Analysis of a Clean Energy Hub Interfaced with a Fleet of Plug-in Fuel Cell Vehicles

by

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Author's Declaration

I hereby declare that I am the sole author of 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.

Abstract

The 'hydrogen economy' represents an energy system in which hydrogen and electricity are the dominant energy carriers for use in transportation applications. The 'hydrogen economy' minimizes the use of fossil fuels in order to lower the environmental impact of energy use associated with urban air pollution and climate change. An integrated energy system is required to deal with diverse and distributed energy generation technologies such a wind and solar which require energy storage to level energy availability and demand. A distributed 'energy hub' is considered a viable concept in envisioning the structure of an integrated energy system. An energy hub is a system which consists of energy input/output, conversion and storage technologies for multiple energy carriers, and would provide an interface between energy producers, consumers, and the transportation infrastructure. Considered in a decentralized network, these hubs would form the nodes of an integrated energy system or network.

In this work, a model of a clean energy hub comprising of wind turbines, electrolyzers, hydrogen storage, a commercial building, and a fleet of plug-in fuel cell vehicles (PFCVs) was developed in MATLAB, with electricity and hydrogen used as the energy carriers. This model represents a hypothetical commercial facility which is powered by a renewable energy source and utilizes a zero-emissions fleet of light duty vehicles. The models developed herein capture the energy and cost interactions between the various energy components, and also calculate the CO_2 emissions avoided through the implementation of hydrogen economy principles. Wherever possible, similar models were used to inform the development of the clean energy hub model. The purpose of the modelling was to investigate the interactions between a single energy hub and novel components such as a plug-in fuel cell vehicle fleet (PFCV). The final model reports four key results: price of hub electricity, price of hub hydrogen, total annual costs and CO_2 emissions avoided. Three

scenarios were analysed: minimizing price of hub electricity, minimizing total annual costs, and maximizing the CO_2 emissions avoided.

Since the clean energy hub could feasibly represent both a facility located within an urban area as well as a remote facility, two separate analyses were also conducted: an on-grid analysis (if the energy hub is close to transmission lines), and an off-grid analysis (representing the remote scenarios).

The connection of the energy hub to the broader electricity grid was the most significant factor affecting the results collected. Grid electricity was found to be generally cheaper than electricity produced by wind turbines, and scenarios for minimizing costs heavily favoured the use grid electricity. However, wind turbines were found to avoid CO_2 emissions over the use of grid electricity, and scenarios for maximizing emissions avoided heavily favoured wind turbine electricity. In one case, removing the grid connection resulted in the price of electricity from the energy hub increasing from $82/MWh to $300/MWh.

The mean travel distance of the fleet was another important factor affecting the cost modelling of the energy hub. The hub's performance was simulated over a range of mean travel distances (20km to 100km), and the results varied greatly within the range. This is because the mean travel distance directly affects the quantities of electricity and hydrogen consumed by the fleet, a large consumer of energy within the hub. Other factors, such as the output of the wind turbines, or the consumption of the commercial building, are largely fixed. A key sensitivity was discovered within this range; the results were 'better' (lower costs and higher emissions avoided) when the mean travel distance exceeded the electric travel range of the fleet. This effect was more noticeable in the on-grid analysis. This sensitivity is due to the underutilization of the hydrogen systems within the hub at lower mean travel distances. It was found that the greater the mean travel distance, the greater the utilization of the electrolyzers and storage tanks lowering the associated per km capital cost of these components. At lower mean travel distances the utilization of the electrolyzers ranged from 25% to 30%, whereas at higher mean travel distances it ranged from 97% to 99%. At higher utilization factors the price of hydrogen is reduced, since the cost recovery is spread over a larger quantity of hydrogen.

Acknowledgements

My parents, Arif Syed and Uzma Arif, have always placed their children's future ahead of their own dreams. They have an unshakable belief in the value of education. My father left behind opportunities of advancement in his country to provide a better environment and education for me and my siblings, and my mother all but gave up her medical career to tutor us day and night. All my efforts are for them.

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Finally, and most importantly, I am extremely grateful to Allah (God), the Most Beneficent, the Most Merciful. I begin this thesis in His name.

Dedication

I dedicate this work to my parents, Arif Syed and Uzma Arif.

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Nomenclature

Energy hub components

Term	Component
B	Commercial building
E	Electrolyzers
F	PFCV fleet
G	Electricity grid
S	Hydrogen storage
T	Electricity transmission system
W	Wind turbines

Modelling terminology

Term	Component
$(P_e)_x$	Electricity input to energy hub component x
$(P_h)_x$	Hydrogen input to energy hub component x

Term	Component
$(L_e)_x$	Electricity output to energy hub component x
$(L_h)_x$	Hydrogen output to energy hub component x
$(C_e)_x$	Electricity generation/consumption for energy hub component x
$(C_h)_x$	Hydrogen generation/consumption for energy hub component x
$(S_e)_x$	Electricity storage for energy hub component x
$(S_h)_x$	Hydrogen storage for energy hub component x
$(a_{ee})_x$	Electricity handling efficiency for energy hub component x
$(a_{hh})_x$	Hydrogen handling efficiency for energy hub component x
$(a_{eh})_x$	Electricity conversion efficiency for energy hub component x
$(a_{he})_x$	Hydrogen conversion efficiency for energy hub component x

Chapter 1
Introduction

The province of Ontario will face considerable energy challenges within the foreseeable future. Traditionally the electricity and transportation sectors have remained distinct due to the different energy carriers involved. The energy carriers dictated energy pathways that did not intersect significantly and there was low interaction between the sectors. Transportation relies on liquid fuels derived from fossils fuels with numerous associated environmental impacts. However this sector is evolving in order to reduce overall environmental impact and improve energy security, sustainability and reliability [1] with the introduction of new power train options. In particular the transportation sector is moving towards an electrified power train to facilitate the introduction of hybrid topologies. This platform includes a battery to reclaim energy from regenerative braking, sometimes a larger battery for a 'plug-in' electrical grid energy charge-deleting range, and liquid or gaseous fuel range extender (e.g. gasoline internal combustion engine or fuel cell). This is a critical technology step toward the ultimate goal of a zero emission hydrogen based transportation sector in order to reduce urban air pollution, reduce greenhouse gas emissions and displace petroleum [2]. Hydrogen is an energy carrier that can be generated with any electricity source, stored in gaseous or liquid form, used onboard vehicles and distributed by pipeline or truck. Hydrogen also provides an energy storage medium which enables the transition to greater use of intermittent renewable energy sources such as wind and solar, as it provides a convenient energy storage medium, and then becomes a high valued transportation fuel. Of most interest hydrogen will enable new interactions between the electricity and transportation sectors. As an energy carrier, the use of hydrogen is complimentary to the use of electricity [3] and it is reasonable to view the sectors as ultimately merging to become part of an integrated energy system which uses electricity and hydrogen as its primary energy carriers and storage medium [4][5]. In this work a facility 'energy hub' is examined where the facility generates some electricity, and supports an zero-emission fleet of hydrogen fuelled plug-in hybrid vehicles.

The province of Ontario is also scheduled to eliminate all coal-fired generation capacity by 2014. Due to a growing awareness of the adverse effects of coal on the environment and public health, a cost-benefit study by the province determined that the best options were to replace coal with renewable energy (such as wind, solar and biomass), nuclear energy and natural gas [6]. This is exacerbated by the fact that as much as 80% of the current generation capacity will also need replacement within the next 20 years, and that peak demand is estimated to rise to 40,000 MW by 2027 (while it is currently 31,214 MW) [7].

A major barrier to adoption of renewable sources is their intermittency; their power output variability is too great to be used to match electricity demand in an efficient and cost-effective manner. Since the output from sources such as wind and solar power cannot be controlled to synchronize with the grid, ensuring reliability will require the use of additional energy services, such as bulk energy storage. The use of hydrogen within an integrated hydrogen economy would allow the storage of electricity until it is needed to match demand, and more importantly generation of hydrogen when electricity is available to be used as a transportation fuel. Previous work has shown the use of hydrogen to enable renewable energy sources could be economically feasible [8], with the use of hydrogen for vehicles to be much more viable economically at this time, then the use of hydrogen to load level between peak and off-peak period. The conversion of electricity to hydrogen can be achieved today in a clean manner through electrolysis, which produces no operational greenhouse gases or air pollution. Future technologies such as Cu-Cl thermochemical cycles [9] also have potential to compliment electrolysis as a means of hydrogen production [10] for large scale production, but this work will focus on production that supports a local vehicle fleet. Distributed production of hydrogen to support small vehicle fleet is a likely transition scenario in the short term. Hydrogen is also preferable for vehicles and other modes of transportation, along with lift trucks within the facility. Vehicle technology is increasingly shifting towards electrification, beginning with mild hybrids, plug-in hybrids, and ultimately becoming fuel cell and low-range electric vehicles [11]. Early hybrids rely on gasoline or diesel for their power while reclaiming energy through regenerative braking and the use of battery storage. Plug-in hybrids (PHEVs) have large battery storage, employ charge depletion control strategies, allow for charging of the battery from stationary electricity sources, but still employ some type of internal combustion engine (ICE) as a range extender. In the future PHEVs will make use of hydrogen fuel cells as the range extender, or in some cases have all energy come from onboard hydrogen, as in purely fuel cell vehicles (FCV). Hydrogen fuel cell vehicles can convert hydrogen stored on board the vehicle to electricity with no operational greenhouse gas emissions, no urban air pollution, as well as improved energy security by displacing the use of petroleum.

Previous studies of the 'energy hub' concept have used assumed load profiles to analyze the hubs. An 'energy hub' is a location that is capable of transforming energy, has some distributed energy generation potential, has demand profile for energy (i.e. electricity or heat), and can often store some energy. Previous works used load profiles that were of limited use since they often did not describe energy demand in a meaningful way. In this work a flexible model was developed to predict the energy demands of a PFCV (plug-in fuel cell vehicle) and a typical medium-sized office/commercial building, and this was used to study the interactions between the fleet and a clean energy hub. This paper discusses the model development as well as the interactions of a vehicle fleet with a clean energy hub and a commercial building.

The structure of this thesis is as follows: in **Chapter 2**, related literature is reviewed to provide background information. **Chapter 3** describes the energy modelling, **Chapter 4** describes the emissions modelling, and **Chapter 5** describes the cost modelling. In **Chapter 6**, the analysis methodology and design of experiment is explained. In **Chapter 7**, the results of the two-stage experimental design are discussed. Finally, **Chapter 8** summarizes the main contributions and conclusions of the presented model, as well as future work to address the limitations of this thesis.

Chapter 2
Literature Review

This chapter presents literature which forms the basis of this thesis, and the topics are presented in order of importance. First, three broad topics are discussed: hydrogen economy, energy hubs, and advanced vehicle powertrains. These sections explain the impetus and considerations of the future of energy systems. In order to understand these topics in a local context, Ontario's electricity system is also discussed. Further sections discuss the individual technologies that are represented in the model development. This chapter concludes with a brief discussion of potential emissions-reduction schemes that could be applied to the modelling.

2.1 Hydrogen Economy

The 'hydrogen economy' represents an energy system in which hydrogen and electricity are the dominant energy carriers, and in which the use of fossil fuels is minimized in order to lower the environmental impact of energy use and increase possibilities for optimization through conversion between energy carriers.

Fossil fuels (such as crude oil, natural gas and coal) and electricity currently form the basis of almost all energy consumption in the world. Both are mature technologies which came into widespread use during the 20th century and have shaped much of the world today. Fossil fuels, and in particular gasoline, became the dominant energy source for transportation, and electricity found use in almost every other application [3]. Since World War II, both sectors have seen a rapid growth in energy demand (Figure 2-1, Figure 2-2) and have spurred further developments of the technology.

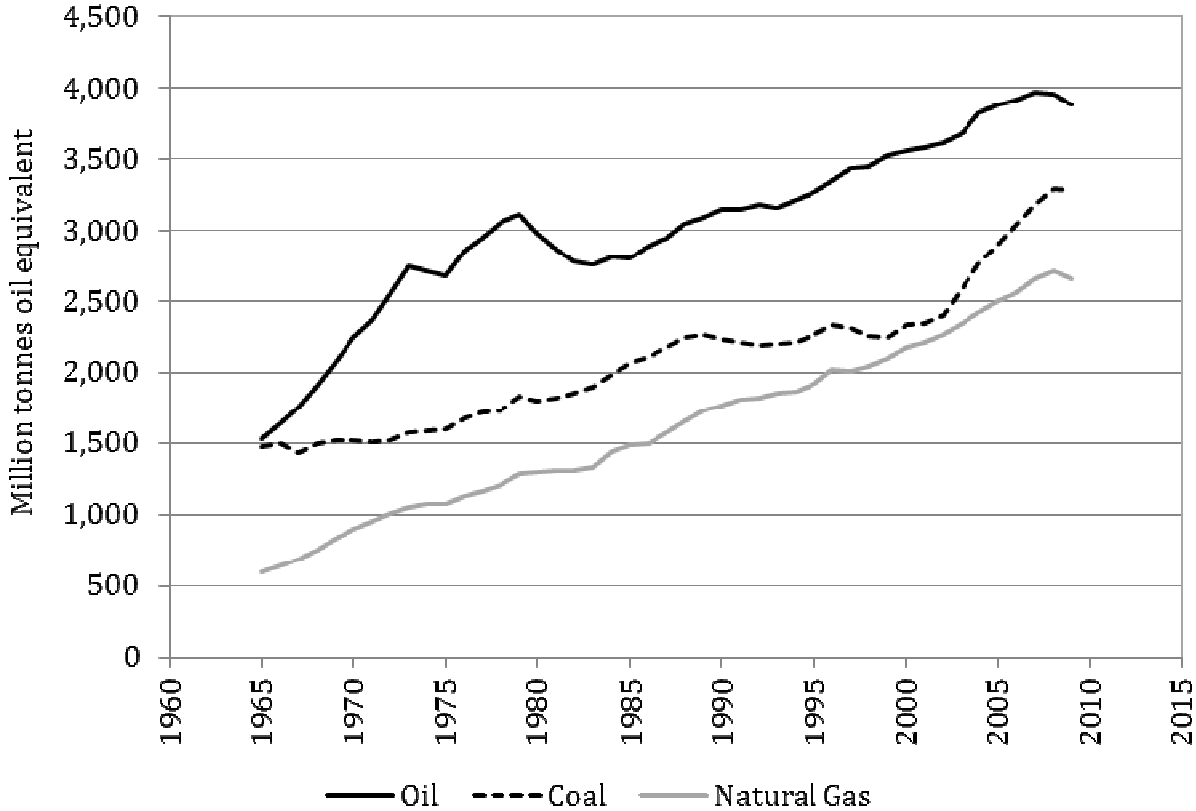


Figure 2-1: Historical world consumption of fossil fuels [12]

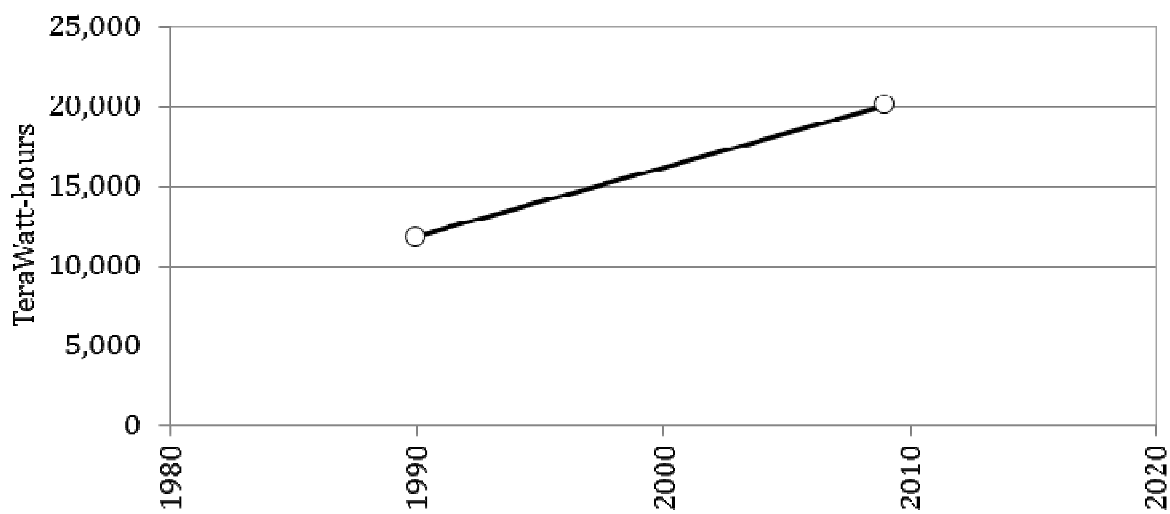


Figure 2-2: Historical world consumption of electricity [12]

The rapid growth in energy demand has also made the limitations of the current energy system more pronounced. These limitations fall into one of three categories:

- adverse environmental impact;
- lack of energy security, and unsustainability; and,
- little optimization of power distribution and flow.

Firstly, the combustion of fossil fuel releases emissions that contribute to air and water pollution, as well as climate change. Pollutants include sulphur dioxide, nitrous oxides, carbon monoxide and dioxide, and particulate matter. Sulphur dioxide is a major contributor to acid rain, which damages farmland, forests, aquatic ecosystems, and buildings. Nitrous oxides and carbon monoxide, primarily from the internal combustion engines of vehicles, contribute to photochemical smog formation in urban areas. Smog is a serious problem in many cities and has adverse effects on human health – it can inflame breathing passages and decrease the working capacity of the lungs, as well as cause shortness of breath pain while inhaling deeply, wheezing, and coughing. The Ontario Medical Association estimates that smog is responsible for 9,500 premature deaths in the province each year [13]. The carbon dioxide emitted is a key greenhouse gas and alters the balance of Earth's natural greenhouse effect, accelerating climate change, also known as anthropogenic global warming AGW. The resulting higher CO_2 levels and temperatures will affect global ecosystems, and are expected to cause extinction in a number of species. It is also expected to cause a rise in sea levels, putting countries that are close to the sea level at risk of land loss. This could in turn lead to freshwater shortages, loss of spread of disease as a secondary consequence. Bangladesh (population: 156 million) is one such country – it is estimated that the rise of sea levels will displace at least 20 million people [14].

Secondly, fossil fuels resources are scarce and finite in nature. Only a few regions in the world have sizable deposits of fossil fuels, and this has led to increased political tensions and lower energy security. As easy-to-exploit fossil fuel deposits are extracted, it becomes increasingly difficult and costly, both financially and environmentally, to extract other fossil fuels. This difficulty, coupled with the growing demand for fossil fuels, leads to scenarios in which the extraction of fossil fuels reaches a peak and declines in response to market forces. This is also known as ‘Peak Oil’, as developed by Hubbert in 1956 [15]. Similar considerations can also be made for peak natural gas and coal extraction. By some pessimistic estimates global oil extraction rates have already peaked, even though countries such as Saudi Arabia, Kuwait and Iraq have yet to reach their peaks. According to optimistic estimates, global oil and natural gas production are expected to reach their peaks around 2030 and 2050 respectively [16]. While coal reserves are expected to last more than 100 years at the current rate of demand, they cannot be expected to suffice in the absence of oil and natural gas. Furthermore, coal is considered to be a primary source of carbon dioxide pollution, a greenhouse gas and the key contributor to climate change.

Finally, the limitations of bulk electricity storage technologies have largely dictated the way in which electricity systems have been developed so far. As demand grows the need for such technologies is more pronounced. Despite ongoing research, bulk electricity storage technologies have not been able to match the energy densities provided by fossil fuels. Despite their widespread use, electricity and fossil fuels have had little interaction historically due to the differences between the two technologies. The high energy density of fossil fuels complement the ease of transporting electricity, but interconversion between the two forms is not feasible and synergistic effects could not be exploited. The future of current transportation technologies depends strongly on a reliable and cheap source of fossil fuels, which are inherently unsustainable.

The hydrogen economy will address these limitations by displacing the use of fossil fuels as a transportation fuel as much as possible. Hydrogen provides a better complement to electricity, as conversion between the two energy carriers is both possible and produces no operational emissions [3].

Hydrogen is an energy carrier which can be generated from a wide variety of energy sources or feedstocks (Figure 2-3), including natural gas (through steam methane reforming), and electricity (through the electrolysis of water). Hydrogen today has a variety of industrial uses, from the production of fertilizers to lubrication for large turbines. However in the context of the hydrogen economy its primary use would be as a medium for energy storage before conversion into electricity. Thus hydrogen would have applications as an energy carrier on board vehicles and as a storage medium for off-peak electricity [3].

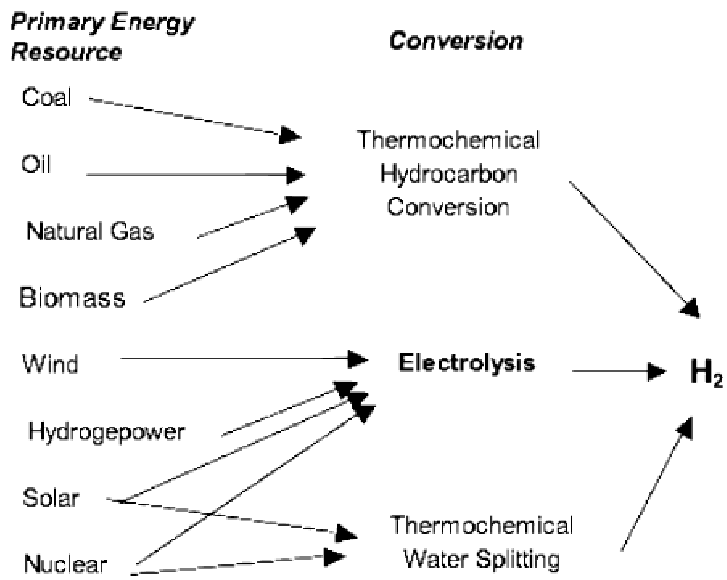


Figure 2-3: Resources and conversion technologies for hydrogen production [3]

The aim of a hydrogen economy would be to minimize the emission of greenhouse gases and air pollution at every point between the energy source and energy consumption. When produced from nuclear and renewable sources of electricity through the electrolysis of water, the emissions associated with hydrogen are minimal. There are no operational emissions associated with the electrolysis of water. All of the life cycle emissions associated with the hydrogen would be a result of fossil fuel used in creating and transporting the required equipment, and with time this would be replaced by hydrogen itself, resulting in hydrogen with no associated emissions. The widespread use of hydrogen fuelled vehicles is expected to greatly reduce urban air pollution costs by the year 2100 (Figure 2-4) [17], and reduce the generation of greenhouse gases. The hydrogen economy would also reduce the reliance on specific sources of fossil fuels, as renewable energy sources could be utilized in almost any region to generate the electricity required to produce hydrogen. This would allow most regions to achieve some degree of energy independence.

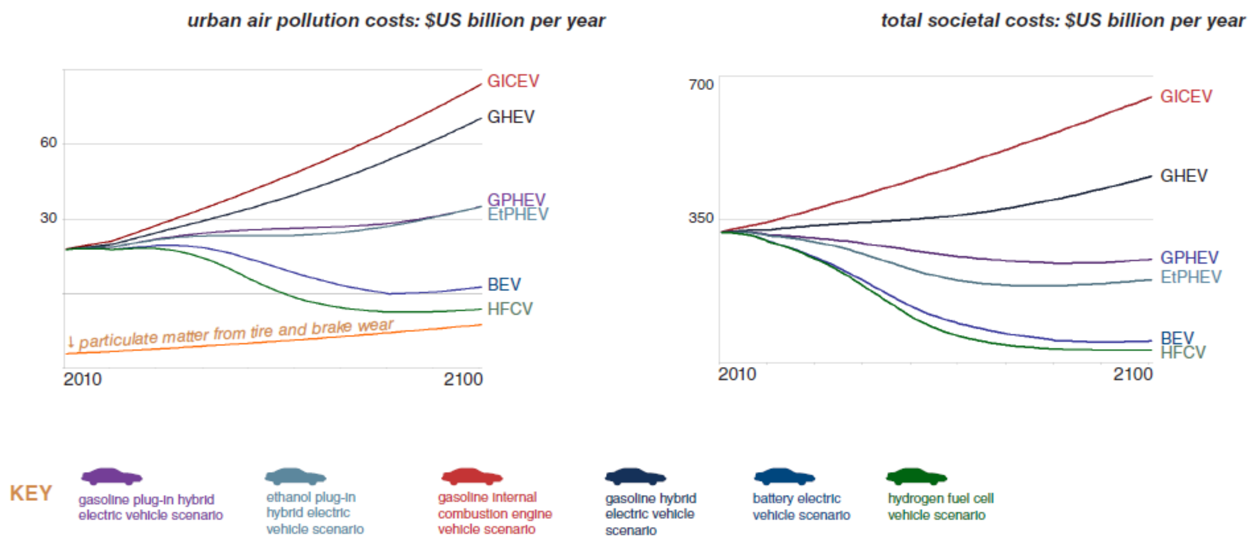


Figure 2-4: Projected costs of air pollution by various transportation technologies [17]

2.2 Energy Hubs

An integrated energy system is required to deal with diverse energy suppliers and multiple energy carriers [18]. A key aspect of a future integrated energy system will be its ability to provide reliable service to energy consumers; it should be able to guarantee a supply of energy in any form or quantity that the energy consumers are likely to demand. There are two prominent challenges to providing reliable energy service:

- the discrepancy in the times at which energy is produced, transported and demanded by consumers, and
- the discrepancy between the mix of energy carriers (electricity and hydrogen) produced, and the mix that is demanded by consumers.

The energy hub has been considered a viable concept in envisioning the structure of an integrated energy system which can adapt to the aforementioned challenges [19]. Energy hubs are relevant to the long term evolution of a future integrated energy system [20][21]. An energy hub is a unit which consists of energy input/output, conversion and storage technologies for multiple energy carriers [22][23]. Figure 2-5 illustrates an example energy hub, as envisioned in the context of a carbon economy.

