			SSP12 Governance			SSP13 Innovation			SD03 GL Tech NET			SD04 CA C Intensity			SD05 CA Income			SD06 CA Tech Freight			SD07 CA Tech Transit			SD-8 CA EV			SD10 CA Economy	
	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	C	D
SD-01/SSP-01 Population (Global)																																																											
Low (<8 billion)				-2	-2	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	-9	9	0	-9	0	0	0	-9	3	6	-3	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Medium (8-13 billion)				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-6	0	6	0	0	0	0	0	0	-7	-1	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
High (>13 billion)				2	2	-4	0	0	0	0	0	0	0	0	0	0	0	0	-3	0	3	-9	0	9	-9	0	9	0	0	0	7	4	-11	3	0	-3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SSP-02 Average Income (Global)																																																											
Low (annual growth <1.5%)	-3	0	3				-6	0	6	-3	0	3	10	-2	-8	0	0	0	3	3	-6	-11	4	7	6	0	-6	-1	2	-1	7	4	-11	9	0	-9	6	-3	-3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Medium (1.5% - 2.0% growth/yr)	0	0	0				0	0	0	0	0	0	-2	4	-2	0	0	0	0	3	-3	0	0	0	-1	2	-1	-4	2	2	-9	3	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
High (annual growth >2.0%)	3	0	-3				6	0	-6	3	0	-3	-8	-2	10	0	0	0	-3	-3	6	7	4	-11	-6	0	6	2	1	1	-11	4	7	-9	0	9	-7	2	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SSP-03 Energy Intensity (Global)																																																											
Low (>1.0% decrease/yr)	0	0	0	0	0	0				3	0	-3	0	0	0	0	0	0	0	0	0	0	0	0	3	0	-3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Medium (0.5% - 1.0% decrease/yr)	0	0	0	0	0	0				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	2	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
High (<0.5% decrease/yr)	0	0	0	0	0	0				-3	0	3	0	0	0	0	0	0	0	0	0	0	0	0	-3	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SD-09/SSP-04 Carbon Intensity (Global)																																																											
Low (>0.5% decrease/yr)	0	0	0	0	0	0	0	0	0				0	0	0	0	0	0	0	0	0	0	0	0	3	0	-3	0	0	0	0	0	0	0	0	0	0	0	0	1	1	-2	0	0	0	6	0	-6	0	0	0	4	-2	-2	0	0	0	3	-3
Medium (0.1% - 0.5% decrease/yr)	0	0	0	0	0	0	0	0	0				0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
High (<0.1% decrease/yr)	0	0	0	0	0	0	0	0	0				0	0	0	0	0	0	0	0	0	0	0	0	-3	0	3	0	0	0	0	0	0	0	0	0	0	0	0	2	-1	-1	0	0	0	-6	0	6	0	0	0	-3	0	3	0	0	0	9	-9
SSP-05 Rate of tech change: Energy (Global)																																																											
Low (AEEI~0.5% per yr)	0	0	0	4	-2	-2	-9	0	9	-9	0	9				3	0	-3	0	0	0	0	0	0	-3	0	3	0	0	0	2	2	-4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Medium (AEEI~1.0% per yr)	0	0	0	0	0	0	0	0	0	-2	4	-2				0	0	0	0	0	0	0	0	0	-1	2	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
High (AEEI~1.5% per yr)	0	0	0	-4	2	2	9	0	-9	0	0	-9				-3	0	3	0	0	0	0	0	0	3	0	-3	0	0	0	-7	-4	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SSP-06 Agricultural productivity (Global)																																																											
Low (<0.75% improvement/yr)	0	0	0	6	0	-6	0	0	0	-5	-2	7	0	0	0				3	0	-3	-11	4	7	9	0	-9	0	0	0	2	2	-4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Medium (0.75%-1.25% improvement/yr)	0	0	0	-1	2	-1	0	0	0	-2	4	-2	0	0	0				-3	3	0	3	3	-6	-1	2	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
High (>1.25% improvement/yr)	0	0	0	-7	2	5	0	0	0	6	0	-6	0	0	0				-3	0	3	9	0	-9	-9	0	9	0	0	0	-7	-4	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SD-02/SSP-07 Urbanization (Global)																																																											