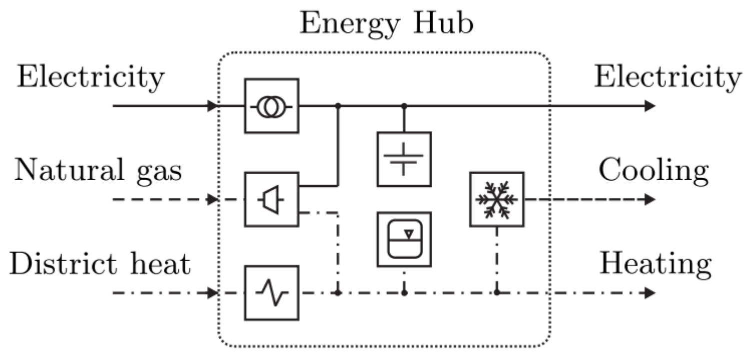


Figure 2-5: Example of a hybrid energy hub

Given their bridging abilities, energy hubs would provide interface between participants: the energy producers, consumers, and the transportation infrastructure [21]. Considered in a decentralized network, these hubs would form the nodes of an integrated energy system or network (Figure 2-6).

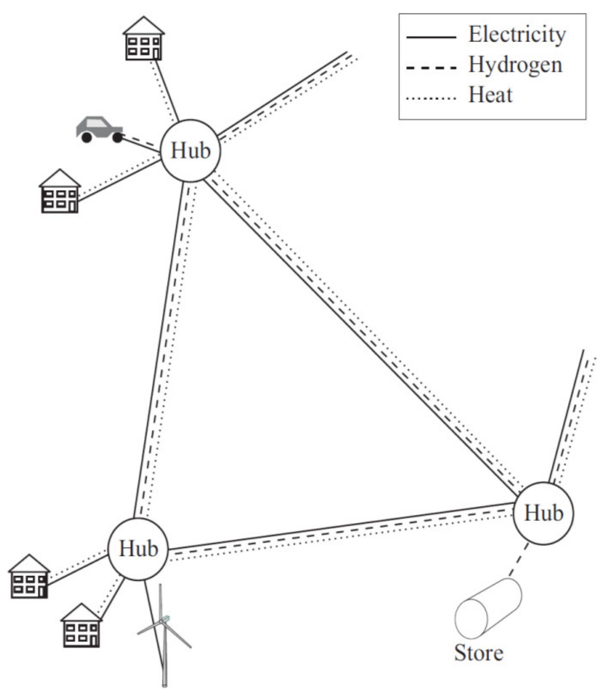
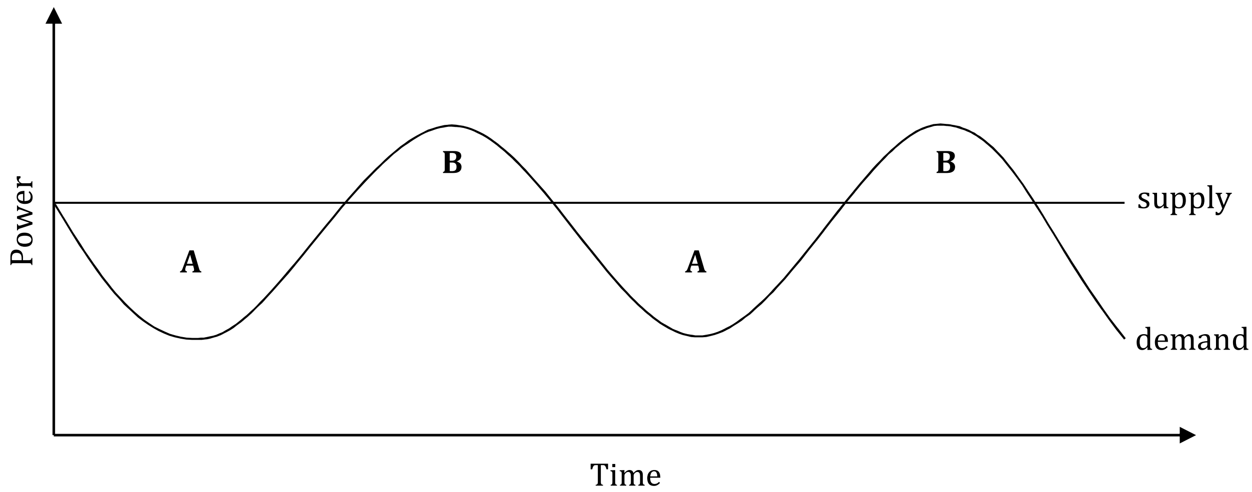


Figure 2-6: A network of potential energy hubs [19]

As Figure 2-6 illustrates, each energy hub could be interfaced with different types of network participants. Some energy hubs may be dedicated to interface a single large energy producer to the transportation infrastructure, whereas other energy hubs may be utilized to interface a diverse set of small energy consumers to the transportation infrastructure. Other energy hubs may even connect energy producers and consumers located in the same geographical region without utilizing the larger transportation infrastructure. Such a network of energy hubs would no doubt require a sophisticated and responsive control system.

At their most basic level, energy hubs could simply be used to transfer energy without converting between energy carriers. An example would be an energy hub which connects a large, centralized electricity generator to the electricity grid. Such a hub would only consist of electricity conditioning equipment, and would likely not require and storage or conversion technologies. Similarly, an energy hub might be used simply to connect a large, centralized hydrogen production plant to a major hydrogen pipeline. Such a hub would only consist of hydrogen pressurization technologies, and would likely not require storage or conversion technologies.

Energy hubs may be used to address the discrepancy in the times and locations at which energy is produced, transported and demanded by consumers. This would be accomplished through the use of energy storage technologies [24]. With careful planning, the energy hub would be designed with sufficient capacity to meet the energy demand of the units to which it is connected to for any amount of time (Figure 2-7). An example would be a hub that used an array of batteries to store electricity, or a compressed gas tank to store hydrogen. Such a storage capability would eliminate the lack of reliability caused by the discrepancy in the times at which energy is produced, transported and demanded by consumers.



A demand < supply, store excess energy
B demand > supply, retrieve stored energy

Figure 2-7: Illustration of the use of energy hubs for peak shaving applications

Energy hubs may also be used to address the discrepancy between the mix of energy carriers (electricity and hydrogen) produced, and the mix that is demanded by consumers. For example, an energy hub may be connected to an electricity generator on one end, and a hydrogen refueling station (or any unit that demands hydrogen) on the other. There is a mismatch between the type of energy supplied and demanded. Such an energy hub would contain conversion technologies such as electrolyzers to generate hydrogen while consuming the input electricity. This hydrogen would then be an output from the energy hub to the source of the hydrogen demand. In a more complicated example, an energy hub may be connected to several electricity and hydrogen generators one on end, and several electricity and hydrogen demand units on the other. If the ratio of electritiy to hydrogen demanded is not the same as that supplied, the energy hub can once again use its conversion technologies to achieve the desired mix. If there is too little hydrogen, the energy hub may contain electrolyzers to generate more hydrogen. If there is too much hydrogen, the energy hub may contain fuel cells or turbines to consume some hydrogen to generate electricity. Energy hubs would allow for greater diversity in supply and more flexibility in the optimization of energy flow and utilization [25].

In the context of the hydrogen economy, a 'clean' energy hub would only contain technologies which do not emit greenhouse gases during operation (e.g. nuclear, wind, solar) and would be limited to handling electricity and hydrogen, as well as the internal use of heat. Previous work has shown hydrogen technologies to be suitable for use in energy hubs [26] and studied the impact of energy pricing and time of use of either fuel cells or electrolyzers [4].

2.2.1 Optimization problems

A review of literature pertaining to distributed generation and multi-energy systems [25] finds that energy hub optimization is addressed through four basic objective functions:

- minimizing energy costs [23][27][28];
- minimizing annual costs [29][30];
- minimizing CO_2 emissions [31][32][33]; and,
- maximizing net present value [34][35].

2.3 Electric Vehicles

2.3.1 Electrification of the powertrain

A hybrid vehicle is defined as a vehicle which uses multiple energy sources onboard the vehicle to provide propulsion. Their advantage over conventional vehicles, which only use gasoline, is lower fuel consumption. The term Hybrid Electric Vehicle (HEV) refers to vehicles with a large onboard battery to supplement the internal combustion engine (ICE). The first mass-manufactured HEV was the Toyota Prius, which went on sale in Japan in 1997 and internationally in 2001. Since then, several vehicle manufacturers have entered the mass-manufactured light-duty HEV market. HEVs enjoy significant acceptance, and accounted for approximately 2.4% of new vehicle sales in the United States of America in 2008 [36]. In April 2009, the Honda Insight was the top-selling HEV in Japan.

HEVs reduce fuel consumption over conventional vehicles by managing onboard energy pathways to optimize the use of energy in the vehicle. There are two main strategies for accomplishing this. The first is regenerative braking; the vehicle captures the kinetic energy while braking to charge the battery instead of wasting the energy as heat. This technique partially recovers the braking energy of the vehicle and is important because it reduces the importance of vehicle weight for fuel consumption. As a result, aerodynamic drag becomes more important for hybrid vehicles.

The second strategy is to use the battery to run the engine at more efficient operating points. If the most efficient operating point is below the level required to maintain a certain speed, then the battery will temporarily provide energy. If the most efficient operating point is above the level then the battery will be charged with the excess electricity. By switching back and forth between lower and higher efficient operating points, the battery charge can be maintained while decreasing overall fuel consumption.

The growth of the HEV market has created several categories of HEVs, in increasing level of electrification of the powertrain, including:

- Battery-alternator starter hybrids;
- Two-mode hybrids;
- Series/parallel hybrids;
- Plug-in hybrid electric vehicle;
- Plug-in fuel cell vehicles; and
- Electric vehicles.

2.3.2 Types of models (forwards-facing vs. backwards-facing)

There are two primary methods of modelling the performance of a vehicle: forwards-facing and backwards-facing [37]. Each method has associated advantages and disadvantages and is suitable to certain situations.

In forwards-facing modelling, an arbitrary throttle is applied to the propulsive subsystems of the vehicle, and the component models (such as engine, transmission, fuel storage) calculate the effects on fuel consumption, speed and other variables. This generally enforces a causal relationship between input and output, and produces generally accurate results. However if the model uses look-up tables to convert between input and output, the model is not considered fully causal. However it is still expected to produce accurate results, assuming high accuracy and interaction-capture in the look-up tables.

Forwards-facing models utilize one or more simulated feedback controllers to actuate the throttle and braking mechanisms in order to match the target speed. Figure 2-8 illustrates the control schematic for a forwards-facing model.

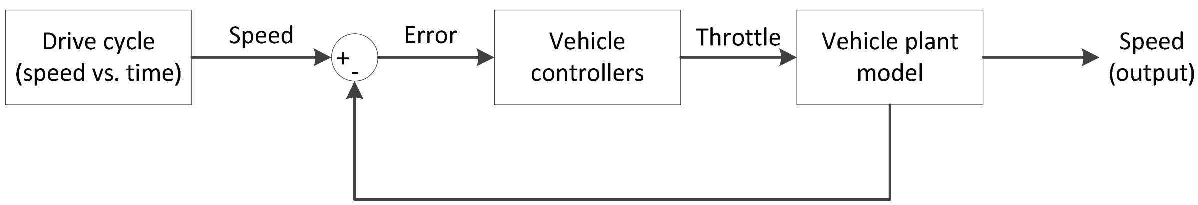


Figure 2-8: Flowchart representation of forwards-facing model schematic

A key advantage to forwards-facing models is that the results produced will remain within operational bounds. If the desired speed is too high for the vehicle to simulate, then the component models will reveal the discrepancy between desired and actual vehicle speed. This is necessary in an architecture selection process as it reveals if the selected components will not be able to perform under regular driving conditions. A proper selection process always studies the sensitivities of the components to determine the maximum performance of a vehicle and ensure that it is able to adequately meet consumer requirements.

As the name implies, backwards-facing models reverse the order of calculation; they back-calculate from target speed to determine the required fuel consumption and throttle. The target speed is assumed to be met by the vehicle at all times.

A key advantage of this approach is speed. Backwards-facing models calculate faster than forwards-facing models due to the lack of a feedback-loop and simpler vehicle controllers. Figure 2-9 illustrates the control schematic for a backwards-facing model.

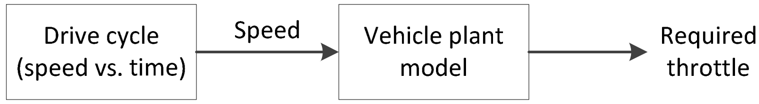


Figure 2-9: Flowchart representation of backwards-facing model schematic

A backwards-facing model may not necessarily stay within operational bounds of the vehicle, and may report speeds that are not achievable by the vehicle. This is due to the lack of the feedback loop which corrects the behaviour of the model. As the backwards-facing model simply calculates the required energy consumption for the desired drive cycle, it does not consider any constraints of the vehicle hardware. In this sense, it is less preferable than a forwards-facing model, which will indicate the suitability of a particular vehicle architecture in meeting speed requirements. In general, backwards-facing models are less accurate than forwards-facing models.

An example of a backwards-facing model is the ADVISOR software [38], developed by the National Renewable Energy Laboratory (NREL).

A vehicle architecture selection process may use both backwards- and forwards-facing models to determine the best architecture. A backwards-facing model may be ideal when screening a large search space where accuracy is not critical and order-of-magnitude estimates are required. The initial screening can determine unsuitable architectures and component combinations quickly and without the computational expense of a forwards-facing model. Once a set of potential architectures have been determined, a forwards-facing model may be used to conduct a thorough analysis in order to determine the best architecture. This approach would leverage both the speed of a backwards-facing model and the accuracy of a forwards-facing model.

Advancements in computer technology, such as increased processing speed and distributed computing, have reduced the disadvantages of forwards-facing models. However models of increased complexity and the communication limits of distributed computing may once again require the use of backwards-facing models in an architecture selection strategy.

2.3.3 Modelling software

Existing vehicle models, such as the Powertrain Systems Analysis Toolkit (PSAT) by Argonne National Laboratory and CRUISE by AVL [39], can simulate energy flow within a vehicle over a given drive cycle. Vehicle powertrain designers primarily use them to perform component sizing and develop vehicle control strategies. They are used mostly for hybrid electric vehicles where the energy can come from a combination of an electricity storage system and a range extender (in this case a hydrogen storage system). These models have high temporal resolution (typically one second) and consist of detailed component models (e.g. engines, electric motors, power converters and accessory loads) that interact to simulate vehicle operation. Both PSAT and CRUISE are examples of forward facing vehicle models. Figure 2-10 illustrates an example representation of a PFCV architecture in PSAT.

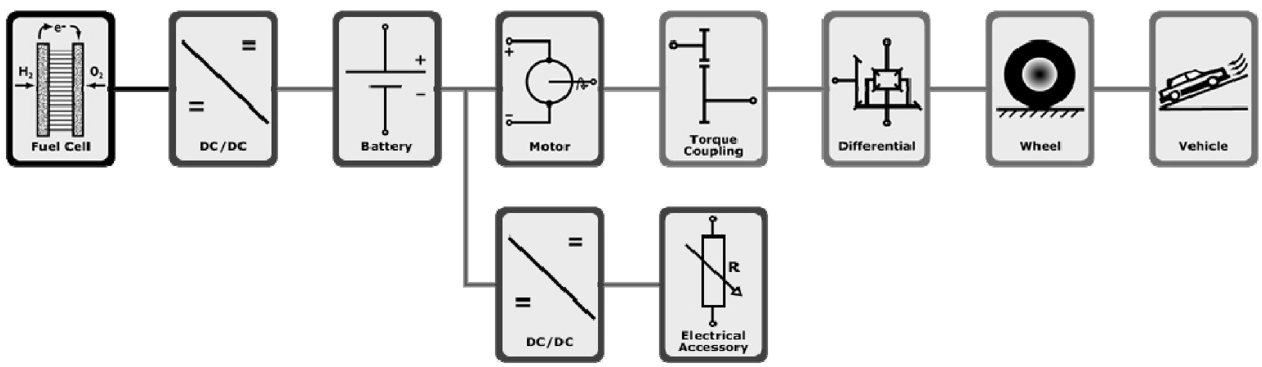


Figure 2-10: Example vehicle architecture representation in PSAT

2.3.4 Operating strategies

The choice of operating strategy can have a significant impact on the fuel consumption of an advanced vehicle. The multiple energy pathways allows for best operating zones which minimize fuel consumption, and the study of operating strategies is an active area of research.

For advanced vehicles with electric drive, there are two main types of operating strategies: electric drive, and blended [40].

The electric drive, has two different modes of travel: charge-depleting and charge-sustaining. In this strategy, the vehicle begins travel in the charge-depleting mode and relies almost exclusively on the battery to provide propulsion, and the battery pack state of charge (SOC) is lower an the end of the trip then the beginning of the trip. The distance drivable in this mode is called the All Electric Range (AER), or the charge-depleting range, and will be an important metric in the marketing of advanced vehicles since it is important in the reduction of gasoline consumption. Once the battery's charge has been depleted to a minimum operating point, the vehicle switches to charge-sustaining mode. In this mode, the vehicle operates like an HEV and only uses the battery for regenerative braking. It maintains the charge-sustaining mode throughout the rest of the travel until the vehicle is charged again (Figure 2-11).

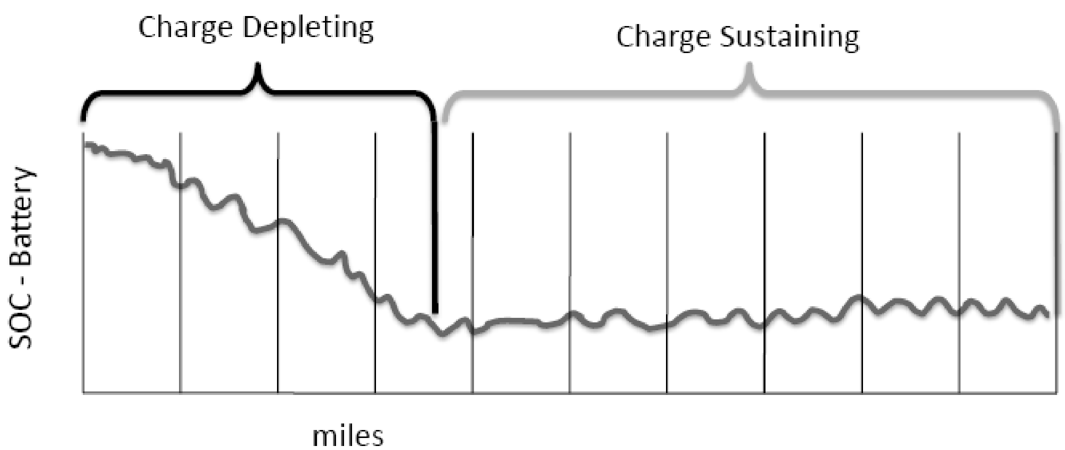


Figure 2-11: Illustration of battery response to charge-depleting and sustaining modes

The vehicle will have different fuel consumption in the charge-depleting and charge-sustaining modes. In the charge-depleting mode, the vehicle will have negligible fuel consumption, whereas in the charge-sustaining mode, the vehicle will have fuel consumption comparable to a regular HEV. This complicates the question of calculating an "overall fuel consumption" for the vehicle. The overall fuel consumption depends heavily on the AER and on how the vehicle is driven.

The second type of operating strategy is the blended strategy. In this case, the vehicle does not have separate charge-depleting and charge-sustaining modes, but rather uses a consistent mix of power from the battery and ICE to drive the vehicle. This results in the battery charge slowly depleting over the duration of the "typical" trip length.

The blended strategy typically has lower fuel consumption than an electric drive strategy over the length of a typical trip, since the battery operates at more efficient regions for a large part of the trip. Therefore, for a driving schedule which will regularly exceed the AER of most electric drive vehicles, a blended strategy is preferred. The benefit of the electric drive strategy is for drivers with a pre-determined daily commute. Given enough data on the driving habits of a population, an electric drive vehicle can be specified which will have a sufficiently large AER to minimize fuel consumption over the entire driving population.

2.4 Electricity in Ontario

Ontario has approximately 35,485 MW of installed electricity generation capacity [41], and it comprises of a diverse set of sources. Much of Ontario's generating capacity comes from nuclear power, with the remaining electricity being generated by hydroelectricity, coal, natural gas, wind and other renewable sources. Table 2-1 lists the composition of the major power sources.

Table 2-1 Composition of 2007 Ontario electricity generation capacity

Source	Capacity (MW)	Fraction (%)
Hydroelectric	7788	24.9
Coal	6434	20.6
Nuclear	11419	36.6
Gas	5103	16.3
Wind	395	1.3
Biomass	75	0.24

The Government of Ontario's plan to shut down all coal-fired power plants by 2014 is intended to reduce the adverse environmental and public health effects of coal. Coal-fired plants emit a variety of pollutants and greenhouse gases, such as carbon dioxide, sulphur oxides, nitrogen oxides, sulphuric and hydrochloric acid, lead, mercury, and other heavy metals. Carbon dioxide is a key contributor to anthropogenic climate change, and sulphur and nitrogen oxides are key contributors to acid rain and photochemical smog. Acid rain poses a serious threat to the large agricultural industry in Ontario. Smog tends to accumulate in densely populated cities, and has lasting effects on the public health. Other heavy metal pollutants have been known to be linked to an increase in birth defects. The largest coal-fired plant in Ontario, located in Nanticoke, is estimated to produce 6% of the total pollution in Canada [42].

The Ontario Integrated Power System Plan (IPSP) calls for the lost coal-fired generating capacity to be replaced by increased hydroelectric, natural gas and renewable power sources. Figure 2-12 illustrates the gap due to develop between electricity supply and demand, as predicted by the IPSP.

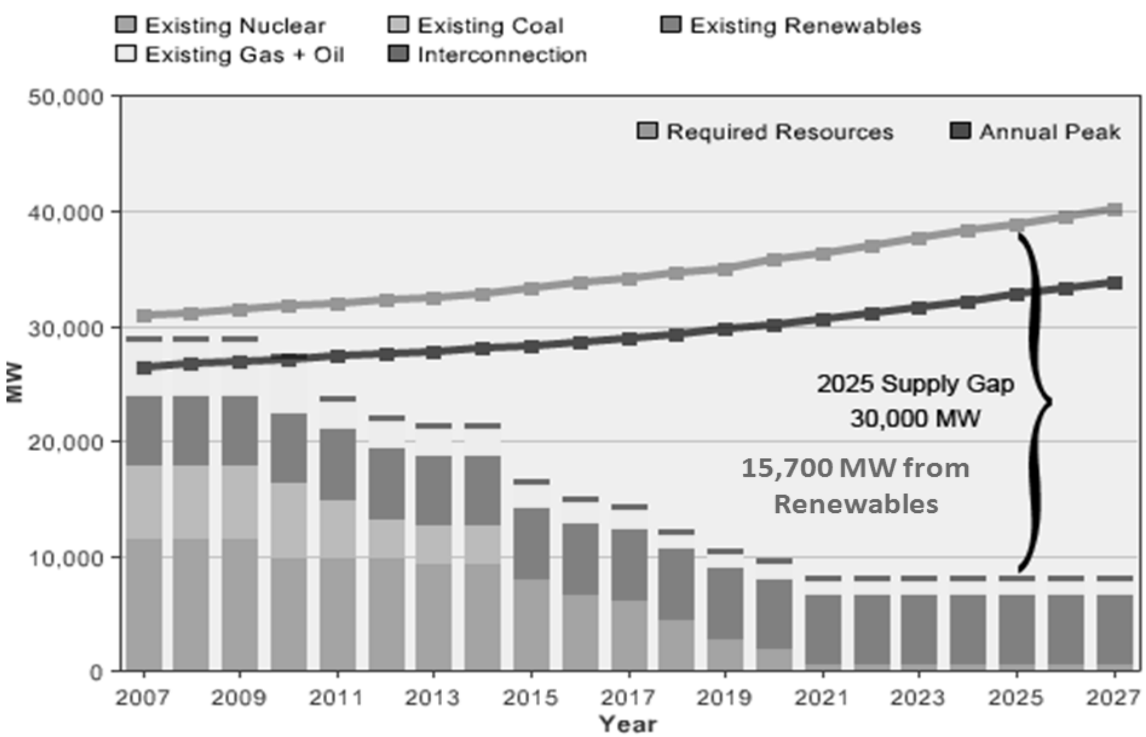


Figure 2-12: Projected of Ontario electricity sources according to the IPSP

2.4.1 *Roles of electricity sources*

An electricity system maintains its reliability by continuously monitoring electricity demand and adjusting the supply accordingly. For this purpose, grid operators produce next-day electricity demand forecasts to help prepare resources for the following day.

Although point sources of demand can be highly variable, when the thousands or millions of point sources are combined into a large grid, the overall electricity demand profile does not change rapidly. This allows grid operators to match supply and demand on a minute-by-minute basis, to ensure reliable electricity service and minimize any waste of electricity resulting from over-supply.

However large electricity systems typically have multiple power sources, such as nuclear, coal, natural gas, hydroelectricity and renewables. The technologies behind each of these power sources have different characteristics that affect their ability to respond to changing demand. For example, Ontario's nuclear reactors are not able increase or decrease power output as fast as coal-fired power plants. As a result nuclear reactors are considered to be a source for **baseload** power: sources which provide the bulk of the supply and cannot be ramped up or down easily. These technologies favour operating at a constant power output and mostly refer to nuclear power, and to a limited extent, hydroelectricity.

The power output of **intermittent** sources, such as wind, tidal, or solar power, cannot be ramped up and down easily to match demand. The power output of these technologies is intrinsically linked to the weather conditions which produce them. Therefore the power output of these sources can be predicted by studying data on past weather conditions. Any system which is fed by intermittent sources should consider the variability of intermittent sources in its design; these sources will not only display variability throughout the day, but the average power output will also fluctuate according to the season. The intermittency of these sources is therefore a barrier to system reliability, despite the environmental benefits associated with them. Electricity systems in which a large percentage of generating capacity comes from intermittent sources must implement means to accommodate the behaviour of these sources.

Electricity systems can accommodate the variability of electricity demand and intermittent sources by relying on **reactive** power sources. These sources can be brought to full generating capacity quickly, and exhibit faster response times to changing demand. In Ontario, these sources are primarily coal- and natural gas-fired power plants.

2.5 Electrolyzers

Water electrolyzers consume electricity to split water into hydrogen and oxygen gas, through the process of electrolysis. Since electrolysis does not involve any combustion processes, electrolyzers do not produce any CO_2 or other greenhouse gas emissions during operation [43], making them a step towards a sustainable hydrogen economy. Electrolyzer efficiencies typically fall in the range of 80% - 90% [44].

There are two types of commercially available water electrolysis technologies: alkaline and polymer electrolyte membrane (PEM). The names refer to the type of electrolyte used in the technology. Of the two technologies, alkaline is the more mature and currently dominates the world market. However, PEM electrolyzers are better suited towards smaller distributed generation applications, due to the lower temperatures required [45].

2.5.1 Alkaline electrolysis

Alkaline electrolysis uses a solution of potassium hydroxide (KOH) as an electrolyte. The chemical reactions in an alkaline electrolyzer are listed below in Table 2.1.

Table 2-2 Reactions in an alkaline electrolyzer

Half cell	Reaction
Anode	$4OH^- \rightarrow O_2 + 2H_2O + 2e^-$
Cathode	$4H_2O + 4e^- \rightarrow 2H_2 + 4OH^-$
Overall	$2H_2O \rightarrow 2H_2 + O_2$

Alkaline electrolyzers can produce hydrogen gas at pressures of up to 25 bar, and they require additional compressors to produce the pressures required for compressed hydrogen storage. They also have a current density of approximately $0.4A/cm^2$ [46].

The low current density, combined with the liquid electrolyte design, leads to a design more suitable for stationary applications [47]. As a result, alkaline electrolyzers are commercially available in large scale units suitable for industrial applications.

The efficiency of alkaline electrolyzers ranges from 60% - 90%, and the purity of the output gases is approximately 99.2% [46]. Figure 2-13 below illustrates the process flow diagram for alkaline electrolysis.

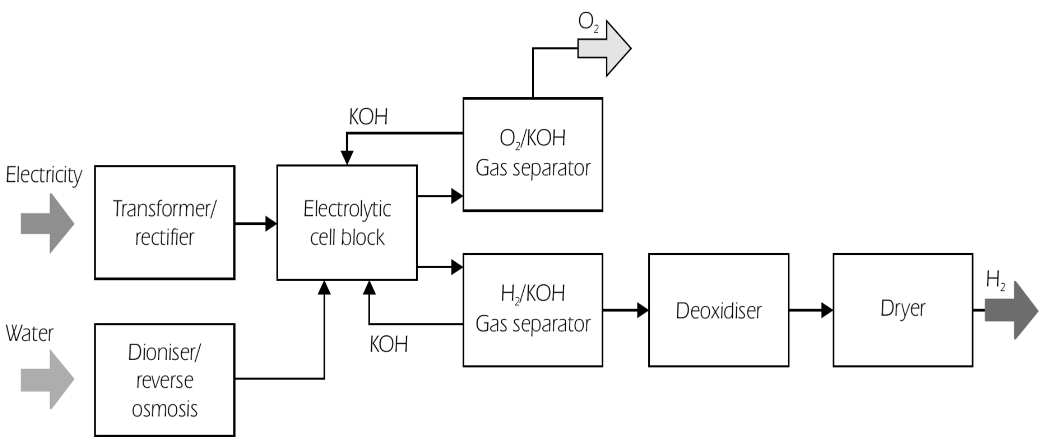


Figure 2-13: Process flow diagram of alkaline electrolysis [47]

2.5.2 *Polymer Electrolyte Membrane (PEM) electrolysis*

PEM electrolyzers have a simpler design than alkaline electrolyzers due to the lack of a liquid electrolyte. PEM electrolyzers use an acidic polymer membrane which is selectively permeable to H^+ ions. The chemical reactions in PEM electrolyzers are listed below in Table 2-3.

Table 2-3 Reactions in a polymer electrolyte membrane electrolyzer

Half cell	Reaction
Anode	$2H_2O \xrightarrow{Pt} 4H^+ + 4e^- + O_2$
Cathode	$4H^+ + 4e^- \xrightarrow{Pt} 2H_2$

Half cell	Reaction
Overall	$2H_2O \xrightarrow{Pt} 2H_2 + O_2$

PEM electrolyzers can produce hydrogen gas at pressures of up to 200 bar without additional compressors. Their current density is higher than that of alkaline electrolyzers: it ranges from 1 - 2A/cm^2 [46]. However at the high end of the current density range the efficiency of the electrolyzer drops.

The high current density, high output pressure and solid electrolyte lead to a design suitable for both stationary and mobile applications. PEM electrolyzers are considered to be a good solution for distributed hydrogen generation [45]. However they are less technologically mature than alkaline electrolyzers and more expensive due to the platinum-based catalyst on the electrolyte membrane. Further research is focused on reducing the cost of the materials and improving the efficiency and lifetime of the membrane, which can be prone to both physical and chemical degradation [48].

The efficiency of PEM electrolyzers ranges from 50% - 90%, and the purity of the output gases is approximately 99.9999% [46], making them ideal for high purity applications.

2.5.3 North American Manufacturers

Due to the chosen location of Toronto, Ontario for the clean energy hub under consideration, a market survey of North American manufacturers of water electrolyzers was conducted [49]. Table 3.1 below lists the identified vendors, and their technical product literature was obtained.

Table 2-4 Selected North American Electrolyzer Vendors

Vendor	Headquarters
Hydrogen Technologies	Clearwater, Florida, USA

Vendor	Headquarters
Hydrogenics Power Inc.	Mississauga, Ontario, Canada
Proton Energy Systems Inc.	Wallingford, Connecticut, USA
Teledyne Technologies	Thousand Oaks, California, USA

2.6 Building Energy Demand

Buildings will be key contributors to electricity demand in a future integrated energy system, and detailed load profiles are needed as input for energy hub simulations. Such a model will be linked to an energy hub model to investigate their interactions. A literature review was conducted to determine a preferred method for generating hourly electricity demand profiles for a commercial building.

2.6.1 Effect of building type

A review of building energy modelling literature determined that the most significant factor in generating hourly electricity demand profiles is the proper specification of building type. The label "commercial building" may refer to a number of different types, for example:

- office building;
- supermarket;
- retail building; and,
- hotel.

Specifying the building type largely determines the shape of the hourly electricity demand profile. The type of building (hospital, school, office building, residential, commercial) will determine whether the bulk of electricity demand is during peak or off-peak hours.

Figure 2-14 to Figure 2-17 illustrate the differences between the hourly electricity demand profiles of four commercial building types.

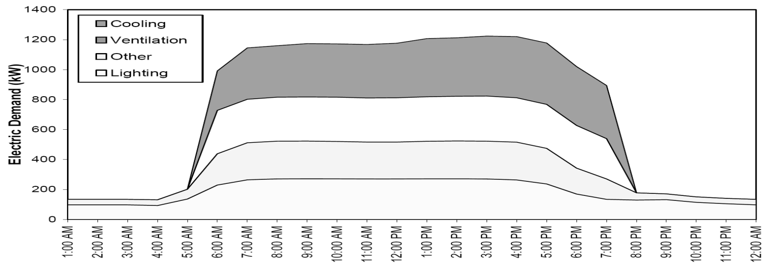


Figure 2-14: Generic Office Building Energy Use Profile [50]

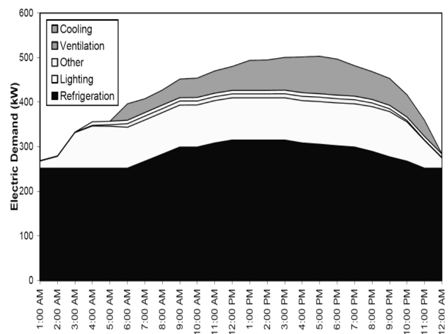


Figure 2-15: Generic Supermarket Building Energy Use Profile [51]

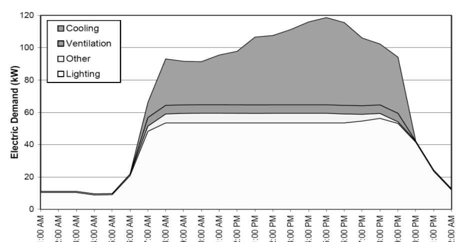


Figure 2-16: Generic Retail Building Energy Use Profile [52]

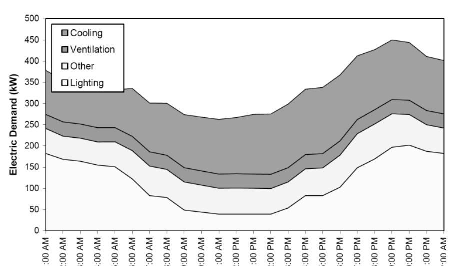


Figure 2-17: Generic Hotel Building Energy Use Profile [53]

The office and retail electricity demand profiles follow an expected shape. The electricity demand is highest during business hours. In particular, the demand due to lighting is consistent and the variability in demand during the business day is primarily due to ventilation requirements. The supermarket profile also follows a shape expected for a building operating 24 hours per day. The dip in electricity demand during the day in the hotel profile is explained by hotel guests increasing electricity demand during non-business hours.

The figures above are only generic representations of electricity demand profiles and the magnitude of a building's electricity demand is determined by assumptions made about the building geometry, size and location.

2.6.2 Approach

The basic method is to separately model major energy demand categories, such as cooling, heating, lighting and appliances. Some of these are time dependent, such as lighting. The operation of the building's heating and cooling systems will be dependent on the weather, so local weather data will be required when modelling the energy use due to those components.

One approach is to take direct, high resolution measurements of the energy use in buildings to obtain the required data. The data could be used to create a stochastic model based on time-of-use curves [54]. The number of devices required to capture the end-use of energy (such as water taps, or individual appliances) would make the survey complex and costly, although there are some counter-examples [55][56][57]. In lieu of detailed measurements, load modelling is the preferred method for analysing building energy use in the context of energy hubs.

Another option is to utilize pre-existing models designed to simulate the hourly electricity demand of a building. An exhaustive review of existing building modelling tools by Jacobs and Henderson [58] identified six state of the art tools, and from among them chose the tool DOE-2 as the most important public-domain tool. DOE-2 was developed by Lawrence Berkeley Laboratory, and it represents a mathematical model for building energy simulation. Several graphical user interfaces have been designed to work with DOE-2. Medrano [59] selected the eQuest interface for DOE-2 for analysis. eQuest was also used in a PhD dissertation [60] to develop a design methodology for high-rise office buildings to optimize energy efficiency and minimize negative environmental impacts. The program was also used to generate the hourly use scenarios for NAPEE [50][51][52][53]. eQuest assists building energy simulation by asking high-level questions about the building's shape and operation through a wizard interface. Figure 2-18 shows a screenshot of the options presented by eQuest.

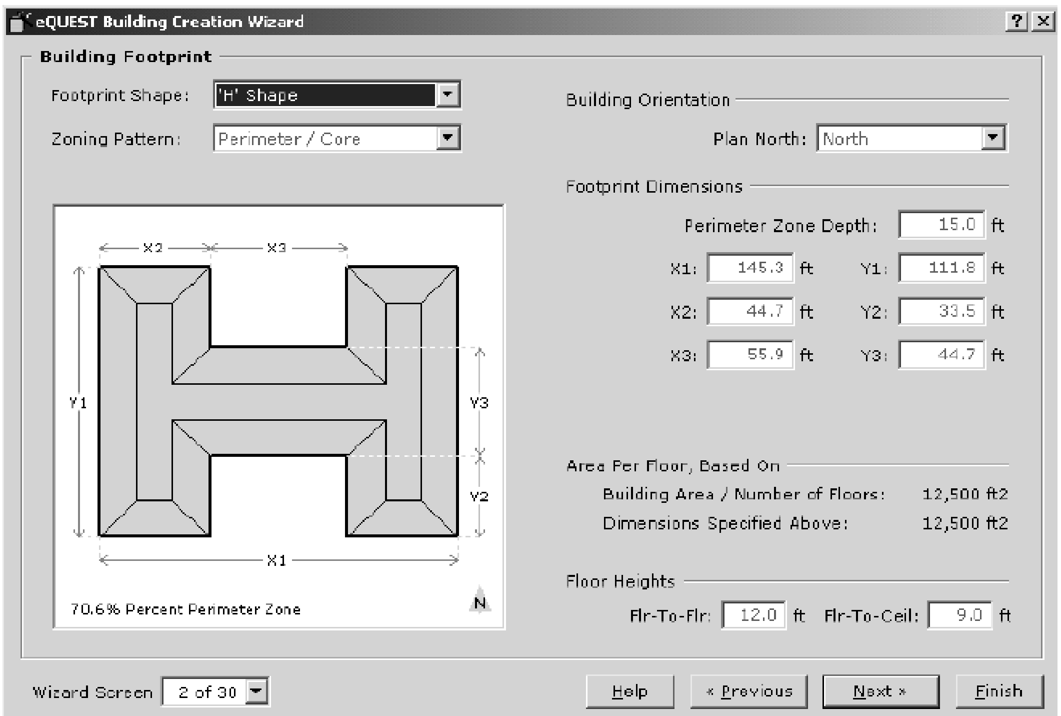


Figure 2-18: Screenshot of eQuest Building Simulation Software

Chapter 3
Energy Modelling

This chapter presents the model development of an integrated energy system in which a clean energy hub interfaces energy supply and demand components. The energy supply consists of wind turbines and a connection to a broader electricity grid. The energy demand comprises of a commercial building and a plug-in fuel cell vehicle fleet. The electricity grid can also receive electricity from the energy hub, in which case it also acts as an energy demand component. First, an overview of the entire system is presented. This includes a discussion on energy modelling for a generalized energy component. After that, the energy modelling of each component is presented in detail. Finally the operating logic of the hub is presented in detail.

The model was implemented in MATLAB, which was chosen due to its suitability as a scientific computing platform, well-maintained documentation, and its widespread use in academia and industry. This will enhance the extensibility, reusability, and flexibility of the model, as users proficient in the software can create custom functionality to enhance the model. The MATLAB code is reproduced in Appendix A.

3.1 System Overview

An integrated energy system was modelled utilizing the concept of an energy hub. The system is considered to be a network of components, with the energy hub as a central component. Energy is transferred between the components as dictated by the model logic. Accordingly, the system model is stated in two parts: power flow *within* and *between* components. The model is based on the following assumptions and simplifications:

- The system is considered to be at quasi steady-state, reached after all transients or dynamic conditions have been dampened;
- Power is characterized through energy transferred per time step (kWh or kg) and efficiency (%) only. No other units are used; and,

- Unidirectional power flow between the inputs and outputs of components is assumed, unless mentioned otherwise.

The purpose of the modelling was to investigate the interactions between a single energy hub and novel components such as a plug-in fuel cell vehicle fleet (PFCV). As such, the modelling of interconnected energy hubs is not required, and is simulated by interfacing the energy hub with a connection to an electricity grid (which is assumed to comprise of other energy hubs). Figure 3-1 illustrates the schematic of the integrated energy system.

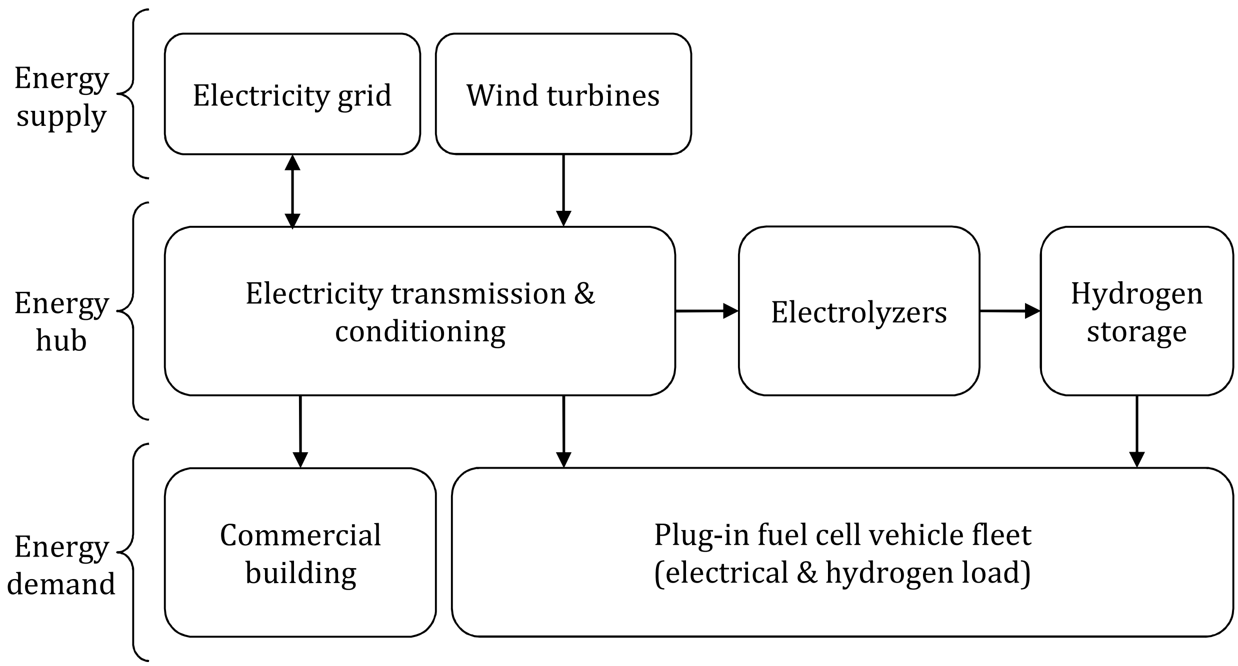


Figure 3-1: Schematic of the integrated energy system

The energy hub is designed to process two energy carriers: electricity and hydrogen. It provides an interface between the electricity supply and electricity demand components, and performs the necessary electricity conditioning (voltage transformation). It also interfaces with hydrogen demand components, namely the vehicle fleet. It is not connected to a hydrogen supply component, but it allows for conversion of electricity to hydrogen through electrolyzers. The electrolyzers are able to consume electricity to generate hydrogen. Although electrolyzers also require a supply of water, this requirement is not considered in this model as the focus is on energy utilization. The hydrogen produced by the electrolyzers is pressurized and stored in the hydrogen storage tanks. At this time the oxygen is not collected, although there is a realization that marketing of the oxygen could contributed to the economic viability of the energy hub.

The energy supply consists of facility wind turbines, as well as a connection to the electricity grid. In this model, the wind turbines are the primary source of electricity. Wind turbines were selected as a zero-emission distributed energy generation system, and the power from a wind turbine would be more significant than power from solar photovoltaic cells at this facility. The electricity grid is both a secondary source of electricity as well as a purchaser of excess electricity produced by the wind turbines. In this sense the electricity grid also acts as an energy demand component. Both the wind turbines and the electricity grid are connected to the energy hub's electricity system. The electricity system is able to control the flow of electricity to each of the attached loads according to the hub logic.

The largest load connected to the electricity system is the commercial building. This building will consume large amounts of electricity during its defined business hours, and a minimal amount of electricity during the remainder of the day. The commercial building is considered a simple electricity sink in the model.

The PFCV is a consumer of both electricity and hydrogen. The individual vehicles in the fleet connect to the electricity system through charging stations, and they also connect to the hydrogen storage through hypothetical stations. The individual charging and refueling stations are not included in the model as they do not affect the overall energy transfer.

The overall system model was developed by dividing the system into its functional components, such as the wind turbines and the vehicle fleet, and an operational model was created for each component. Each component model is able to balance the energy inputs, outputs and accumulation of the component. Each component model was then linked to recreate the overall system model, according to Figure 3-1 above. First, the hub schematic is presented in Figure 3-2, with each component represented by a Latin letter.

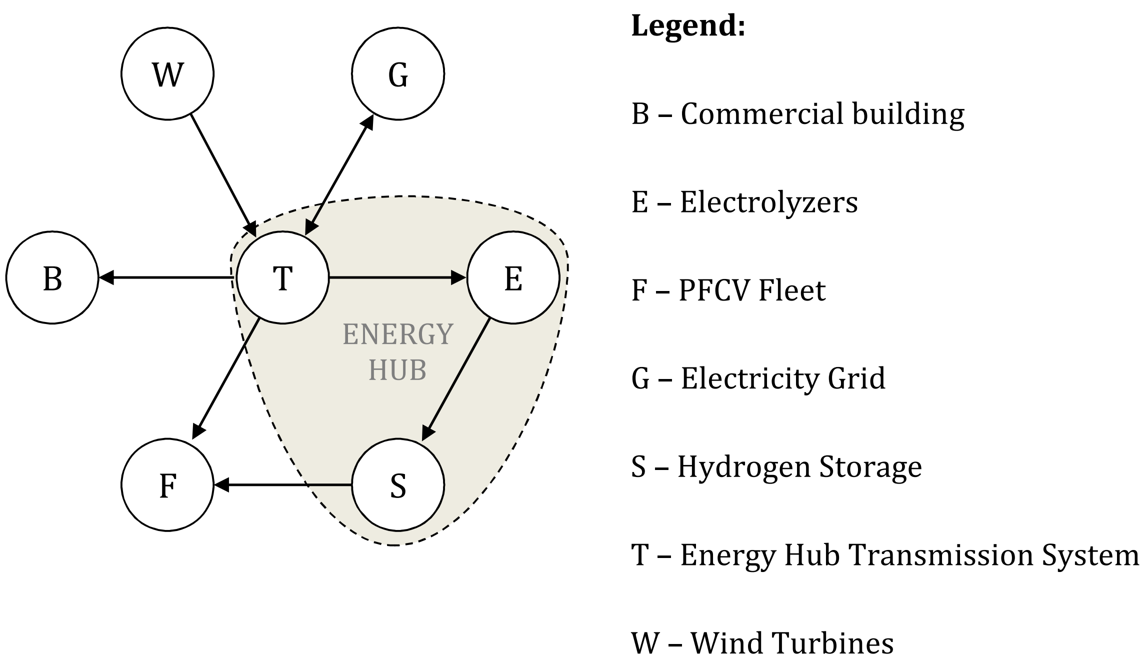


Figure 3-2: Graph of nodes and interactions within the integrated energy system

3.2 General Component Model

A general component model was developed in order to facilitate the development of each component model and the linked of energy inputs and outputs to recreate the system model, the interactions between components were standardized. Figure 3-3 illustrates the resulting general component model.

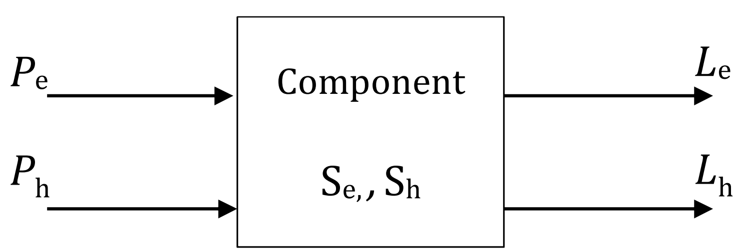


Figure 3-3: Schematic of the general component model

The generalized component model captures all of the different types of units present in the energy system. Energy input(s) and output(s) are represented by the letters P and L respectively. The energy carriers are denoted by the subscript: e for electricity and h for hydrogen. Energy storage within a component is represented by the letter S. This model captures simple transmission devices as well as complex devices consisting of converters and storage units. This leads to a general energy balance for both energy carriers in any component:

$$\frac{d}{dt}S_e = P_e - L_e + c_e \tag{3-1}$$

$$\frac{d}{dt}S_h = P_h - L_h + c_h \tag{3-2}$$

where c_e and c_h are variables that represent generation and consumption within the component.

However this model does not account for transmission losses, or for the possibility of conversion between energy carriers. These effects are enabled by associating coefficients with each input (P) and output (L) term in the model, and also adding cross-carrier terms as such:

$$\frac{d}{dt}S_e = a_{ee}P_e + a_{he}P_h - L_e + c_e \tag{3-3}$$

$$\frac{d}{dt}S_h = a_{hh}P_h + a_{eh}P_e - L_h + c_h \tag{3-4}$$

This model above is generalized enough that it can capture energy transmission, conversion, storage, withdrawal, generation, and consumption behaviours. The a terms act on energy inputs and represent transmission efficiency (in the case of a_{ee} and a_{hh}) and conversion efficiency (in the case of a_{he} and a_{eh}).

The general component energy model is now complete. The coefficient factors may not necessarily be constant. Depending on the behaviour desired, they are calculated from the model logic. In some cases the components may actually be functions of the energy input and storage variables, making the model non-linear. All terms in the model, except for C terms, must be positive as they represent real values. The C terms may be either positive (for energy generation) or negative (for energy consumption).

Equation 3-6 captures all the important modes of behaviour (transmission, conversion, storage, withdrawal, generation, and consumption), but it does not reflect certain real world constraints which affect the dynamics of the system. For example, any use of storage in the system must be constrained by the physical capacity of the technology. In the case of batteries, the upper limit represents the maximum charge they can carry. In the case of compressed gas tanks, the upper limit represents the maximum amount of hydrogen they can hold.