Low (<70% by 2100)	-3	0	3	0	0	0	-3	0	3	0	0	0	3	0	-3	0	0	0				0	0	0	0	0	0	6	3	-9	0	0	0	-6	0	6	4	-2	-2	0	0	0	0	0	0	0	0	0	1	1	-2	0	0	0	0	0	0	0	0
Medium (70% - 80% by 2100)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				0	0	0	0	0	0	-5	1	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	-2	-4	2	2	0	0	0	0	0
High (>80% by 2100)	3	0	-3	0	0	0	3	0	-3	0	0	0	-3	0	3	0	0	0				0	0	0	0	0	0	-9	0	9	-2	1	1	6	0	-6	-4	2	2	0	0	0	0	0	0	0	0	0	1	1	-2	-4	2	2	0	0	0	0	0
SSP-08 Extreme poverty (Global)																																																											
Low (>4% decrease/yr)	3	0	-3	-7	-4	11	0	0	0	0	0	0	0	0	0	0	0	0	3	0	-3				0	0	0	0	0	0	-11	4	7	-3	0	3	-5	4	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Medium (1% - 4% decrease/yr)	0	0	0	-5	10	-5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				0	0	0	0	0	0	4	4	-8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
High (<1% decrease/yr)	-3	0	3	11	-4	-7	0	0	0	0	0	0	0	0	0	0	0	0	-3	0	3				0	0	0	-1	2	-1	7	4	-11	3	0	-3	4	-2	-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SSP-09 Water scarcity (Global)																																																											
Low (<10% global population)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-6	0	6	0	0	0	2	2	-4				0	0	0	0	0	0	-3	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Medium (10% - 20% global population)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	-2	-5	0	0	0	0	0	0				-3	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
High (>20% global population)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	-4	-7	0	0	0	-4	2	2				-4	2	2	0	0	0	3	0	-3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SSP-10 Population near coast (Global)																																																											
Low (<40% global population)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Medium (40%-50% global population)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
High (>50% global population)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SSP-11 Educational attainment (Global)																																																											
Low (<65% global population)	-3	0	3	11	-4	-7	0	0	0	0	0	0	0	0	0	3	0	-3	0	0	0	3	-6	3	0	0	0	0	0	0				9	0	-9	5	2	-7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Medium (65% - 75% global population)	0	0	0	-5	10	-5	0	0	0	0	0	0	0	0	0	0	0	0	-3	0	3	6	6	-12	0	0	0	0	0	0				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
High (>75% global population)	3	0	-3	-7	-4	11	0	0	0	0	0	0	0	0	0	-3	0	3	3	0	-3	9	0	-9	0	0	0	0	0	0				-9	0	9	-7	2	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SSP-12 Quality of governance (Global)																																																											
Low (>20% governments fail)	-3	0	3	7	-2	-5	-3	0	3	0	0	0	7	-2	-5	3	0	-3	-3	0	3	-7	2	5	-6	0	6	0	0	0	7	4	-11				3	0	-3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Medium (10% - 20% governments fail)	0	0	0	-3	6	-3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	-6	-1	2	-1	0	0	0	4	4	-8				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
High (<10% governments fail)	3	0	-3	-5	-2	7	3	0	-3	0	0	0	-7	2	5	-3	0	3	3	0	-3	8	-1	-7	-6	0	6	0	0	0	-11	4	7				-3	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SSP-13 Innovation capacity (Global)																																																											
Low (deterioration)	0	0	0	6	-3	-3	-6	0	6	-7	2	5	11	-4	-7	11	-4	-7	0	0	0	0	0	0	-6	0	6	0	0	0	7	4	-11	3	0	-3				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Medium (no/modest improvement)	0	0	0	-3	6	-3	0	0	0	-3	3	0	-4	8	-4	0	0	0	0	0	0	0	0	0	-1	2	-1	0	0	0	4	4	-8	0	0	0				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