Let $S_e|_{max}$ represent storage capacity of any electricity storage S_e (measured in kWh), and let $S_h|_{max}$ represent the storage capacity of any hydrogen storage S_e (measured in kg). The following two constraints are then applied to the general energy model to respect the upper bounds of storage modelling:

$$0 < S_e < S_e|_{max} \tag{3-5}$$

$$0 < S_h < S_h|_{max} \tag{3-6}$$

Another constraint which applies in certain scenarios is an upper limit on input or output electricity (P_e). This is useful in situations where the energy demanded by a component is greater than the maximum energy that can be supplied to it. This must be defined to enable decision making functionality in certain component models. Let these be represented by

$P_e|_{max}$ and $L_e|_{max}$. The following constraints then apply to the general energy model:

$$P_e < P_e|_{max} \tag{3-7}$$

$$L_e < L_e|_{max} \tag{3-8}$$

The nomenclature used in the general component model is sufficient for defining the behaviours of a single component. However modifications are needed in order to define interactions between components. The nomenclature was modified such that each energy term (P, L, c, S) would be linked to its component through parentheses and a subscript, following the letter assignment presented in Figure 3-2. For example, when the hydrogen interaction between the electrolyzers and hydrogen storage system may be represented by:

$$(P_h)_S - (L_h)_E = 0 \tag{3-9}$$

In another example, the interactions between the components connected to the energy hub transmission system may be represented by:

$$(P_e)_T - (L_e)_W - (L_e)_G = 0 \tag{3-10}$$

$$(P_e)_G + (P_e)_B + (P_e)_G - (L_e)_T = 0 \tag{3-11}$$

3.2.1 Examples

Some examples are presented below to illustrate how the general model will capture various behaviours. The simplest case is the generation of electricity in a wind turbine. Only two terms are involved here: generation and output. This is represented by:

$$c_e - L_e = 0 \tag{3-12}$$

Energy transmission involves three terms: output, input and a coupling coefficient. For the case of electricity, this is represented by:

$$a_{ee}P_e - L_e = 0 \qquad (3\text{-}13)$$

The model for conversion between energy carriers is similar to that of energy transmission, but involves terms with different subscripts. For example, the generation of hydrogen from electricity by an electrolyzer may be represented by:

$$a_{eh}P_e - L_h = 0 \qquad (3\text{-}14)$$

where a_{eh} is a factor which takes into account both the losses in receiving the input electricity (P_e) and also of converting it into hydrogen (L_h).

The retrieval of hydrogen from hydrogen storage (e.g. a compressed gas tank) may be represented by:

$$-L_h + \frac{d}{dt}S_h = 0 \qquad (3\text{-}15)$$

where b_e represents the discrepancy between the energy reduced in the battery and the energy retrieved as output.

3.3 Wind Turbine Model

The function of this component is to model the generation of electricity by wind turbines. Therefore, this component has only one mode of operation, generation, and it does not have any energy inputs or storage. The behaviour of this component can thus be represented by:

$$-(L_e)_W + (C_e)_W = 0 \qquad (3\text{-}16)$$

where C_e represents the dynamic output of the wind turbine. The connection of the wind turbine to the energy hub is represented by:

$$(P_e)_T - (L_e)_W = 0 \qquad (3\text{-}17)$$

The wind turbine model is illustrated in Figure 3-4 below. Although the wind turbine model does not have an input through which it receives an energy carrier, it does depend on the input of wind speed data. This data is considered part of the model, and is an input to a power conversion sub-model, which represents the performance of the wind turbine.

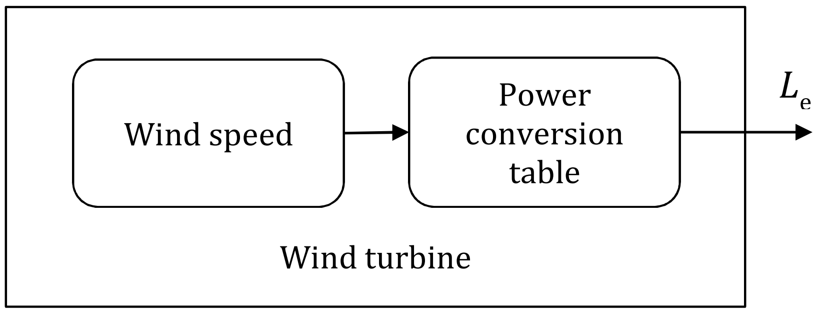


Figure 3-4: Schematic of wind turbine component model

Wind speed data was obtained for Nanticoke, Ontario, Canada for an entire year, which is a proposed location for a clean energy hub due to its high electricity transmission capacity. This data consisted of monthly wind speed averages and 24-hour relative wind speed profiles for each season. This data was applied to a model of a Vestas V80 turbine, which has a maximum capacity of 2,000kW and a height of 80m (Vestas, 2009). The wind turbines' maximum capacity is reached at a wind speed of 15 m/s, and the power output does not increase for higher wind speeds. Beyond wind speeds of 25 m/s, safety mechanisms on the wind turbine engage and there is no power output.

Table 3-1 Average wind speed at rotor height (80 m) by month

Month	Avg. Wind Speed (m/s)
January	12.1
February	13.2
March	11.7

Month	Avg. Wind Speed (m/s)
April	12.9
May	12.9
June	10.5
July	9.0
August	7.4
September	6.6
October	8.2
November	10.1
December	12.9

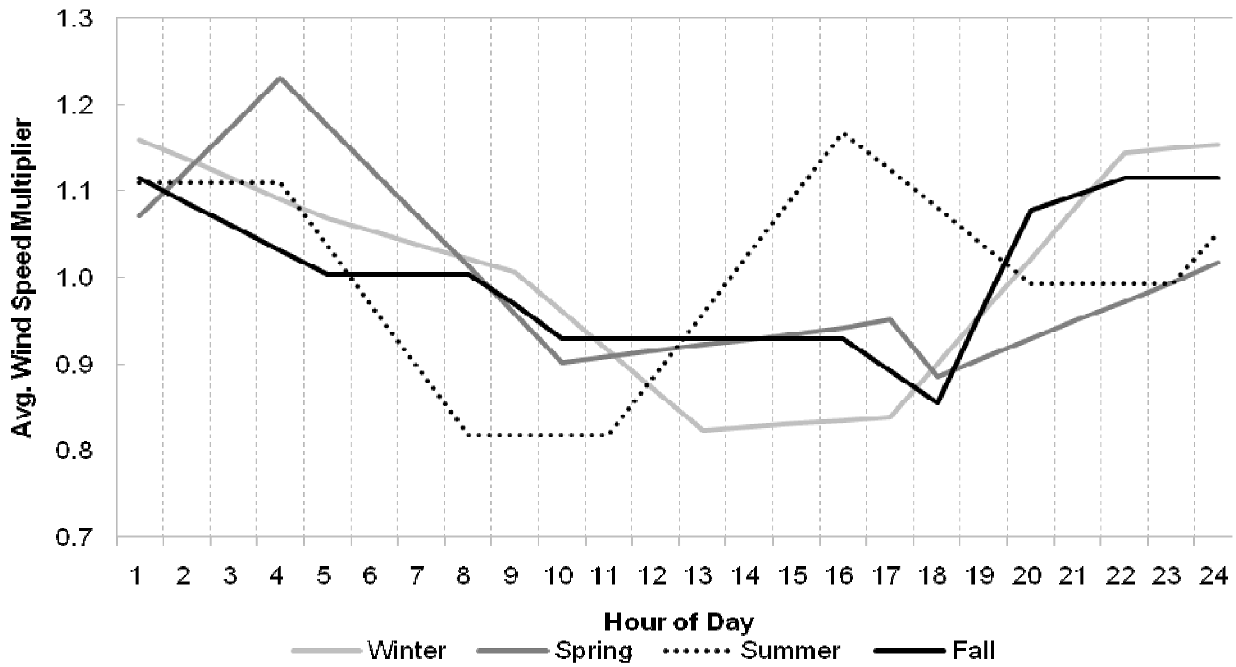


Figure 3-5: 24-hour relative wind speed profiles by season

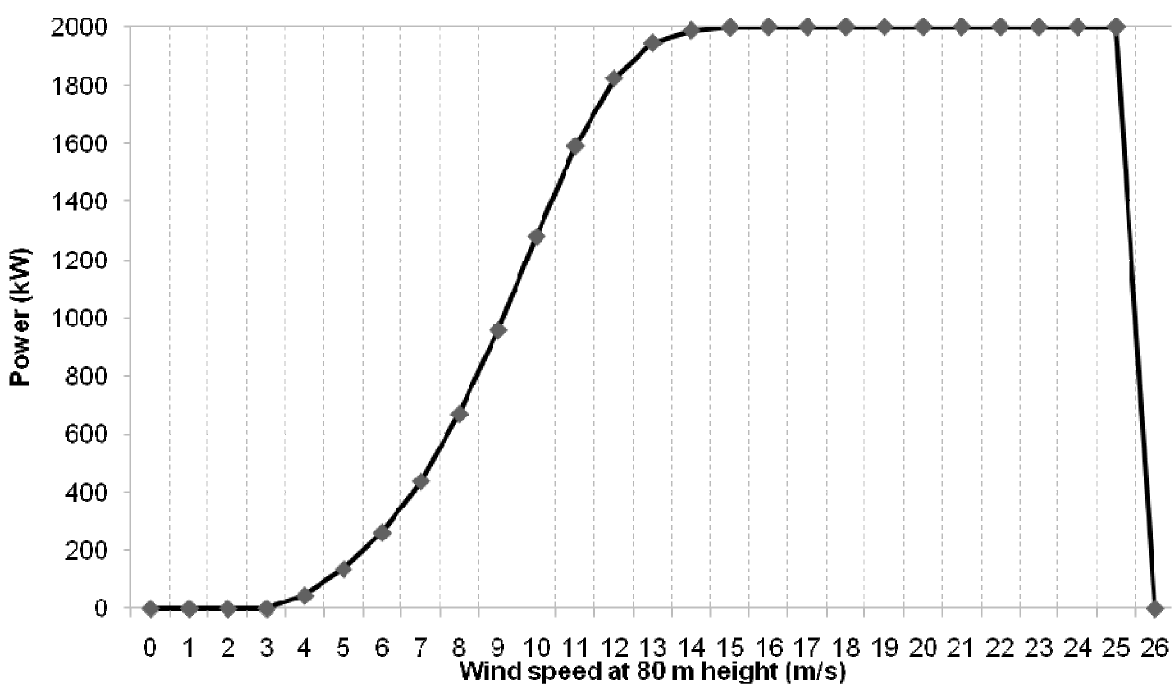


Figure 3-6: Wind turbine power output (kW) vs. wind speed (m/s)

3.4 Electricity Grid Model

The function of this component is to model the connection of the energy hub to a larger electricity grid. It will have two modes of interaction with the energy hub: generation and consumption. The electricity generation (or purchase) behaviour can be represented by:

$$-(L_e)_G + (C_e)_G = 0 \tag{3-18}$$

where C_e represents the electricity requested by the energy hub from the electricity grid. The electricity consumption (or sale) behaviour can be characterized by:

$$(P_e)_G + (C_e)_G = 0 \tag{3-19}$$

where C_e represents the electricity supplied by the energy hub from the electricity grid. The connection of the electricity grid input to the energy hub output is represented by:

$$(P_e)_G - (L_e)_T = 0 \tag{3-20}$$

The connection of the electricity grid output to the energy hub input is represented by:

$$(P_e)_T - (L_e)_G = 0 \tag{3-21}$$

The electricity grid component should provide electricity to the energy hub and accept electricity from the energy hub as required. This requires the assumption that the electricity grid is an abstract electricity source/sink that is unlimited in transmission capacity. For the purposes of modelling the operation of a single energy hub it is a reasonable assumption because of the difference in orders of magnitude of the power flows in each. However this assumption would have to be reviewed for larger energy hubs or a network of energy hubs, since their effects on the electricity grid could no longer be considered negligible. In a larger network of energy hubs, the electricity grid may not be able to guarantee a reliable source of power upon demand, or may not be able to purchase all of the energy hubs' excess electricity.

This analysis will also consider scenarios in which the connection to the electricity grid is not present. This will change the dynamics of the energy hub and affect revenues generated by the hub. Therefore a model parameter is used to indicate whether the clean energy hub is connected to the electricity grid. This parameter is used to run studies for the defined scenarios, and it will be reflected in the coupling factors used in the model.

3.5 Building Model

The function of this component is to model the consumption of electricity by commercial buildings. Therefore, this component has only one mode of operation, consumption, and it does not have any energy inputs or storage. The behaviour of this component can thus be represented by:

$$(P_e)_B + (C_e)_B = 0 \tag{3-22}$$

where $(C_e)_B$ represents the energy demand function of the building model. The connection of the building input to the energy hub output is represented by:

$$(P_e)_B - (L_e)_T = 0 \tag{3-23}$$

The program eQuest was used to generate hourly electricity demand profiles that could be used in conjunction with the clean energy hub model. Table 3-2 below lists the key parameters for the commercial building model used for eQuest. These parameters were taken from the building types defined by Medrano [59]. Where specific parameters were not defined, the default values as suggested by eQuest were used.

Table 3-2: Key parameters for commercial building model

Parameter	Value	Unit
Area	8,361	m^2
Number of floors	2	-
Base power demand	100	kW

Parameter	Value	Unit
Average power demand	165	kW
Peak power demand	460	kW

Table 3-3: Average building power demand during business hours by month

Month	Avg. Power Demand (kW)
January	170.3
February	170.3
March	167.5
April	165.5
May	176.2
June	230.2
July	256.9
August	250.7
September	192.6
October	165.3
November	169.0
December	170.3

3.6 Fleet Model

The function of this component is to model the consumption and storage of electricity and hydrogen by a fleet of plug-in fuel cell vehicles (PFCVs). The modelling of a fleet entails the modelling of each individual vehicle; the PFCV fleet component is actually a set of vehicle components with identical underlying structure and similar behaviour (due to randomized parameters).

First, a vehicle model was defined. This model was designed to capture the energy interactions of an individual vehicle. The fleet model was then defined as a set of vehicle models. The two modes of vehicle behaviour, storage and consumption, were defined at both the vehicle and the fleet level.

3.6.1 Vehicle model

A model was created to represent an individual vehicle in the PFCV fleet. The function of this component is to model the consumption and storage of electricity and hydrogen by an individual PFCV. This is the most complicated model in the entire system, involving consumption and storage of both energy carriers. The general equations for this model are given by:

$$\frac{d}{dt}(S_e)_V = (a_{ee})_V (P_e)_V + (c_e)_V \tag{3-24}$$

$$\frac{d}{dt}(S_h)_V = (a_{hh})_V (P_h)_V + (c_h)_V \tag{3-25}$$

The general equations do not contain an energy output term; vehicle-to-grid (or 'V2G') behaviour was not considered in this PFCV model. All energy inputs to the vehicles are stored for later consumption.

Commercially available models such as PSAT and CRUISE were considered, but were deemed unsuitable for the purpose of this work. The level of detail in models provided by PSAT and CRUISE was unnecessary in this analysis, which is only interested in the steady-state and macro-level behaviour of such vehicles. Specifically of interest is the total energy demand in the form of hydrogen and electricity. Rather, the general format of these models was used to create a simpler model for plug-in fuel cell vehicles, and this is illustrated in Figure 3-7 below.

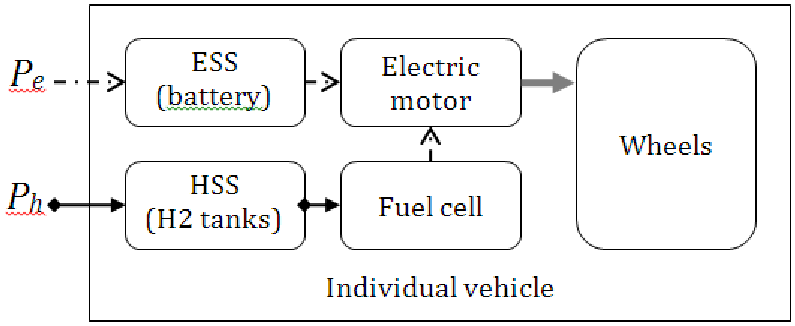


Figure 3-7: Schematic of the vehicle model

Contrast the vehicle model with the example vehicle representation in PSAT (Figure 2-10). The simplified model architecture does not define or limit the physical vehicle architecture or energy management strategy, which can include series, parallel, series-parallel or other hybrid configurations. It simply represents a model for the storage of energy carriers and their conversion to propulsive power and driving range onboard the vehicle.

The vehicle model will have two modes of operation: storage and consumption, which correlate to charging/refuelling and travelling respectively, in terms of real-world behaviour. The modelling for these modes is elaborated below.

3.6.1.1 Charging

In storage (or charging/refuelling) mode, the vehicle model is equipped to receive both types of energy carriers as inputs (i.e. hydrogen and electricity). These inputs are directly routed to the onboard storage systems. Each vehicle is equipped with a storage system for each type of energy carrier: an electricity storage system (ESS, e.g. battery) and hydrogen storage system (HSS, e.g. a tank of compressed hydrogen). An ESS is an integral feature of all hybrid vehicles. It can refer to specific equipment, such as batteries, ultracapacitors, or any combination thereof, and it allows for energy management techniques such as regenerative braking and operation of other power sources (such as gasoline engines or hydrogen fuel cells) at more efficient operating points. A large ESS can also allow for an all-electric drive range, commonly called 'plug-in' architecture. The 'plug-in' label refers to the idea that the ESS can be connected to the electricity grid for charging when the vehicle is not in use, and then the vehicle is operated in an ESS charge depleting mode (i.e. the vehicle has less charge in the ESS at the end of the trip then the start). A hydrogen storage system is required for hydrogen fuelled vehicles. Conventional hydrogen storage technologies include gaseous storage (i.e. compressed hydrogen at 5,000 or 10,000 psig) or less commonly liquefied hydrogen storage. The technologies are quite mature and are being used by vehicle manufacturers such as General Motors or Honda in their demonstration fleets.

The specific technology is irrelevant to the modelling framework in this work; it is valid whether a vehicle uses gaseous or liquid hydrogen for onboard storage, and also valid whether a vehicle uses strictly batteries or a combination of batteries and ultracapacitors to store electricity. Nevertheless the program does accommodate for the energy required to compress the hydrogen with the hydrogen generation calculation, and the charge efficiency of the battery system.

The general equations for storage mode can be simplified to:

$$\frac{d}{dt}(S_e)_V = (a_{ee})_V (P_e)_V \tag{3-26}$$

$$\frac{d}{dt}(S_h)_V = (a_{hh})_V (P_h)_V \tag{3-27}$$

It is assumed that no hydrogen is lost due to hydrogen storage. This results in the following simplification of the hydrogen mass balance:

$$\frac{d}{dt}(S_h)_V = (P_h)_V \tag{3-28}$$

The storage systems on board the vehicles will have a limit on the amount of energy they can hold. These upper limits must be reflected in the model. Let $(S_e)_V|_{\max}$ represent storage capacity of the ESS (measured in kWh), and let $(S_h)_V|_{\max}$ represent the storage capacity of the HSS (measured in kg). Equations 3-7 and 3-8 are applied to the vehicle model to respect the upper bounds of storage modelling.

In certain ESS technologies, such as electrochemical batteries, only a fraction of the actual capacity can be used. The battery capacity must be within a certain range in order to maintain its health. In such a case it is conventional to discuss ESS storage in codified terms, where zero storage refers to the ESS being at the required minimum (and not actually empty), and full storage refers to the ESS being at the required maximum (and not actually at full). It is assumed in the model that in such a case, the term $(S_e)_V|_{\max}$ is modelled on such a scale.

It is also useful to define a parameter to describe the energy input from the charging station. Let this be represented by $(P_e)_V|_{\max}$. This is the maximum power that be drawn from a charging station connected to the vehicle. Equation 3-9 is then applied to the vehicle model to respect the upper bound of charging. The vehicle model itself does not define an upper limit to the charging power of the battery, as it is assumed that the power available through the charging station does not exceed this upper limit.

The parameter a_{ee} represents the charging efficiency of the ESS, and will be determined by the specific ESS technology used on board the vehicle, in this case 0.98 for LiIon batteries.The value of P_e will be determined by the fleet model – it is not decided or calculated on the level of an individual vehicle.

The refuelling of the HSS is modelled as a discrete and instantaneous process:

$$\Delta(S_h)_V = (S_h)_V|_{max} - (S_h)_V \tag{3-29}$$

The approach of modelling the HSS refuelling as a discrete and instantaneous process is justified because of the short time required to refuel hydrogen storage systems (on the order of minutes). The system model time step will be likely an order of magnitude higher to allow transients in ESS charging to settle, and the charging of an ESS is in the order of hours.

3.6.1.2 Travelling

In consumption (or 'travelling') mode, the two storage systems are depleted due to consumption of energy on board the vehicle. In the case of the ESS, the electricity is routed to electric motors, which convert the input electricity into kinetic energy for the wheels. In the case of the HSS, the hydrogen is routed into fuel cells, which convert the input hydrogen into electricity. This electricity is then routed to the electric motors.

Since an individual vehicle is not interacting with an energy hub during this period, the model of energy consumption during travel can be simplified by calculating all depletion at the beginning of the travel period. This is a justifiable simplification because ultimately the interactions of the vehicle and energy hub will depend on the state of the ESS and HSS at the beginning of the charging period and are independent of the depletion path during the travelling period or when the travel takes place, which is a function of the vehicle operation model itself. This simplification would no longer be valid in future work that includes multiple charge and travel periods. Figure 3-8 illustrates a sample response of the ESS SOC (State of Charge, the stored energy as a percentage of the total storage capacity) during the two periods. Figure 3-8 does not imply that every vehicle's ESS is depleted completely during the travelling phase – this depends on the travel distance.

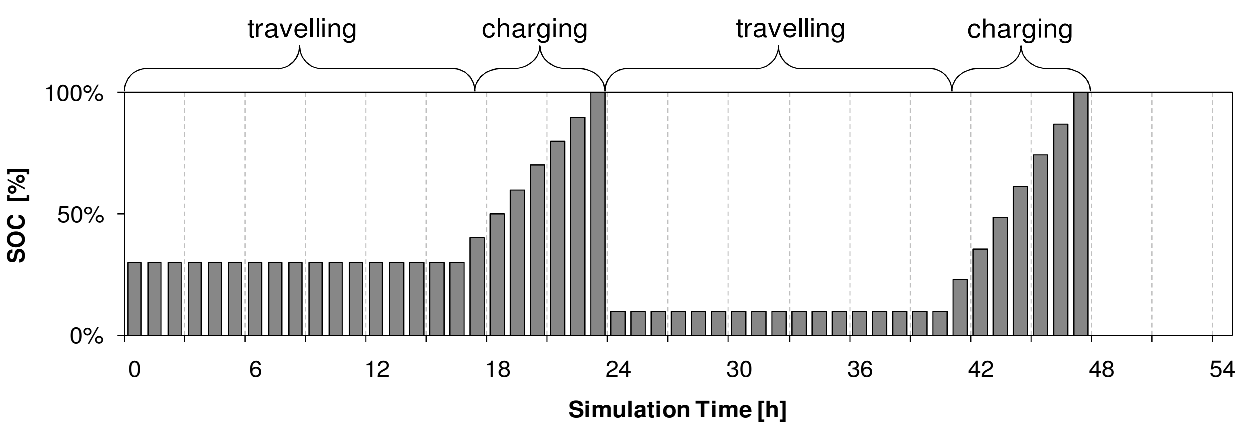


Figure 3-8: Demonstration of ESS SOC response during charging and travelling modes

The general equations for consumption mode can be simplified from the general model to:

$$\frac{d}{dt}(S_e)_V = (C_e)_V \tag{3-30}$$

$$\frac{d}{dt}(S_h)_V = (C_h)_V \qquad (3\text{-}31)$$

where $(C_e)_V$ and $(C_h)_V$ represent the energy drawn from the ESS and HSS (represented by $\frac{d}{dt}(S_e)_V$ and $\frac{d}{dt}(S_h)_V$ respectively) by the electric motor and fuel cell respectively.

Energy consumption during travel depends on the specific vehicle architecture and control strategy, as well as the travel distance. These factors affect the rates at which the vehicle's ESS and HSS are depleted. A general model of energy consumption was developed to accommodate a variety of vehicle architectures. First, two modes of travel are defined: charge-depleting and charge-sustaining. Then, an algorithm for modelling the depleting of the ESS and HSS during travel is elaborated. After that, the algorithm is incorporated into the general model.

During charge-depleting travel, a vehicle will use electricity as the primary source of energy for propulsion and hydrogen will not be consumed, thus depleting only the ESS. In this work it was assumed that a vehicle will always begin travelling in charge-depleting mode until the ESS is depleted to a level at which recharging is required, at which point the vehicle will switch to charge-sustaining mode to hold the battery at that specific state of charge. In this mode, hydrogen will be used as the primary source of energy for propulsion, and the ESS will only be used to provide energy management features such as regenerative braking, thus depleting only the HSS. This mode will continue until the HSS is depleted, at which point the vehicle will stop travelling.

Through the energy consumption model described above, the depletion of the ESS and HSS can be calculated as a function of travel distance. An algorithm for calculating the ESS and HSS depletion is illustrated in Figure 3-9 below.

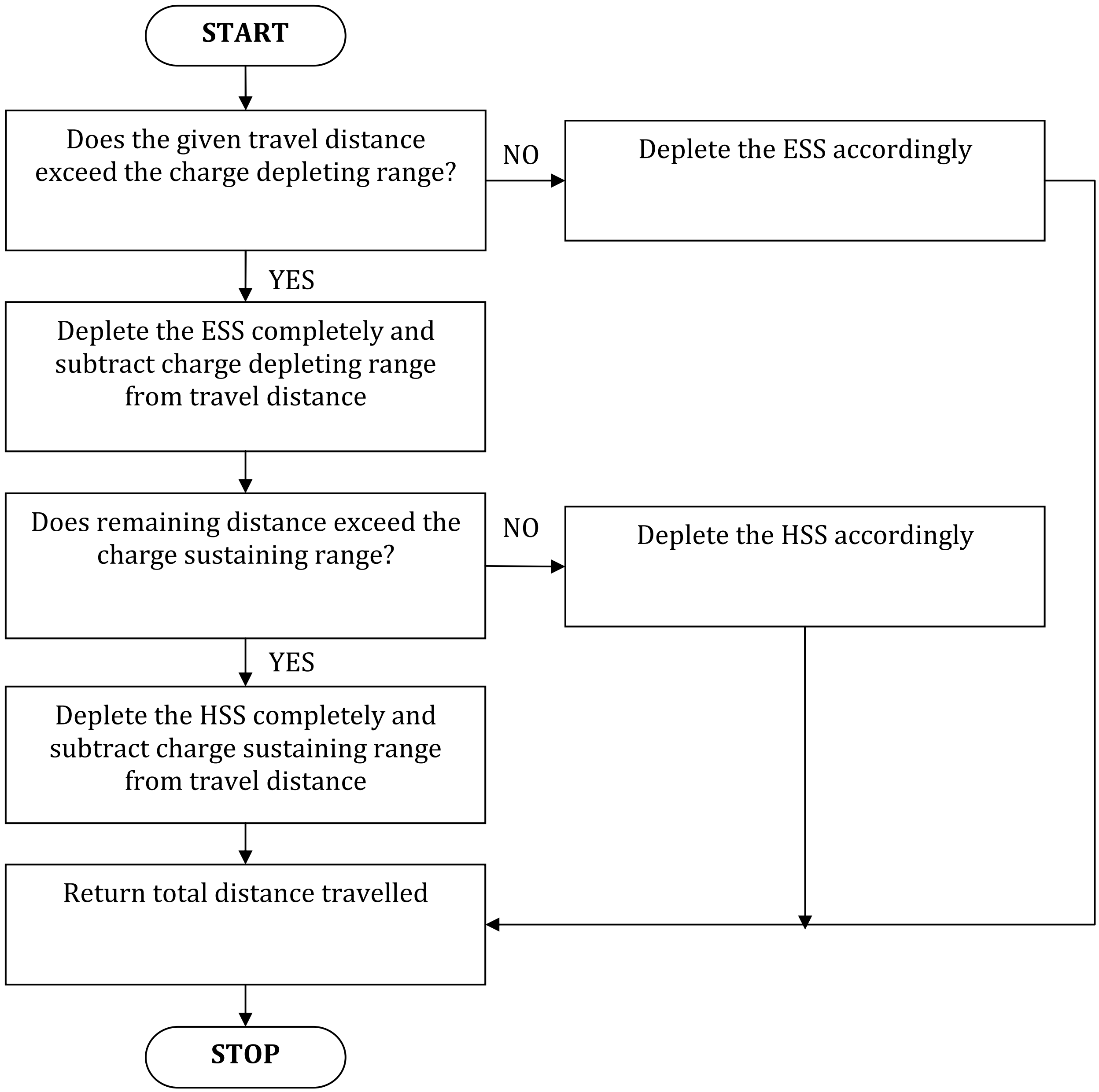


Figure 3-9: Energy consumption algorithm for individual vehicle model

This travel model is general enough to simulate both plug-in hybrid vehicles and mild hybrid vehicles which always travel in charge-sustaining mode. Mild hybrid vehicles may be simulated by defining their ESS capacity as zero. This results in skipping the charge-depleting mode and demanding zero electricity during the charging period.

In order to incorporate the above algorithm into the vehicle model, it is important to first define a few function parameters. First, energy/fuel consumption parameters must be defined for each travel mode:

- *Charge-depleting electricity consumption* (FC_e): the distance a vehicle can travel by consuming 1 kWh of electricity (km/kWh); and,
- *Charge-sustaining hydrogen consumption* (FC_h): the distance a vehicle can travel by consuming 1 kg of hydrogen (km/kg).

The final parameter needed in order to model energy consumption during travel is the *desired travel distance*. Let this be represented by $T_{desired}$.

Now the general model is defined as a function of energy stored, energy consumption ratios and desired travel distance:

$$\frac{d}{dt}(S_e)_V = f\left(S_e, FC_e, T_{desired}\right) \tag{3-32}$$

$$\frac{d}{dt}(S_h)_V = g\left(S_e, S_h, FC_e, FC_h, T_{desired}\right) \tag{3-33}$$

A few other parameters are also defined for convenience:

- *Electric travel range* (T_e): the total distance a vehicle can travel by consuming all of the stored energy in the ESS (km). This is associated with charge-depleting travel.
- *Hydrogen travel range* (T_h): the total distance a vehicle can travel by consuming all of the stored energy in the HSS (km). This is associated with charge-sustaining travel.
- *Actual travel distance* (T_{actual}): the total distance that was travelled by the vehicle (km). This will either be equal to T_{total} if it is within the vehicle's total travel range ($T_e + T_h$), or equal to $T_e + T_h$ if $T_{desired}$ is greater than the vehicle's total travel range.

First, the electric and hydrogen travel ranges are calculated. This is a simple conversion:

$$T_e = (S_e)_V \cdot FC_e \tag{3-34}$$

$$T_h = (S_h)_V \cdot FC_h \tag{3-35}$$

The ESS depletion depends on whether or not the desired travel distance exceeds the electric travel range:

$$-\Delta(S_e)_V = \begin{cases} \left(\frac{T_{desired}}{FC_e}\right), & T_{desired} \leq T_e \\ (S_e)_V, & T_{desired} > T_e \end{cases} \tag{3-36}$$

If the desired travel distance exceeds the electric travel range, the amount depleted is defined as the total amount stored, i.e. it is completely depleted, else it is depleted according to the charge-depleting electricity consumption ratio.

The HSS depletion is only non-zero when the desired travel distance exceeds the electric travel range, i.e. the vehicle enters charge-sustaining mode. If so, then it depends on whether the remaining distance (after the desired travel distance has been subtracted by the electric travel range) exceeds the hydrogen travel range:

$$-\Delta(S_h)_V = \begin{cases} 0, & T_{desired} \leq T_e \\ \left(\frac{T_{desired} - T_e}{FC_h}\right), & T_{desired} \leq T_e + T_h \\ (S_h)_V, & T_{desired} > T_e + T_h \end{cases} \tag{3-37}$$

If the desired travel distance does not exceed the electric travel range then the HSS is not depleted at all. If it does exceed the electric travel range, then the HSS is depleted according to the charge-sustaining hydrogen consumption ratio. However, this is limited by the total amount of hydrogen stored in the HSS. If the desired travel distance exceeds the sum of the electric and hydrogen travel range, then the HSS depletion is equal to the amount of hydrogen stored in the HSS, i.e. it is completely depleted.

Finally, it is useful to calculate the actual distance travelled by the vehicle:

$$T_{actual} = \begin{cases} T_{desired}, & T_{desired} \leq T_e + T_h \\ T_e + T_h, & T_{desired} > T_e + T_h \end{cases} \tag{3-38}$$

This will either be equal to the desired travel distance, if it is within the total travel range of the vehicle, or it will equal to the total travel range of the vehicle. It cannot be greater than the total travel range of the vehicle.

3.6.2 Fleet model

The fleet model was defined as a set of individual vehicle models. Just as the charging (storage) and travelling (consumption) behaviours were defined on the level of the individual vehicle, they must also be defined on the fleet level.

The set of sub-components, i.e. vehicles, in the fleet model is illustrated in Figure 3-10 below.

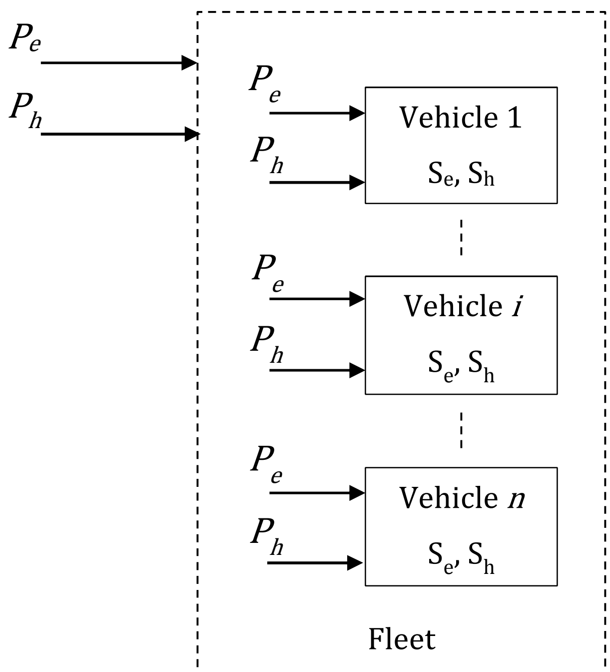


Figure 3-10: Fleet model represented as a set of vehicle models

It is not necessary to define a general energy model at the fleet level, since it is merely a grouping of vehicle models which adhere to the general energy model. It is only necessary to define a relationship the links the fleet energy inputs to the individual vehicle energy inputs. Let n be the number of vehicles in the fleet F . The energy inputs of the fleet and every vehicle i are linked by:

$$(P_e)_F = \sum_{i=0}^{n} (P_e)_i \tag{3-39}$$

$$(P_h)_F = \sum_{i=0}^{n} (P_h)_i \tag{3-40}$$

By grouping the energy inputs, the above equations define the relationships necessary to link all the individual vehicle models to the rest of the integrated energy system. It is not necessary to define a similar relationship for the consumption of energy by the individual vehicle models, since it does not affect the connection to the rest of the integrated energy system.

The connection of the fleet inputs to the energy hub outputs are represented by:

$$(P_e)_F - (L_e)_T = 0 \tag{3-41}$$

$$(P_h)_F - (L_h)_S = 0 \tag{3-42}$$

3.6.2.1 Charging

One of the functions of the fleet model is to charge every vehicle. Calculations for the energy input of each vehicle are performed at the fleet level, rather than at the vehicle level. The basic mechanisms for charging the entire fleet are already provided by Equations 3-40 and 3-41. They group the energy inputs of each individual vehicle into a single fleet energy input, which can then be interfaced with an energy hub. All that is needed at the fleet level is a calculation to determine the energy supplied to each vehicle.

All charging is carried out during a defined charging period, and all travelling occurs outside of the charging period. During the charging period, the following assumptions are made:

- The entire fleet participates in charging; and,
- Each vehicle charges for a defined interval of the charging period.

A number of schemes could be applied to these calculations, but first it is important to define the desired characteristics in a charging strategy. These pertain to ESS charging, as the HSS refuelling is calculated in a simplified manner:

- All vehicles should be completely charged;
- The level of total energy input should be minimized; and,
- Charging should take advantage of lower energy prices during periods of excess supply (i.e. off-peak hours).

There are two charging schemes possible under the current model framework: uncontrolled charging, and controlled charging.

Uncontrolled charging is the simplest approach, in which each vehicle is allowed to demand the maximum amount of power allowed, i.e. the power delivery capacity of the charging station (a user defined value). This charging scheme is represented by:

$$\forall i \in F: \ (P_e)_i = (P_e)_V\big|_{\max} \qquad (3\text{-}43)$$

Uncontrolled charging maximizes the power drawn by the fleet and minimizes the time required to charge, as illustrated in Figure 3-11.

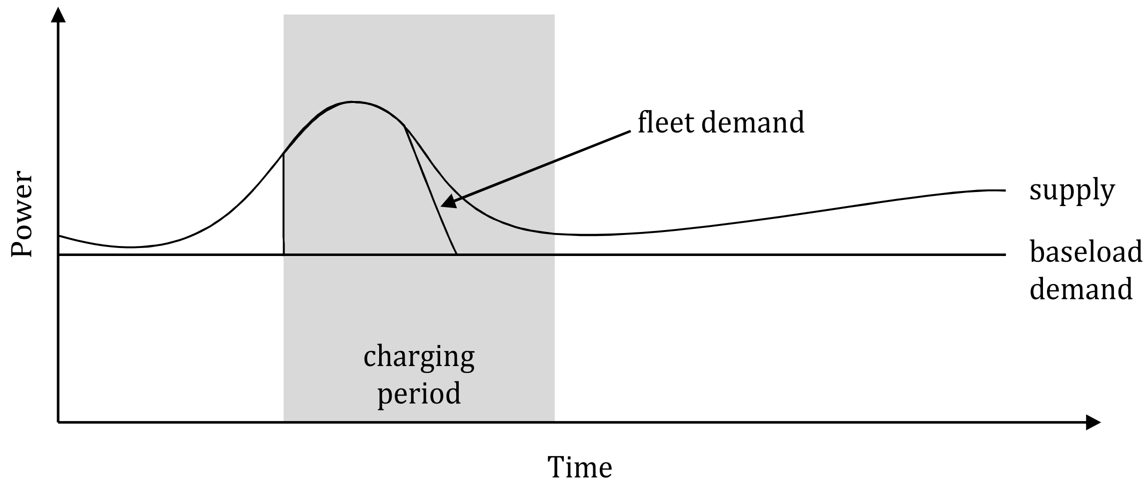


Figure 3-11: Illustration of uncontrolled charging

This approach may be useful when it is desired to take advantage of short periods of excess electricity supply. In this case, excess energy that might have been wasted or sold to the grid for low prices is utilized. However, maximizing the power (i.e. with high rates of charge) into the batteries may adversely affect their health and decrease their life.

Figure 3-11 is only intended to illustrate the flexibility of the uncontrolled charging scheme and should not imply that the fleet will always completely consume the available energy supply. The input constraints of the charging stations may prevent it from doing so.

Controlled charging attempts to maximize the time it takes for each vehicle to reach full charge within the charging period, with the goal of minimizing the load on the batteries. Let $t_{remaining}$ represent the time remaining in the charging period. The controlled charging scheme is represented by:

$$\forall\, i \in F:\ (P_e)_i = \frac{(S_e)_V|_{max} - (S_e)_i}{t_{remaining}} \tag{3-44}$$

This calculates the power required to charging the vehicle at a minimum load during the whole charging period. It is beneficial for the vehicle batteries because the minimized load will reduce degradation of the battery due to charging. Figure 3-12 illustrates how charging works under a controlled charging scheme.

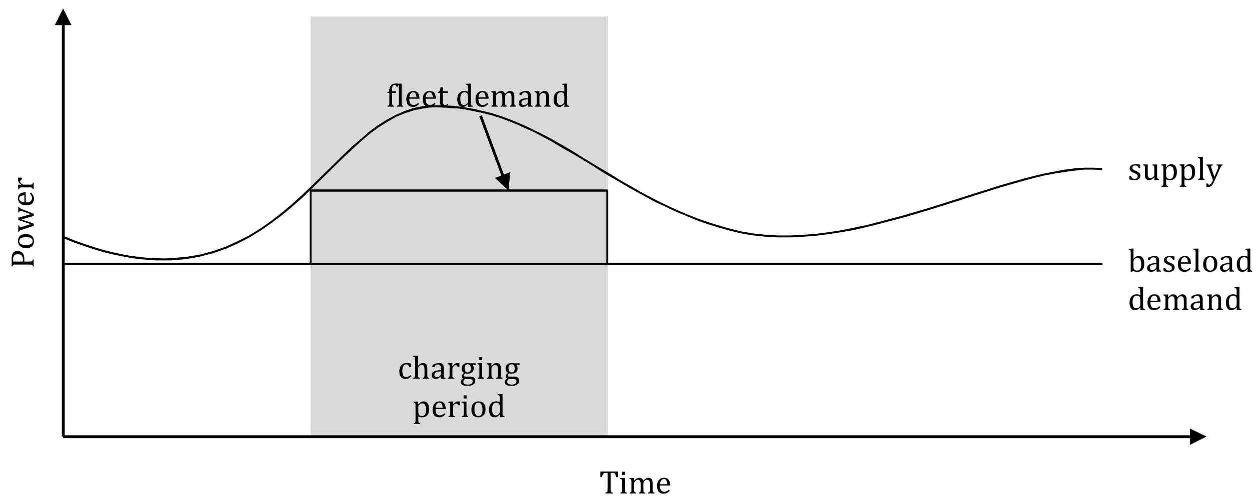


Figure 3-12: Illustration of controlled charging

The most salient difference between the uncontrolled and controlled charging schemes is the shape of the fleet demand profile. Under the uncontrolled charging scheme (Figure 3-11), the fleet demand rises and falls to match the available electricity supply, and tails off once the fleet is done charging. Under the controlled charging scheme (Figure 3-12) the fleet demand is constant and remains non-zero until the end of the charging period.

Both charging schemes have their advantages and disadvantages. With respect to maximizing the utilization of excess energy supply, the uncontrolled charging scheme performs better. Since charging periods will generally be defined during off-peak hours, it is reasonable to assume that electricity supply will be in excess during the charging period. However with respect to minimizing the stress on the vehicles' batteries, the controlled charging scheme performs better. Minimizing the stress from rapid charging reduces the degradation of the battery caused by charging.

The controlled charging scheme can lead to a lower maximum fleet demand than the uncontrolled charging scheme. Whether or not this occurs depends upon the specific shape of the electricity supply curve. This difference could be exploited by switching between charging schemes based on the electricity supply. When connected to an energy hub with renewable energy, it is reasonable to expect that the electricity supply will be lower in some months and higher in others. It would be possible to switch between charging schemes to utilize excess supply in the higher supply months, while maintaining a lower demand in the lower supply months. Even the controlled charging can take advantage of short periods of excess supply. This is just a matter of tuning the charging period to the characteristics of the energy supply.

A complication arises when the electricity demanded by the fleet is greater than the electricity available from the energy hub. This is not considering situations in which the energy hub responds by converting other energy carriers into electricity. If the electricity available to the fleet is less than the amount demanded, the fleet model must make some adjustments to the demand. In the equations below, $(P_e)_F|_{\max}$ refers to the maximum electricity available to the entire fleet. The simplest adjustment is to scale all the vehicle demands down proportionally. The scaling factor is first calculated by:

$$\varphi = \frac{(P_e)_F|_{max}}{(P_e)_F} \quad (3\text{-}45)$$

This factor is then applied to the power demand of every vehicle. For each vehicle i in fleet F, the power demand is scaled down to:

$$(P_e)_i' = \varphi \left(P_e\right)_i \quad (3\text{-}46)$$

where $(P_e)_i'$ is the scaled down power demand. The total fleet demand $(P_e)_F$ is then recalculated with $(P_e)_i'$ instead of $(P_e)_i$, and it is now equal to $(P_e)_F|_{\max}$. Note that this assumes that the fleet does not want to draw power from the grid (which is possible), as it could be costly. Ultimately drawing power from the grid may be required.

Hydrogen demand calculations are simplified and are performed for the entire period, rather than at every time step. The vehicle model refills the HSS at the beginning of each charging period and demands the amount needed from the clean energy hub. This demand is reported by the vehicle model at the beginning of the charging period. The reason for the simplified modelling of hydrogen refilling is due to the generic HSS representation in the vehicle model. Different HSS technologies will have different refill behaviours and therefore there is no generic method to modelling hydrogen refilling in a detailed fashion. However, the implemented method of performing hydrogen refill is valid for conventional technologies such as gaseous or liquefied hydrogen storage given that there exists a distribution infrastructure that allows the entire fleet to refill the vehicles' HSS within a fraction of the time step (e.g. a few minutes). This allows for a cascade refuel from high pressure storage tanks, or a compressor feed system from lower pressure storage tanks. Although the present method of calculating hydrogen demand may not provide details on scheduling HSS refilling for individual vehicles, it is still useful for calculating total hydrogen demand during the charging period and therefore for sizing the hydrogen generation and storage capacity of a connected energy hub.

3.6.2.2 Travelling

The purpose of the travel period is to perform calculations to deplete the ESS and HSS before the next charging period. This depletion should be realistically modelled and consider the different travel needs of different vehicles. As discussed above, travelling period calculations are performed for the entire period and not for each time step. In this model, it is assumed that the vehicle control strategy first depletes the ESS first and only then uses hydrogen to extend the range of the vehicle – a charge-depleting strategy. Thus only the total distance travelled by a vehicle, not the exact travel profile, will have an effect on the vehicle requirements during the charging period. Variations in the vehicle control strategy would affect the energy split required and the thus the design of the energy hub.

Travel simulation is further divided into two models: driver behaviour and energy consumption. The driver behaviour model predicts the daily travel distance for each vehicle and the energy consumption model calculates the ESS and HSS depletion based on a given travel distance.

A simple approach to simulating driver behaviour would be to assume that every vehicle in the fleet has the same daily travel distance. However this is not a realistic travel pattern and available data [61] can be used to create detailed models. A suggested approach is to use a stochastic model based on probability distributions generated from actual driver behaviour data. The creation of a more detailed driver behaviour model is beyond the scope of the vehicle model in this work at this time.

3.7 Electrolyzer Model

The electrolyzer forms one component of the energy hub, and the function of this component is to model the conversion of electricity to hydrogen by electrolyzers. Therefore, this component has only one mode of operation, conversion, and it does not have any energy storage. The behaviour of this component can thus be represented by:

$$(a_{eh})_E (P_e)_E - (L_h)_E = 0 \tag{3-47}$$

where a_{eh} represents the conversion efficiency of the electrolyzers. The connection of the electrolyzer input to the energy hub output is represented by:

$$(P_e)_E - (L_e)_T = 0 \tag{3-48}$$

The connection of the electrolyzer output to the hydrogen storage input is represented by:

$$(P_h)_S - (L_h)_E = 0 \tag{3-49}$$

Ideal conversion between hydrogen and electricity is defined by the Higher Heating Value (HHV) of hydrogen, which is 39.4 kWh/kg. Actual conversion is simulated through specific interaction parameters which define the efficiency and capacity of each direction of conversion. Through this method a generic hydrogen system model is developed which may be used to simulate a range of technologies.

Electricity to hydrogen conversion is further defined through two parameters and calculated through Eq. 1:

- Conversion efficiency ($efficiency_{e \to h}$): this parameter is used to reduce the amount of electricity that is actually converted to hydrogen and simulates energy losses of the specific electricity-to-hydrogen technology being simulated.
- Conversion capacity ($capacity_{e \to h}$): this parameter is used to limit the rate of hydrogen generation and represents the physical sizing of the hydrogen generation technology employed. It has units of kg/h.

$$mass_{hydrogen} = \left({}^{energy_{electricity}} / _{HHV} \right) \times efficiency_{e \to h} \tag{3-50}$$

where $mass_{hydrogen}$ is the mass of hydrogen generated in the hydrogen system and $energy_{electricity}$ is the electrical energy supplied by the electricity system.

No maximum hydrogen withdrawal capacity is defined, since it is assumed that the clean energy hub also contains a hydrogen distribution infrastructure that is capable of supplying the vehicle fleet. In the case of compressed gas vehicles, it is assumed that the hydrogen storage is compressed gas respectively. The extra energy for compression and distribution is included in the efficiency factor for hydrogen generation. Future analysis may consider compression during the storage phase vs. compression at the point of delivery to the vehicle.

3.8 Hydrogen Storage Model

The hydrogen storage forms one component of the energy hub, and the function of this component is to model the storage of hydrogen by compressed gas tanks. Therefore, this component has only two modes of operation: storage and withdrawal. The behaviour of this component in storage mode can be represented by:

$$\frac{d}{dt}(S_h)_V = (a_{hh})_V (P_h)_V \tag{3-51}$$

It is assumed that hydrogen storage is a loss-less process. This results in the following simplification of the hydrogen mass balance:

$$\frac{d}{dt}(S_h)_V = (P_h)_V \tag{3-52}$$

The connection of the electrolyzer input to the energy hub output is represented by:

$$(P_e)_E - (L_e)_T = 0 \tag{3-53}$$

The connection of the electrolyzer output to the hydrogen storage input is represented by:

$$(P_h)_S - (L_h)_E = 0 \tag{3-54}$$

3.9 Transmission System Model

The transmission system forms one component of the energy hub. The function of the transmission system is to provide an electricity interface between all components connected to it, and to behave in a way that prioritizes certain energy inputs and outputs over others. As its name suggests, its only behaviour is the transmission of electricity between inputs and outputs; there is no generation/consumption or storage/withdrawal involved. Its general behaviour can be represented by:

$$(a_{ee})_T\,(P_e)_T - (L_e)_T = 0 \tag{3-55}$$

Additionally, all loses through the transmission system are considered to be negligible. This simplifies the model to:

$$(P_e)_T - (L_e)_T = 0 \tag{3-56}$$

The interactions between the components connected to the energy hub transmission system may be represented by:

$$(P_e)_T - (L_e)_W - (L_e)_G = 0 \tag{3-57}$$

$$(P_e)_G + (P_e)_B + (P_e)_G - (L_e)_T = 0 \tag{3-58}$$

The above model provides the interactions needed to connect energy inputs to outputs, but does not define the hub logic necessary to balance inputs and outputs. There are two important scenarios to consider when balancing energy inputs and outputs: excess demand and excess supply. They are important because they affect how the hub interacts with the electricity grid and the electrolyzers.

The hub model is unique amongst components in that it has multiple energy inputs and outputs, and therefore its operational logic must be able to distinguish between the inputs and outputs. During normal hub operation, the hub first compares electricity supply from any connected non-dispatchable supply, such as wind turbines, with the electricity demand from other connected components, such as buildings or vehicles. If the electricity supply does not match the electricity demand, the hub logic must decide on how to balance them before proceeding.

In the case of excess demand, the hub has two options: to limit electricity demand to the available electricity supply, or to import the remaining power from the electricity grid. In cases where the hub is not connected to an electricity grid, then only the former option is viable. The simplest option is to import the remaining power from the electricity grid.

3.10 Simulation and Numerical Integration

A finite difference method was employed to solve the system of continuous different equations that represent the integrated energy system. The differential equations were converted to algebraic form (listed in Table 3-4).

Table 3-4: List of component equations comprising the integrated energy system

Component	Symbol	Equations
Wind turbine	W	3-16, 3-17
Electricity grid	G	3-18, 3-19, 3-20, 3-21
Building	B	3-22, 3-23
Fleet	F	3-24, 3-46
Electrolyzer	E	3-47, 3-48, 3-49, 3-50
Storage	S	3-51,-3-52, 3-53, 3-54
Transmission	T	3-55, 3-56, 3-57, 3-58

The model employs a fixed time step of 60 minutes, which is sufficient to catch major events such as vehicle charging and large fluctuations in electricity supply. This allows the model to operate under the steady-state assumption. At each time step, the model runs a core simulation routine that manages energy interactions both within the hub and between the electricity supply and energy demand.