High (substantial improvement)	0	0	0	-7	-1	8	6	0	-6	9	-3	-6	-8	-2	10	-5	1	4	0	0	0	0	0	0	-6	0	6	0	0	0	-9	0	9	-3	0	3				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SD-03 Tech dev in NET (Global)																																																											
Low (remove <10 GtCO2/yr by 2100)	0	0	0	0	0	0	0	0	0	-3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				-3	0	3	-3	0	3	0	0	0	1	1	-2	2	2	-4	3	-3
Medium (10-15 GtCO2/yr removal by 2100)	0	0	0	0	0	0	0	0	0	-4	5	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				-6	0	6	-6	0	6	0	0	0	0	0	0	6	-3	-3	-6	6
High (remove >15 GtCO2/yr by 2100)	0	0	0	0	0	0	0	0	0	-3	6	-3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				-9	0	9	-9	0	9	0	0	0	0	0	0	8	-4	-4	-9	9
SD-04 Carbon Intensity (Canada)																																																											
Low (>1.4% decrease/yr)	0	0	0	0	0	0	0	0	0	-3	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	-1	-1				3	0	-3	0	0	0	1	1	-2	-5	4	1	-9	9
Medium (+0.38% to -1.4% change/yr)	0	0	0	0	0	0	0	0	0	-6	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-2	1	1				6	0	-6	0	0	0	0	0	0	2	-1	-1	3	-3
High (>0.38% increase/yr)	0	0	0	0	0	0	0	0	0	-9	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-2	2	2				0	0	-9	0	0	0	1	1	-2	-2	1	1	9	-9
SD-05 Income Growth (Canada)																																																											
Low (<US$86K per yr by 2100)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				0	0	0	6	-3	-3	4	-2	-2	0	0
Medium (US$86K to US$120K /yr by 2100)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-3	0	3				0	0	0	-6	6	0	2	-1	-1	0	0
High (>US$120K per yr by 2100)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-3	-3	6				0	0	0	-6	0	6	-2	1	1	0	0
SD-06 Tech dev in green freight (Canada)																																																											
Low (Uptake after 2030, <50% by 2100)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	-3	-3	3	0				6	-3	-3	0	0	0	3	-3
Medium (50% uptake by 2100)	0	0	0	0	0	0	0	0	0	-1	2	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	-6	-6	3	3				-6	6	0	0	0	0	-3	3
High (Fully adopted by 2070)	0	0	0	0	0	0	0	0	0	-1	2	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	3	-9	-9	3	6				-6	0	6	0	0	0	-9	9
SD-07 Tech dev in green transit (Canada)																																																											
Low (<75% by 2100)	0	0	0	0	0	0	0	0	0	1	-2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	-3	-3	3	0	1	1	-2				2	-1	-1	3	-3
Medium (>50% uptake by 2080)	0	0	0	0	0	0	0	0	0	1	-2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	-6	-6	3	3	1	1	-2				-2	1	1	-3	3
High (Fully adopted by 2060)	0	0	0	0	0	0	0	0	0	1	-2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	3	-9	-9	3	6	-3	3	0				-4	2	2	-9	9
SD-08 Adoption of EVs (Canada)																																																											
Low (>80% uptake after 2075)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	-3	-3	3	0	1	1	-2	-11	7	4				3	-3
Medium (>80% after 2050 but before 2075)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	-6	-6	3	3	1	1	-2	0	0	0				-3	3
High (>80% uptake by 2050)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	3	-9	-9	3	6	-3	3	0	3	0	-3				-9	9
SD-10 Decarbonized Economy (Canada)																																																											
Coupled (Econ coupled with fossil fuel income)	0	0	0	0	0	0	0	0	0	-3	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-9	0	9	-6	0	6	0	0	0	0	0	0	7	-2	-5		
Decoupled (Econ decoupled with fossil fuel inc)	0	0	0	0	0	0	0	0	0	6	0	-6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	-3	9	0	-9	3	3	-6	0	0	0	0	0	0	-6	3	3		

Note: Highlighted cells are adjusted influence judgment