Chapter 4

Emissions Modelling

The environmental benefit of the hub derives from the carbon dioxide and other emissions avoided. This model will consider the three largest sources of carbon dioxide reduction:

- Wind turbines displace the electricity provided by the electricity grid;
- Electrolyzers displace the hydrogen provided by Steam Methane Reforming; and
- Fuel cell vehicles displace the gasoline consumed by conventional vehicles

Naturally there is also the benefit in the reduction of urban air pollutants (e.g. VOCs, NO_x, SO_x) associated with the use of hydrogen in the vehicles.

Based on the operation of the energy hub, the emissions model will tally the total energy consumed and therefore the total energy sources displaced by the hub. Based on assumptions made regarding the alternative sources of energy, the emissions model will calculate the emissions associated with each displaced source of energy and thereby calculate the emissions displaced by each source. Finally, the model will apply the price of carbon credits to calculate the total emissions revenue earned by the energy hub.

4.1 Reduction due to displacement of grid electricity

The wind turbines provide electricity to the grid that would otherwise have come from Ontario's electricity grid (Table 2-1). The environmental benefit associated with the wind turbines is the emissions displaced by the use of the wind turbines. In these calculations, both the emissions associated with Ontario's electricity grid and the emissions associated with the wind turbines will have to be considered.

Table 4-1 lists the lifecycle emissions and pollutants associated with major Ontario electricity sources, and these values were used to determine the overall CO_2 emissions associated with Ontario grid electricity.

Table 4-1: Lifecycle emissions and pollutants associated with major electricity sources

Source	Percentage	Amount (kg CO_2/kg H_2)
Hydroelectric	25%	0.09
Coal	21%	1.25
Nuclear	37%	0.015
Gas	16%	0.575
Wind	1%	0.015

The CO_2 emissions associated with Ontario grid electricity were calculated to be 0.38 kg/kWh. Therefore every kWh of electricity provided by the wind turbines will displace the emission of approximately 0.38 kg of CO_2.

However, the CO_2 emissions associated with wind turbines must also be accounted for. Wind turbines are associated with 0.015 kg of CO_2 emissions for every kWh of electricity produced, due to the nature of their production, transportation, installation and decommissioning processes. Therefore the CO_2 emissions displaced by the use of wind turbines in the energy hub are 0.365 kg/kWh.

4.2 Reduction by displacement of gasoline

To calculate the environmental benefit associated with the PFCV fleet, consider an alternative fleet of gasoline-powered conventional vehicles. This is the fleet that would be used if the PFCV fleet was not being used, and therefore the use of the PFCV fleet results in the avoidance of the gasoline that would be consumed by the alternate fleet. Therefore the environmental benefit associated with the PFCV fleet is the gasoline consumption that is displaced.

Similar to the approach taken in developing the PFCV fleet model, the gasoline consumption of a conventional vehicle fleet is calculated by considering the gasoline consumed by a single vehicle that is assumed to be typical of the fleet. Following the approach taken by Maniyali [7], the typical model for a conventional vehicle is assumed to be a 2009 Chevrolet Impala. The emissions calculated for the typical car are based on the composition of the Ontario electricity generation capacity (Table 2-1).

The grid composition in Table 2-1 can be used as an input to the software Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET) version 1.8c to calculate the emissions of the conventional vehicle model (Table 4-2).

Table 4-2: Emissions associated with the conventional vehicle model

Type	Amount (g/km)
CO_2	234.2
N_2O	0.00745
VOC	0.113
NO_X	0.0881
PM_{10}	0.0181
$PM_{2.5}$	0.00938
SO_X	0.00375

As electrolyzers have no operational emissions of carbon dioxide, the use of the PFCV fleet in the clean energy hub results in the displacement of 603.2 g/km travelled by the fleet.

The model may then tally up the total distance travelled by the PFCV fleet and calculate the total carbon dioxide reduction accomplished.

In order to simplify the calculation, the emissions model instead considers the amount of carbon dioxide emissions reduced in terms of the mass of hydrogen consumed by the fleet. Since the fleet is the sole consumer of hydrogen in the hub, the carbon reduction of the fleet can be linked directly to the hydrogen produced by the electrolyzers through the fuel consumption ratio of the fleet. This conversion is represented by Equation 4-9.

$$(CO_2)_E = (CO_2)_F * FC_h * \left(\frac{1kg}{1{,}000g}\right) \tag{4-1}$$

where $(CO_2)_E$ is the carbon reduction associated with the electrolyzer [kg CO_2/kg H_2], $(CO_2)_F$ is the carbon reduction associated with the PFCV fleet [g CO_2/km], and FC_h is the hydrogen consumption ratio of the fleet [kg H_2/km].

Applying the standard ratio of 1kg of hydrogen consumed per 70km travelled, Table 4-3 lists the converted emissions.

Table 4-3: Emissions associated with the electrolyzers

Type	Amount (kg/kg H_2)
CO_2	16.493
N_2O	0.000525
VOC	0.00788
NO_X	0.00617
PM_{10}	0.00127

Type	Amount (kg/kg H_2)
$PM_{2.5}$	0.000656
SO_X	0.000263

Chapter 5
Cost Modelling

This chapter presents the model development of an integrated energy system in which a clean energy hub interfaces energy supply and demand components. The energy supply consists of wind turbines and a connection to a broader electricity grid. The energy demand comprises of a commercial building and a plug-in fuel cell vehicle fleet. The electricity grid can also receive electricity from the energy hub, in which case it also acts as an energy demand component. First, an overview of the entire system is presented. This includes a discussion on energy modelling for a generalized energy component. After that, the energy and cost modelling of each component is presented in detail. This is followed by a discussion on the cost modelling of emissions rebates that could potentially be earned by the energy hub, and finally the operating logic of the hub is presented in detail.

The cost model was implemented in MATLAB, and the code is reproduced in Appendix B.

5.1 Electricity Grid Model

Just as the energy modelling for the electricity grid reflected both generation and consumption of electricity, the cost modelling reflects both purchase and sale of electricity.

Electricity use is measured through the use of meters. Conventional meters only recorded net electricity transfer, and were unsuitable for facilities that both purchased electricity from and sold back to the grid. With conventional meters, the electricity purchased and sold would be reported as net electricity transfer, and a price difference between electricity purchased and sold was unenforceable. Conventional meters also could not record electricity usage by time of day, and so they were unsuitable for advanced pricing schemes which differentiated between peak and off-peak usage of electricity. However the introduction of smart meters now allows for such advanced pricing schemes which differentiate between electricity purchased and sold, and also by time-of-day. It is assumed that such a smart meter is installed in the energy hub to enable this behaviour.

5.1.1 Purchase

A three-tier time-of-use based model was developed, as suggested by the IESO [62] and OEB [63]. The distribution of the tiers throughout the day is illustrated in Figure 5-1 below. The three tiers correspond to the levels of demand experienced by the electricity grid throughout the day: off-peak, mid-peak, and on-peak.

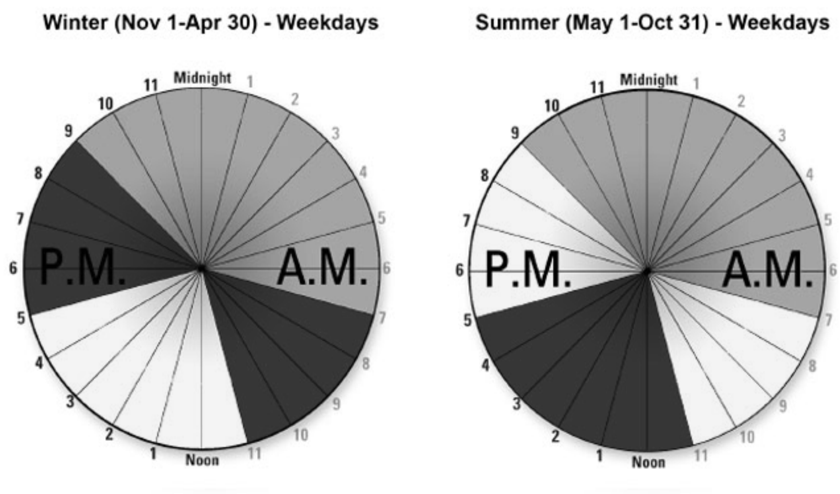


Figure 5-1: Distribution of tiers in time-of-use pricing [63]

Weekends and holidays are considered off-peak hours during both winter and summer months.

First, the off-peak rate is represented by R_{off}. This is the lowest electricity rate, and all other tiers will be defined in relation to it. The mid-peak electricity rate is defined as:

$$R_{mid} = \alpha_{mid} R_{off} \tag{5-1}$$

where R_{mid} is the mid-peak electricity rate, and α_{mid} is the coefficient linking the mid-peak rate to the off-peak rate. Similarly, the on-peak rate is defined as:

$$R_{on} = \alpha_{on} R_{off} \tag{5-2}$$

where R_{on} is the on-peak electricity rate, and α_{on} is the coefficient linking the on-peak rate to the off-peak rate.

It is through controlling the coefficients α_{mid} and α_{on}, as well as the variable R_{off}, that the electricity rates are manipulated within the model. R_{mid} and R_{on} are merely intermediate variables. Since the mid- and on-peak rates are by definition higher than the off-peak rate, the following constraint applies to α_{mid} and α_{on}:

$$\alpha_{mid} > 1 \tag{5-3}$$

$$\alpha_{on} > 1 \tag{5-4}$$

The base case is defined by considering values provided by the OEB [63], as listed in Table 5-1.

Table 5-1: Base case electricity rates

Tier	Rate (¢/kWh)
Off-peak	5.3
Mid-peak	8.0
On-peak	9.9

Values for the parameters R_{off}, α_{mid} and α_{on} were calculated based on the base case electricity rates, as defined in Table 5-1 in Table 5-1.

Table 5-1. They are listed in Table 5-2.

Table 5-2: Base case parameter values

Parameter	Value
R_{off}	5.3
α_{mid}	1.51
α_{on}	1.87

5.1.2 Sale

The sale of electricity to the grid is complicated by contracts and bidding processes between the grid operators and energy produces. Modelling such a process is beyond the scope of this work, and therefore the model simplifies the cost modelling of electricity sale to the grid by assuming that electricity is sold at wholesale prices to the grid. Wholesale prices are published by grid operators, such as the Hourly Ontario Electricity Price (HOEP) as published by the IESO [64].

The base case is defined by assuming that electricity sold to the grid is sold at the HOEP.

5.2 Electrolyzer Model

Figure 5-2 outlines the major steps in the electrolyzer cost modelling process, the purpose of which is to calculate the total annualized electrolyzer cost. The approach taken is to calculate the annualized cost of a single electrolyzer using parameters and methods obtained from literature, and to multiply by the number of electrolyzers in the energy hub to obtain the total annualized electrolyzer cost.

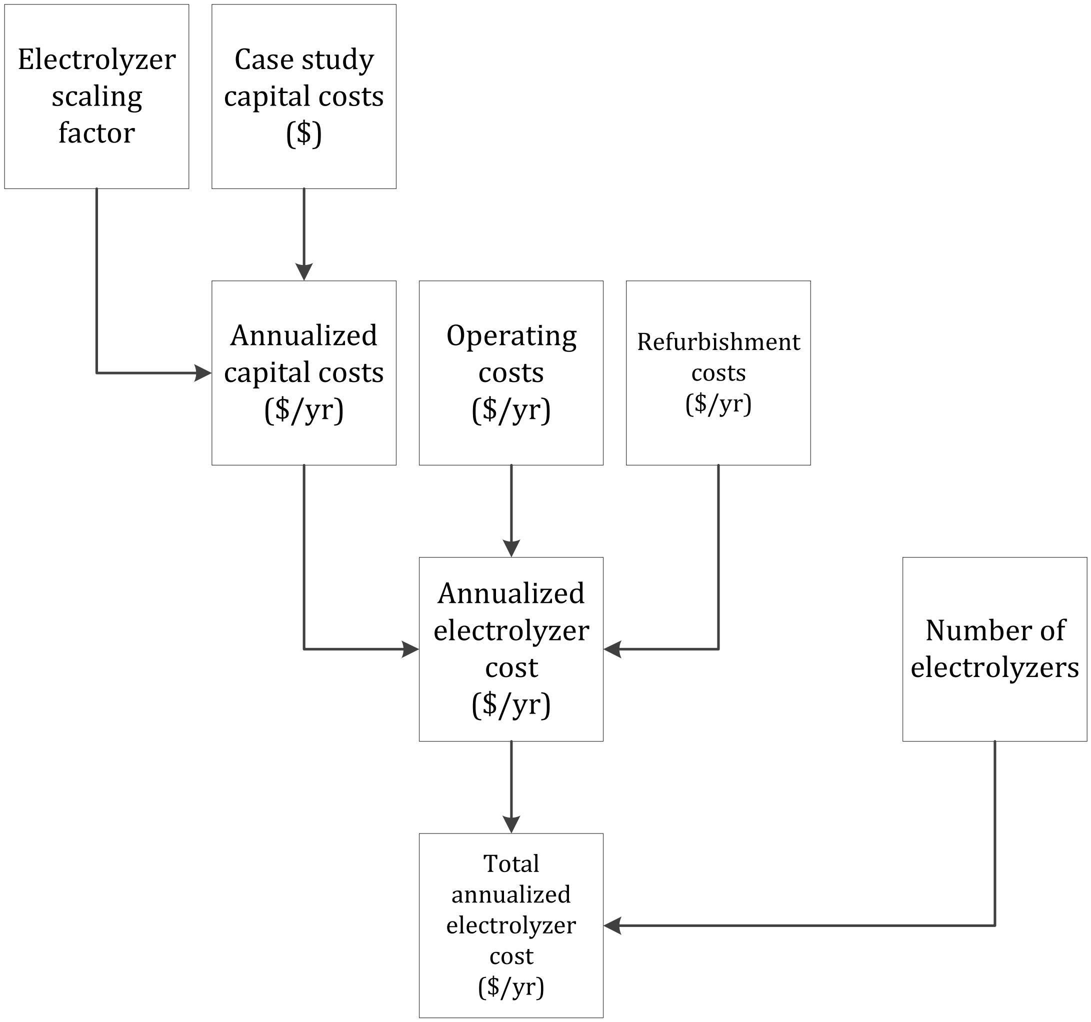


Figure 5-2: Electrolyzer cost modelling flowchart

The electrolyzer capital costs and lifetime estimates were obtained from a National Renewable Energy Laboratory (NREL) case study that considered a 485 Nm^3/h electrolyzer facility at a total installed capital cost of $2,479,950. NREL considered the installed capital costs of the electrolyzers as well as annual operating costs, which included land rental, maintenance, water costs and electricity costs, at a cost of 9% of the annualized capital costs. NREL also considered the refurbishment of the electrolyzers. The NREL electrolyzers had a lifetime of 20 years but required refurbishment after 10 years at a cost of 30% of the total installed capital cost. A scaling factor was used to account for the different in capacity between the NREL case study and the clean energy hub, and an interest rate calculation was used to convert 20-year figures into annualized costs. These calculations are outlined below:

$$C_{cap} = \frac{(C_{cap})_{case} * \left(\frac{\frac{15Nm^3}{h}}{\frac{485Nm^3}{h}} \right) * (1+i)^{0.46l}}{l} \quad (5\text{-}5)$$

where C_{cap} is the annualized capital cost associated with a single electrolyzer ($/year), $(C_{cap})_{case}$ is the capital cost associated with case study electrolyzer ($), l is the electrolyzer lifetime (years), and i is the interest rate (%).

$$C_{op} = 0.09 * C_{cap} \quad (5\text{-}6)$$

where C_{op} is the annual operating cost associated with a single electrolyzer ($/year).

$$C_{ref} = \frac{0.30 * C_{cap}}{(1+i)^{10}} \quad (5\text{-}7)$$

where C_{ref} is the annualized refurbishment cost associated with a single electrolyzer ($/year).

$$C_{electrolyzer} = (C_{cap} + C_{op} + C_{ref}) * n_{electrolyzers} \quad (5\text{-}8)$$

where $C_{electrolyzer}$ is the total annualized electrolyzer cost associated with the energy hub ($/year), and $n_{electrolyzers}$ is the number of electrolyzers in the energy hub.

Chapter 6
Analysis Methodology

This chapter presents the methodology applied to the analysis of the energy hub. First, a number of considerations regarding the analysis are presented. These considerations are then applied to create a suitable design of experiment for the project. Finally, unreliable cases are identified and discarded from the design of experiment to improve the analysis and reduce the number of test cases required.

6.1 Considerations

6.1.1 Grouping by mean travel distance

Due to the way all the components in the energy network are connected, there are a lot of interactions in this model. All the components are sized to suit each other, and changing capacity or performance factors directly or indirectly affects every block in the energy network. For example, the charge-depleting and charge-sustaining range of the fleet may be altered by adjusting the ESS and HSS capacities of the individual vehicles respectively. If the ESS capacity is increased with respect to the HSS capacity, then the fleet will travel farther on electricity and consume less hydrogen as a result. Conversely if the ESS capacity is decreased with respect to the HSS capacity, then the fleet will not travel as far on electricity and will consume more hydrogen as a result. Adjusting the ESS/HSS balance on the individual vehicle level affects the electricity and hydrogen demand of the entire fleet. Changing the hydrogen demand of the fleet affects the suitability of the energy hub's hydrogen storage. If the hydrogen demand is increased then the hydrogen production and storage capacity may not be large enough to reliably supply hydrogen to the fleet. If the hydrogen demand is decreased then the hydrogen storage may be oversized and represent a waste of capital investment in storage capacity. Adjusting the ESS/HSS balance requires adjusting the energy hub's hydrogen storage capacity as well, which in turn is connected to the electrolyzers. If the fleet hydrogen demand is increased and the energy hub's hydrogen storage capacity is also increased, then the electrolyzers will now be undersized.

Conversely, if the fleet hydrogen demand and the energy hub's hydrogen storage capacity are decreased, then the electrolyzers will be oversized and represent a waste of investment in excess electrolyzer capacity.

Adjusting the ESS/HSS balance on the individual vehicle level affects many components in the energy hub, but it also affects the price of hydrogen produced. Since a change on the vehicle level affects a change throughout the hub, the capital investment in the energy hub is changed. For example, increasing the hydrogen demand of the fleet (and also the hydrogen storage and electrolyzer capacities) results in an increase in investment, leading to increased total costs. However, since a greater volume of hydrogen is being produced, the cost of hydrogen produced may possibly remain the same, or even be reduced due to economies of scale. Conversely if the hydrogen demand is reduced the price of hydrogen will also be affected. Since electrolyzer performance capacity and hydrogen storage capacity can only be changed in discrete units, the system may result in discrete changes in the price of hydrogen produced as the ESS/HSS balance is altered.

Altering the electrolyzer capacity also has an effect on other components in the system, such as the wind turbines. The electrolyzer capacity represents a means for the system to capture excess electricity produced during off-peak hours, instead of the electricity being wasted. While increasing the electrolyzer capacity increases the cost of hydrogen produced, it also prevents the waste of electricity (if the connection to the grid is disabled or not utilized). This may result in a reduction in the price of electricity produced. Conversely, lowering the electrolyzer capacity might lower the price of hydrogen, but result in an increased amount of wasted electricity during off-peak hours.

The best ESS/HSS balance will be specific to the travel distance of the fleet. Electricity yields higher km travelled per kWh of electricity consumed than hydrogen, and ideally the vehicles would be purely electric in all cases. Emissions are also higher for hydrogen than for electricity under the current model. However, real-world considerations such as battery weight and cost limit the size of the battery. The maximum feasible charge-depleting range is considered to be approximately 65 km (i.e. assuming the projected all-electric range of the Chevrolet Volt). Beyond a daily travel distance of 65 km, the vehicles will need hydrogen capability and the balance will shift towards the HSS. Therefore, a number of daily travel distances will be considered between 20 km and 100 km (in intervals of 20 km). The daily travel distance is one of the independent variables of this model.

6.1.2 Grouping by off-grid vs. on-grid scenarios

Off-grid scenarios represent energy hubs that are located far from urban centres, and are significantly different from on-grid scenarios. Grid connection is vital to reliable hydrogen generation because the output of the wind turbines falls significantly during the summer months. Without a grid connection, the wind turbines, hydrogen storage and electrolyzers have to be greatly oversized in order to provide a reliable hydrogen supply for the fleet. Therefore, two separate analyses shall be completed: on-grid analysis and off-grid analysis.

6.1.3 Wind vs. grid

Wind turbines represent a significant capital investment, and the price of the electricity produced by the turbines will not match the price of electricity from the grid (even after environmental rebates are applied). Therefore, if the objective of the analysis is to determine scenarios in which the price of electricity is minimized then any number of wind turbines will always move the network farther from the best scenario. However, the model was designed to also study hypothetical cases in which an energy hub would not be connected to the grid and simply powered by the wind (i.e. the off-grid scenario). In such cases, a grid connection is not possible or desired for reasons not relating to the model (e.g. remote facility, or off grid based on a policy decision), leaving the network reliant on wind turbines. Since hydrogen is produced solely through electricity, the price of hydrogen will be higher in scenarios which contain wind turbines.

6.1.4 Electricity price sensitivity: analysis on ratio between tiered price levels

The results are likely sensitive to the differences in price between off-peak, mid-peak and on-peak price levels for electricity. This would possibly have interactions with the charging schedule of the fleet. Overnight fleet charging takes advantage of lower off-peak electricity prices and is always expected to be cheaper. However, if for reasons not related to this model (such as logistics) split-charging is preferred, then its sensitivity to electricity prices should be determined.

Adjusting electricity price levels may also affect the economic viability of wind turbines. At a certain point the price of electricity produced by both wind turbines and the grid will be equal, and this may lead to the best cases which contain wind turbines.

6.2 Design of Experiment

Based on the considerations presented above, a factorial experiment was designed to analyse the energy network. The experiment shall be based on full-year simulations of the model, since the model includes weather-dependant components such as wind and solar power.

Table 6-1 lists the factors and the chosen levels to investigate. This factorial design spans a total of 900 test points across 6 dimensions.

Table 6-1: Factors and levels for analysis of the design of experiment

Factor	Meaning	Value 1	Value 2	Value 3	Value 4	Value 5
A	Number of 1MW wind turbines	0	1	2	-	-
B	Number of 15 Nm^3/hr electrolyzers	0	1	2	3	4
C	Number of 400.95 kg compressed hydrogen storage tanks	0	1	2	-	-
D	Charging schedule of the fleet	Together	Split	-	-	-
E	Mean travel distance (km)	20	40	60	80	100
F	Grid connection enabled	No	Yes	-	-	-

If either factor B or C is set to zero, then both must be zero. Cases with storage but no electrolyzers, or vice-versa, should not be tested. The size of the hydrogen storage was expected to have a strong interaction with the size of the electrolyzers. If the hydrogen storage is undersized with respect to the electrolyzers, this represents a significant waste of money.

The connection with the electricity grid was expected to have a strong interaction with the optimal sizing of the wind power through the model operational logic. If there is no connection to the grid, then the wind power will have to be oversized to ensure that it can meet current electricity demand. However if there is a connection to the grid, then the wind power can be scaled back to a more optimal size. Electricity produced by the wind power can be sold back to the grid. Alternatively, it can also be converted to hydrogen for sale to the fleet.

The charging schedule of the fleet was expected to have a strong interaction with both the variable price of grid electricity and the intermittent supply of wind and solar power throughout the day. If the charging of the fleet coincides with off-peak hours, then the total cost of electricity be less than if the charging of the fleet coincides with peak hours.

To determine the significant effects and interactions of the above factors, a full-factorial design was chosen. The factorial design of experiment will be used to study the main effects and interactions of the most important factors in detail.

A number of different specific objectives can be considered in the analysis, as detailed in Section 2.21, including energy costs and emissions reduction. The following objectives were chosen for this analysis:

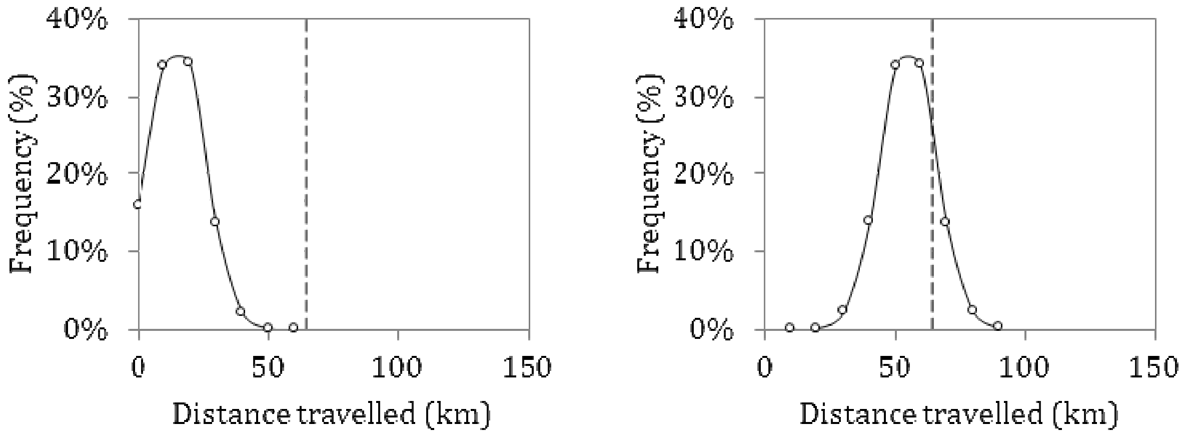
A. Minimize price of electricity (measured in $/kWh);
B. Minimize annual energy network costs for transportation and facility electricity demands (assuming no gasoline is used); and,
C. Maximize overall emissions reduced while meeting transportation and facility electricity demands.

6.3 Unreliable cases

Unreliable cases from amongst the factorial design must be discarded to ensure the usefulness of results. An unreliable case is a case in which the combination of electrolyzers and hydrogen storage and unable to sustain the levels of hydrogen needed for year-after-year of demand by the fleet. As hydrogen is consumed, the electrolyzers must be able to replenish the hydrogen stored to full capacity by the end of the year, and the storage must be of adequate capacity to provide hydrogen for the fleet even at the maximum level of depletion. The number of electrolyzers controls the rate of hydrogen generation, and the number of storage tanks controls the storage capacity. Therefore, the number of electrolyzers and storage tanks must be matched to the amount of hydrogen demand throughout the year. Under sizing the system will provide an unreliable supply of hydrogen to the fleet, and oversizing the system will waste resources. Once the best values of these factors are discovered with respect to the level of hydrogen demand then they shall remain fixed.

The level of hydrogen demand is most significantly affected by the mean travel distance of the fleet. A shorter travel distance will require less hydrogen than a longer travel distance, and beyond a certain level it may even require no hydrogen at all (if all travel distances are within the electric range of the vehicles). Therefore the number of electrolyzers and storage tanks will be matched to the fleet mean travel distance.

The electric range of the fleet as defined by the base case is 64.4km, and the standard deviation of the travel distribution defined as 10km. A mean travel distance less than 64km should not consume any hydrogen at all, and a mean travel distance of 64km or above should consume significant amounts of hydrogen. This is confirmed in Figure 6-1 below, where the dashed line represents the electric range of an individual vehicle. In the case of 20km mean travel distance, shown in Figure 6-1 (a), none of the vehicles travel farther than their electric range, and in the case of 60km mean travel distance, shown in Figure 6-1 (b), a significant portion of the fleet travels farther than the individual vehicle electric range. Therefore, all cases below 64km mean travel distance should not require any electrolyzers or hydrogen storage tanks.



(a) 20km mean travel distance (b) 60km mean travel distance

Figure 6-1: Travel distance distributions for 20km and 60km mean travel distances where frequency represents the percentage of the vehicle fleet that travels that distance.

This assumption was first tested for case with a 20km mean travel distance. Figure 6-2 shows the mass of hydrogen stored throughout the full year of simulation, and no hydrogen is consumed from the storage tank. Therefore, no electrolyzers or hydrogen storage tanks are required for all cases with a 20km mean travel distance.

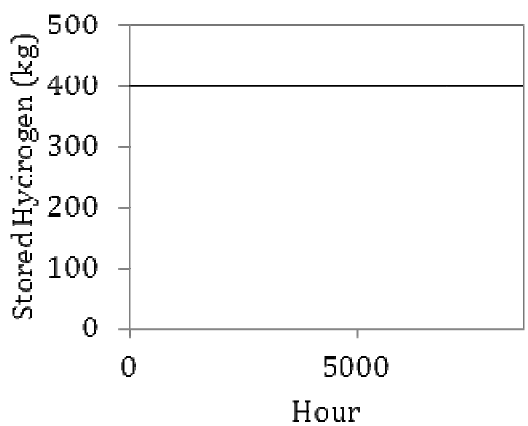
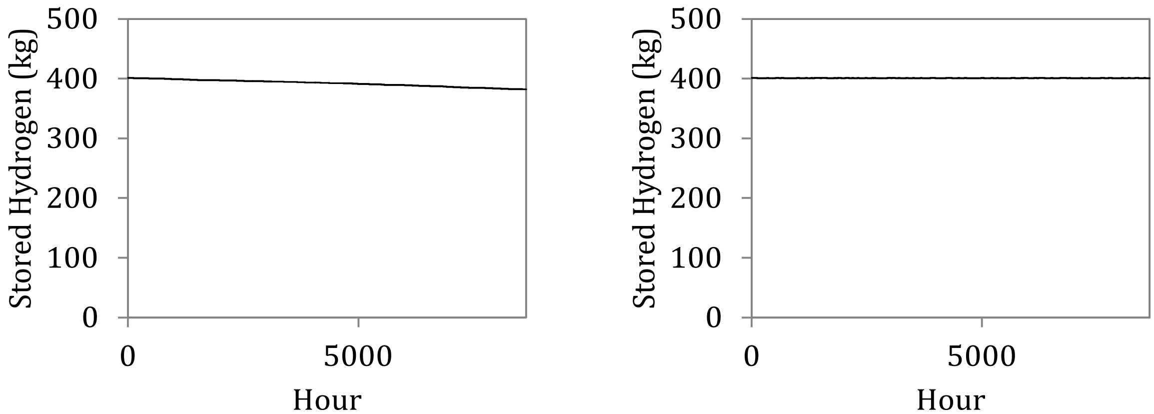


Figure 6-2: Hydrogen storage response for 20km mean travel distance

Figure 6-3 shows the mass of hydrogen stored throughout the full year of simulation in two different cases, both with 40km mean travel distance. Figure 6-3 (a) shows the results of a case with no electrolyzers (i.e. no hydrogen generation), and Figure 6-3 (b) shows the results of a case with one electrolyzer. Although only a small amount of hydrogen is consumed throughout the year in Figure 6-3 (a), over the lifetime of the storage tanks the supply would likely become unreliable as there is no electrolyzer. In Figure 6-3 (b), the supply of hydrogen will be reliable throughout the lifetime of the storage tanks. Therefore, one electrolyzer and one hydrogen storage tank are required for all cases with a 40km mean travel distance.



(a) 0 electrolyzer, 1 tank

(b) 1 electrolyzer, 1 tank

Figure 6-3: Hydrogen storage response for 40km mean travel distance

Figure 6-4 shows the mass of hydrogen stored throughout a full year of simulation in a case with 60m mean travel distance, and the storage tanks remain at full capacity throughout the year. Therefore, one electrolyzer and one hydrogen storage tank are required for all cases with a 60km mean travel distance.

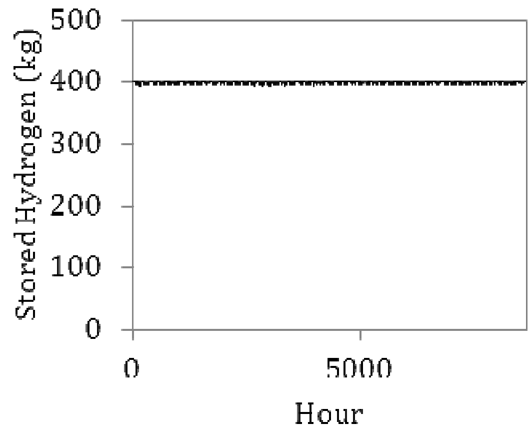
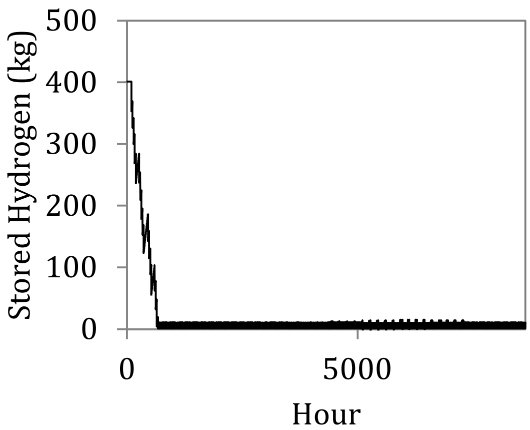
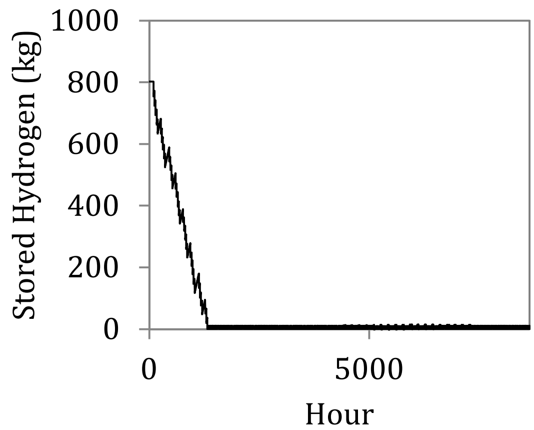


Figure 6-4: Hydrogen storage response for 60km mean travel distance

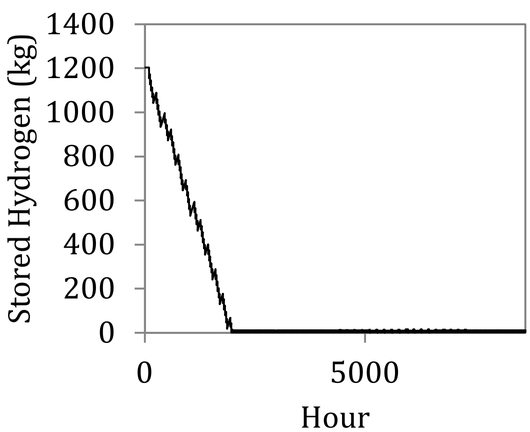
Figure 6-5 shows the mass of hydrogen stored throughout the full year of simulation in four combinations, all of which have an 80km mean travel distance. The base case of one electrolyzer and one storage tank, as shown in Figure 6-5 (a) is unreliable, as are the cases in Figure 6-5 (b) and (c). The case presented in Figure 6-5 (d) is the only reliable option with two electrolyzers and one storage tank. Extra hydrogen generation capacity is required to offset the great hydrogen demand. Therefore, two electrolyzers and one hydrogen storage tank are required for all cases with an 80km mean travel distance.



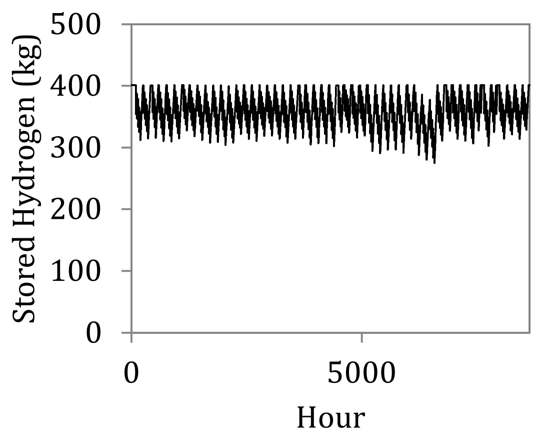
(a) 1 electrolyzer, 1 tank



(b) 1 electrolyzer, 2 tanks



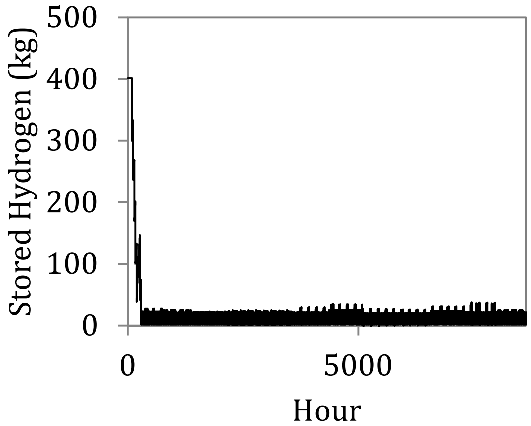
(c) 1 electrolyzer, 3 tanks



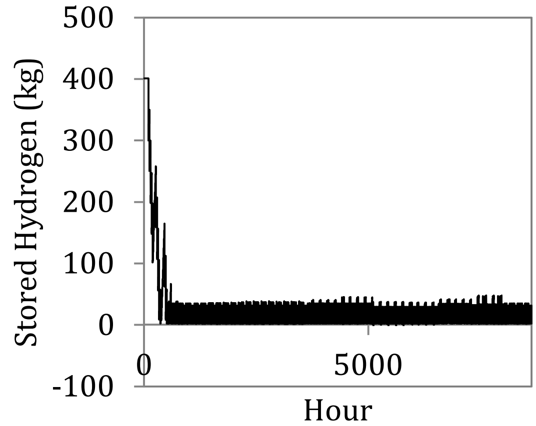
(d) 2 electrolyzers, 1 tank

Figure 6-5: Hydrogen storage responses for 80km mean travel distance

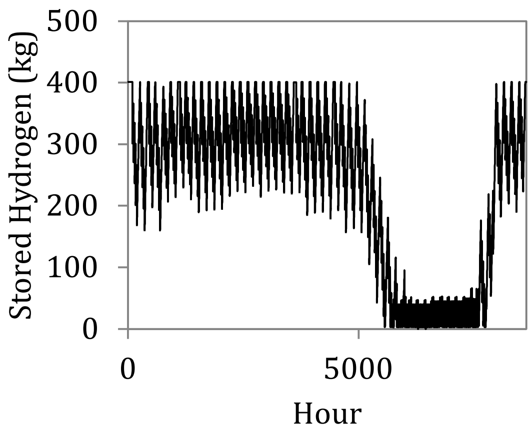
Figure 6-6 shows the mass of hydrogen stored throughout the full year of simulation in four combinations, all of which have a 100km mean travel distance. The previous case of two electrolyzers and one storage tank, as shown in Figure 6-6 (a) is unreliable, as are the cases in Figure 6-6 (b) and (c). The case presented in Figure 6-6 (d) is the only reliable option with four electrolyzers and two storage tanks. Extra hydrogen generation and storage capacity is required to offset the even great hydrogen demand. Therefore, four electrolyzers and two hydrogen storage tanks are required for all cases with a 100km mean travel distance.



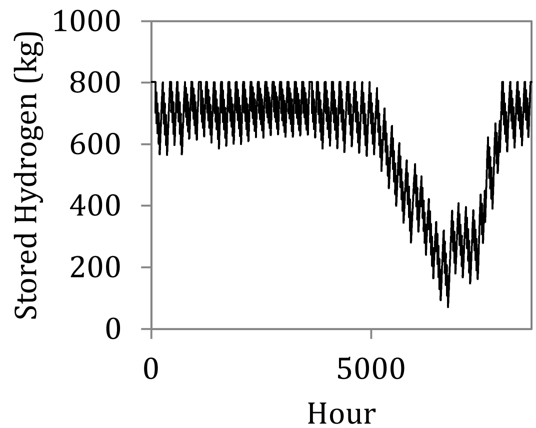
(a) 2 electrolyzer, 1 tank



(b) 3 electrolyzers, 1 tank



(c) 4 electrolyzers, 1 tank



(d) 4 electrolyzers, 2 tanks

Figure 6-6: Hydrogen storage responses for 100km mean travel distance

A summary of the analysis of cases with unreliable hydrogen supply scenarios is presented in Table 6-2.

Table 6-2: Summary of electrolyzer and storage combinations for mean travel distances

Mean travel distance (km)	Number of electrolyzers	Number of storage tanks
20	0	0
40	1	1
60	1	1
80	2	1
100	4	2

This analysis has reduced the span of the factorial design from 900 cases to 60 cases, due to the elimination of the electrolyzer and storage tank factors. Therefore, at least 840 cases in the original factorial design can be considered to be unreliable, and this analysis has eliminated the possibility of choosing an best case that would provide an unreliable supply of hydrogen.

Chapter 7
Results & Discussion

This chapter discusses the results of the analysis outlined in Chapter 6. The energy network was analyzed according to a factorial design of experiment to determine the desired conditions for four criteria: minimum electricity price, minimum hydrogen price, minimum total annual costs, and maximum emissions reduced. Cases deemed unreliable were not included in the analysis. First, all the data from a sample case is presented in order to show the workings of the model. Then, the results of the on-grid and off-grid analyses are discussed. Finally, the sensitivity of the final model outputs to the price of grid electricity is discussed.

7.1 Effects of charging schedules

The charging schedule of the fleet determines the shape of the daily operational profiles of every other node in the integrated energy system; it affects everything from electrolyzer operation to the timing of power purchased from the grid. Two cases were run in order to demonstrate the effects of the charging schedule, as well as to show the workings of the model and the data it produces. The base case represents an on-grid scenario which also contains one wind turbine. The mean travel distance of the fleet was set to 60 km, and the fleet charging schedule was set to overnight. The base case was chosen to have one electrolyzer and one hydrogen storage tank, as a result of the analysis of unreliable cases presented earlier.

Table 7-1 outlines the factor values for the base case. The alternate case is identical to the base case in all aspects except the charging schedule. In the alternate case, the fleet charging schedule was set to split instead of overnight. Table 7-2 outlines the factor values for the alternate case.

Table 7-1: Outline of factor values in the base case

Factor	Meaning	Value
A	Number of 1MW wind turbines	1
B	Number of 15 Nm^3/hr electrolyzers	1
C	Number of 400.95 kg compressed hydrogen storage tanks	1
D	Charging schedule of the fleet	Overnight
E	Mean travel distance (km)	60
F	Grid connection enabled	Yes

Table 7-2: Outline of factor values in the alternate case

Factor	Meaning	Value
A	Number of 1MW wind turbines	1
B	Number of 15 Nm^3/hr electrolyzers	1
C	Number of 400.95 kg compressed hydrogen storage tanks	1
D	Charging schedule of the fleet	Split
E	Mean travel distance (km)	60
F	Grid connection enabled	Yes

Two types of results are charted below for each case: whole year charts, and daily profiles by season. The whole year charts contain the unaltered response of a single model variable across an entire year, and the daily profiles contain the hourly response of a single model variable averaged across all the days in the season. The daily profiles are the average of all daily values, and may be normalized to help compare the shape of the daily profiles across seasons. The y-axis shows the "net energy movement for that hour" in the 24 hour days. The daily profile charts are only averaged profiles; each hour in the daily profile is the average of values from that hour for each day (i.e. hour 1 of the daily profile is the average value from hour 1 of all days). Daily profile charts do not represent any single day. Therefore a daily profile may indicate both electricity purchase and sale from the grid at the same hour, but this is only a mix of several days. The daily profiles are useful for comparing the peak and off-peak regions for several variables of interest throughout the day, rather than to obtain exact values. So they cannot be directly compared (i.e. purchase to sale). Figure **add figure** shows the profile for specific single day to highlight the energy is not transfers into and out of the energy hub to the grid at the same time (while the daily profile plots may indirectly imply this as they are average for the season).

Figure 7-1 shows the whole year plot for the electricity produced by the wind turbines, and Figure 7-2 shows the daily profile plots for the electricity produced by the wind turbines.

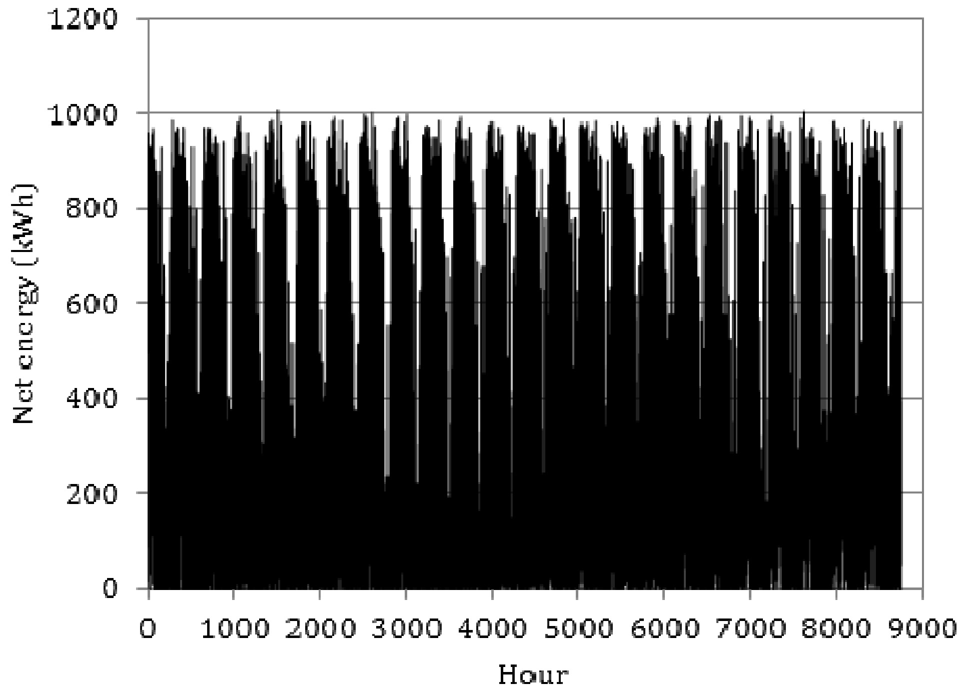


Figure 7-1: Base case: electricity generated by wind turbines (whole year)

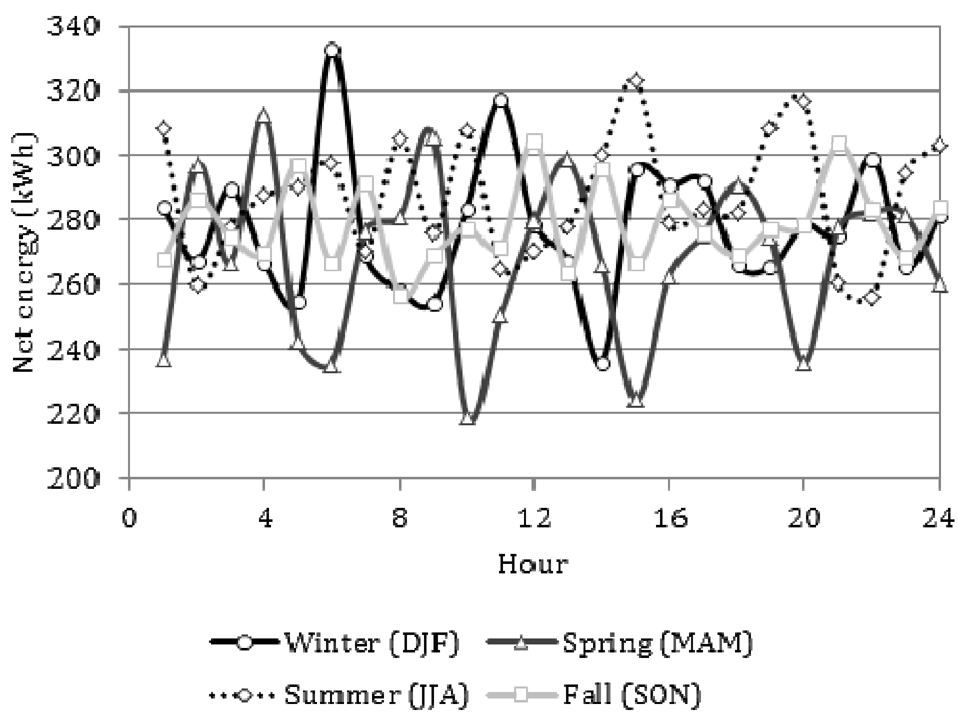


Figure 7-2: Base case: electricity generated by wind turbines (daily profile, by season)

Figure 7-3 and Figure 7-4 show the whole year plots for the electricity purchased from the grid for the base case and alternate case respectively. Figure 7-5 and Figure 7-6 show the daily profile plots for the electricity purchased from the grid for the base case and alternate case respectively. Figure 7-7 and Figure 7-8 show the plots for the electricity purchased from the grid for a sample day respectively. The changing of the charging schedule does not make a significant change in the whole year purchase of electricity from the grid, but significant differences are visible on the daily profile level. During the first charging period (11PM – 7AM) it is seen that the electricity purchased from the grid is higher in the base case than in the alternate case; in the base case the electricity purchased ranges from 50kWh to 100kWh, whereas in the alternate case the electricity purchased is generally lower than 50kWh. This is due to the lower number of vehicles charging during the first period in the alternate case. During the second charging period (8AM to 4PM) the electricity purchased is lower in the base case than in the alternate case. In the base case the electricity purchased ranges from 100kWh to 150 kWh during the second period, except in the summer when it ranges from 200kWh to 250kWh. In the alternate case the electricity purchased ranges from 150kWh to 200kWh, except in the summer when it generally ranges from 250kWh to 300kWh. This is due to the increased number of vehicles charging during the second period in the alternate case. Therefore, changing the charging schedule of the fleet from overnight to split causes the electricity purchased from the grid to decrease during the first period and increase during the second period, thereby increasing the gap in average demand between the two periods. The electricity purchased profiles are similar between the base and alternate case beyond the two charging periods (i.e. after 4PM).

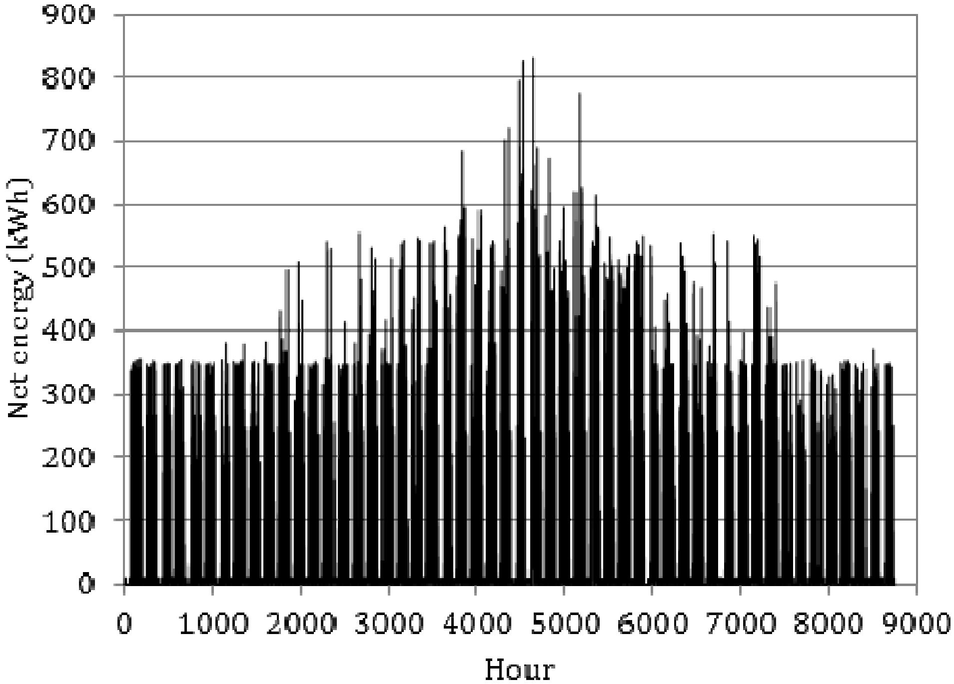


Figure 7-3: Base case: electricity purchased from grid (whole year)

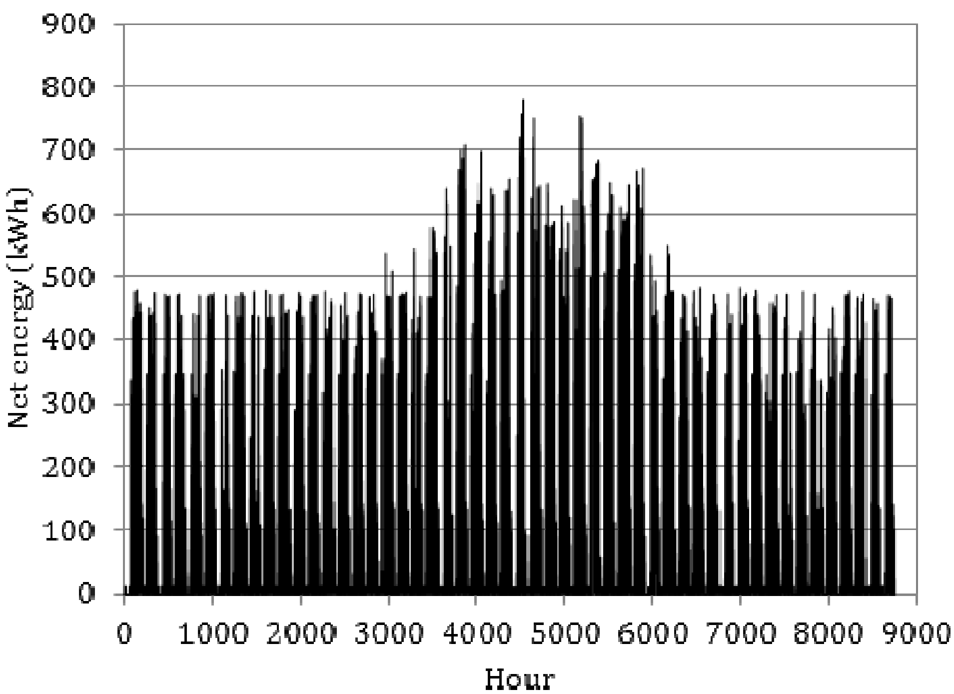


Figure 7-4: Alternate case: electricity purchased from grid (whole year)

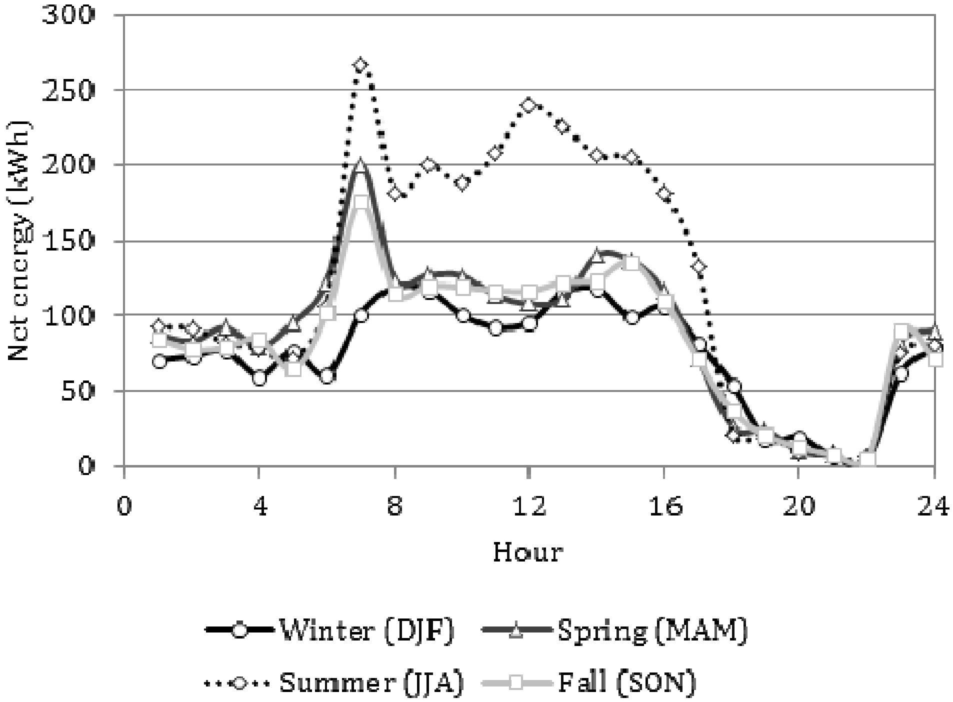


Figure 7-5: Base case: electricity purchased from grid (daily profile, by season)

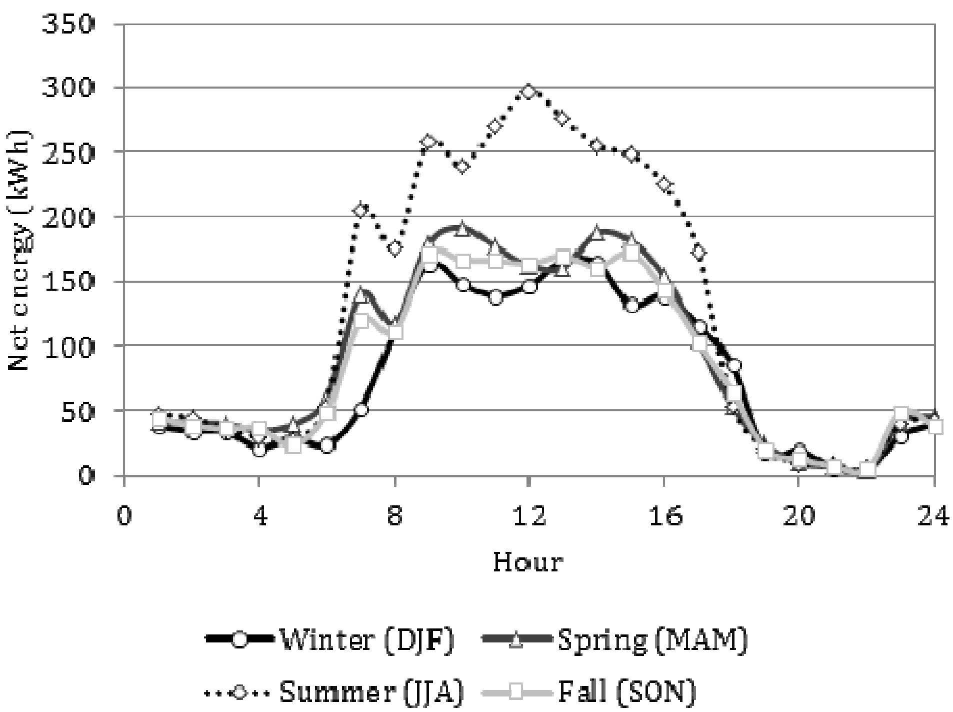


Figure 7-6: Alternate case: electricity purchased from grid (daily profile, by season)

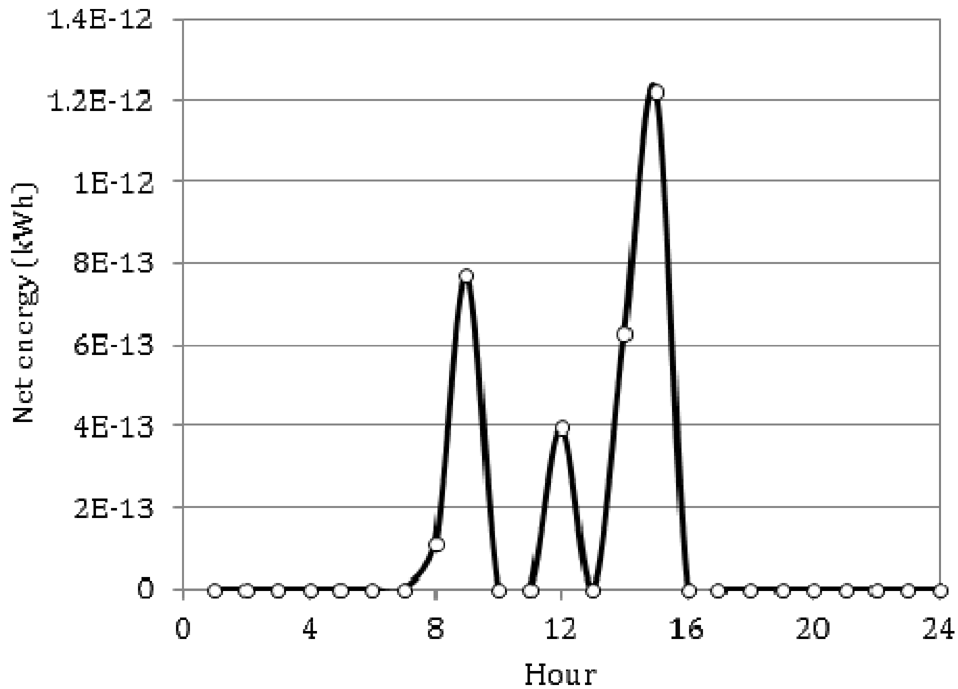


Figure 7-7: Base case: electricity purchased from grid (sample day)

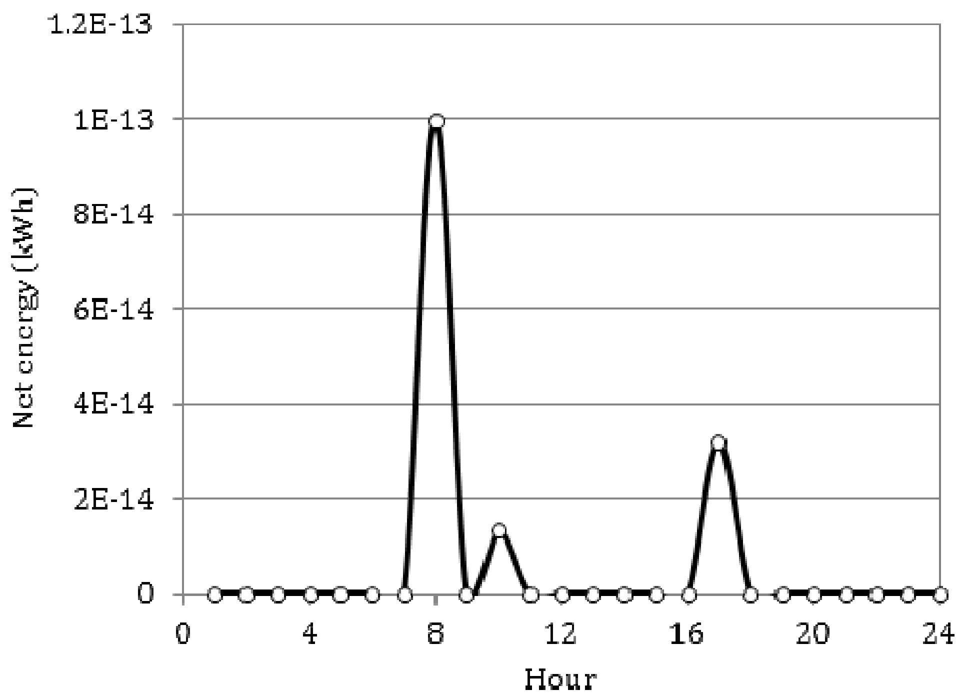


Figure 7-8: Alternate case: electricity purchased from grid (sample day)

Figure 7-9 and Figure 7-10 show the whole year plots for the electricity sold to the grid for the base case and alternate case respectively. Figure 7-11 and Figure 7-12 show the daily profile plots for the electricity sold the grid for the base case and alternate case respectively. Figure 7-13 and Figure 7-14 show the plots for the electricity sold the grid for the base case and alternate case for a sample day respectively. The changing of the charging schedule does not make a significant change in the whole year sale of electricity to the grid. The most significant differences visible on the daily profile level is during the first period of charging. During this time, less electricity is sold to the grid in the base case than in the alternate case. In the base case, the electricity sold to the grid during the first charging period ranges from 150kWh to 200kWh, whereas in the alternate case it ranges from 200kWh to 250kWh.

Figure 7-15 shows the whole year plot for the electricity consumed by the commercial buildings, and Figure 7-16 shows the daily profile plots for the electricity consumed by the commercial buildings.

Figure 7-17 and Figure 7-18 show the whole year plots for the electricity consumed by the fleet for the base case and alternate case respectively. Figure 7-19 and Figure 7-20 show the daily profile plots for the electricity consumed by the fleet for the base case and alternate case respectively. The difference between the base case and alternate case is noticeable in both the whole year plots and the daily profile plots. In the whole year plots, the maximum electricity demand from the fleet at any time in the base case is always higher than in the alternate case. This is due to the lower number of vehicles charging simultaneously in the alternate case. The daily plots indicate both the timing of the charging period(s) and the ratio of vehicles charging between cases. The maximum electricity demand from the fleet in the base case is higher than in the alternate case, whereas the duration of electricity demand is longer in the alternate case than in the base case. This is due to the difference in charging periods and number of vehicles charging simultaneously between the two cases.

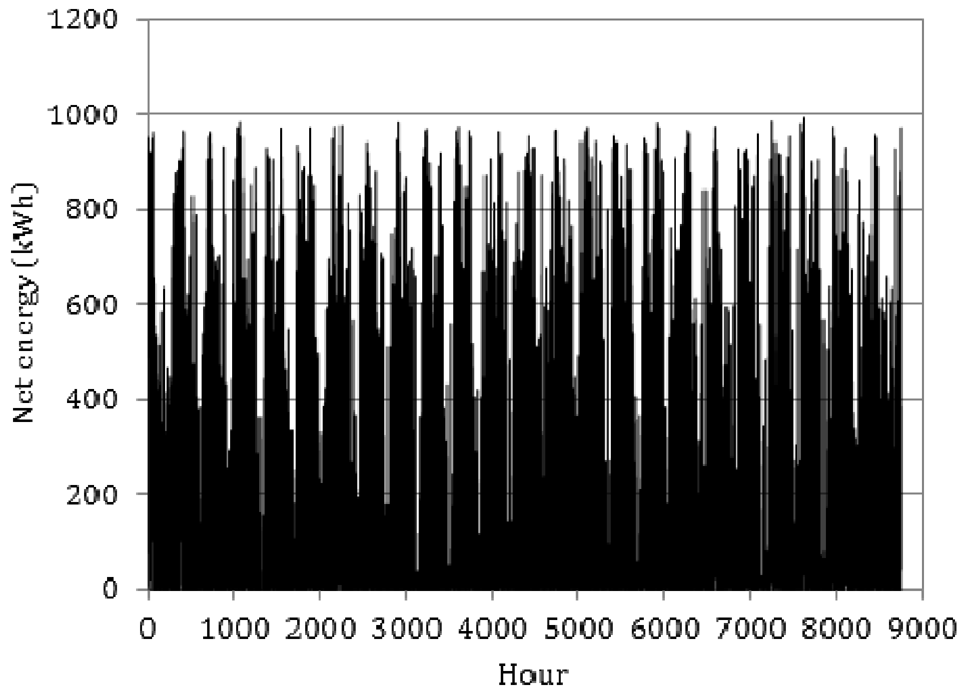


Figure 7-9: Base case: electricity sold to grid (whole year)

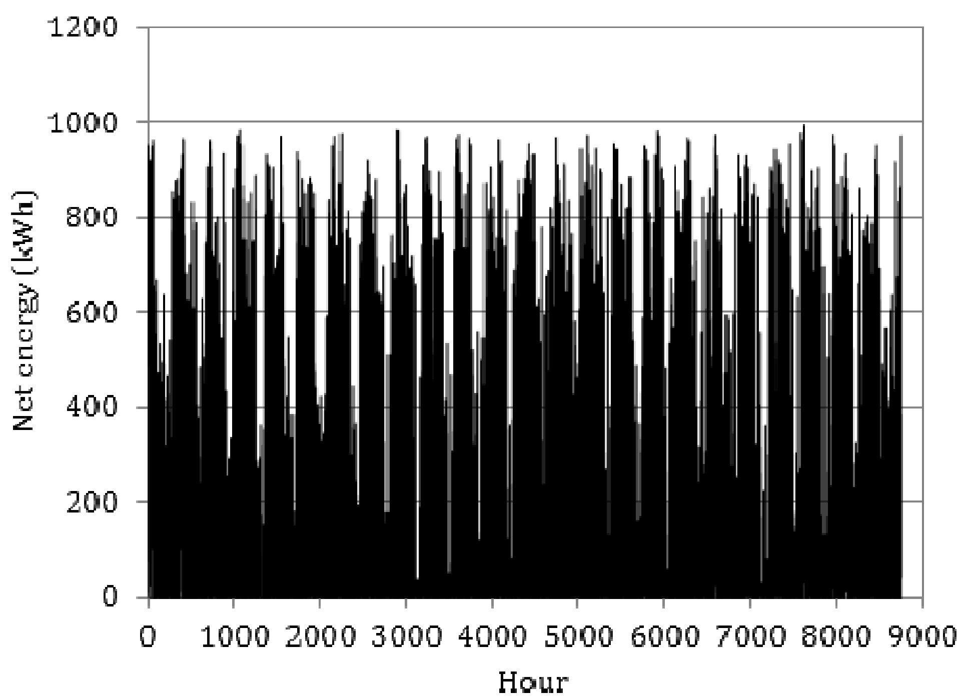


Figure 7-10: Alternate case: electricity sold to grid (whole year)

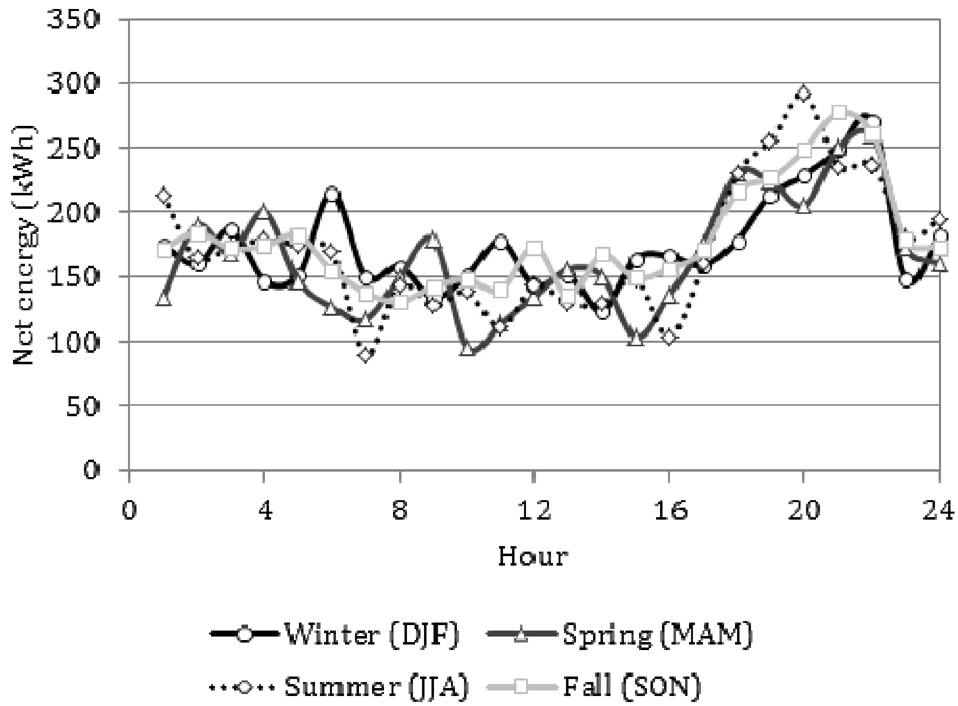


Figure 7-11: Base case: electricity sold to grid (daily profile, by season)

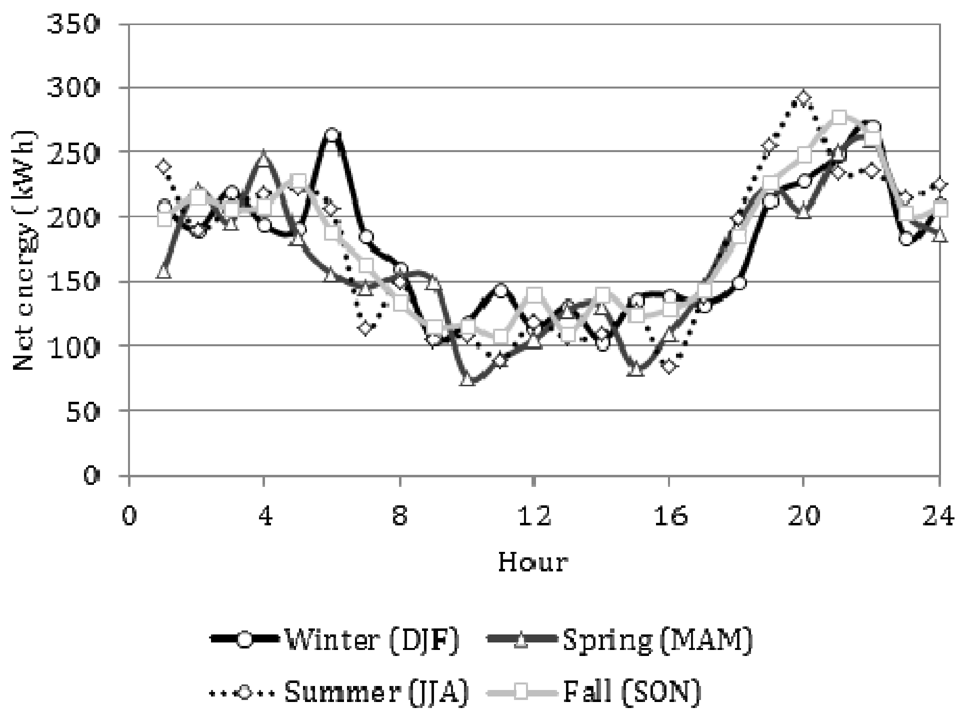


Figure 7-12: Alternate case: electricity sold to grid (daily profile, by season)

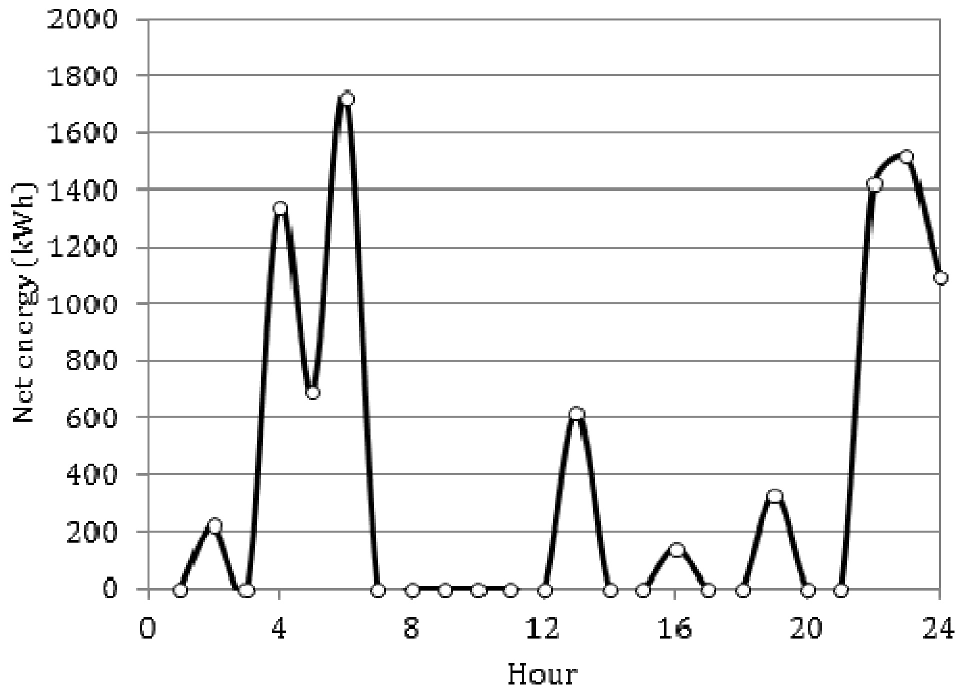


Figure 7-13: Base case: electricity sold to grid (sample day)

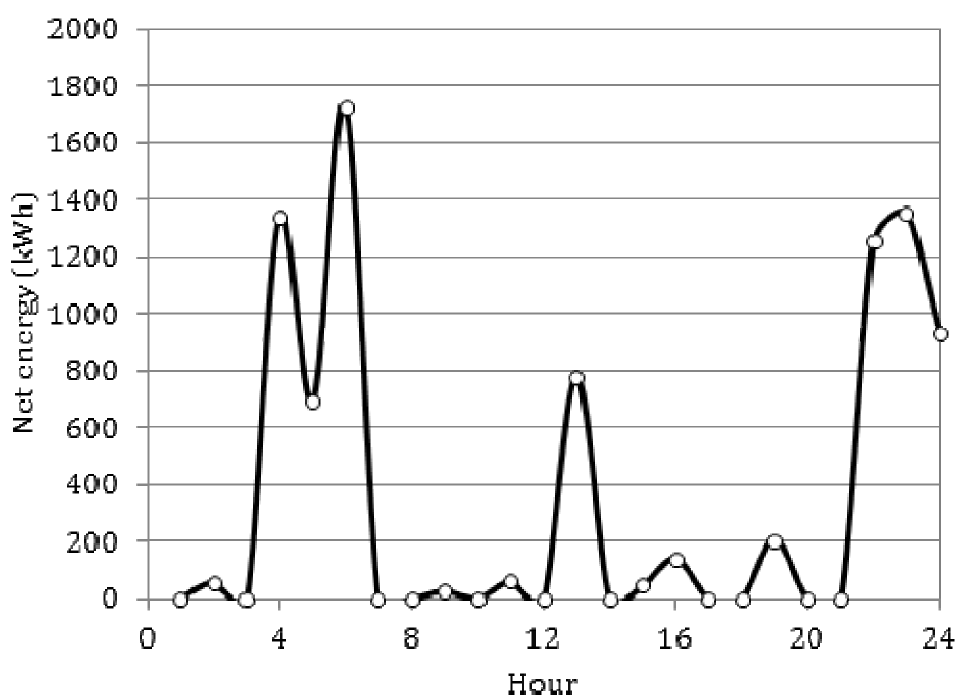


Figure 7-14: Alternate case: electricity sold to grid (sample day)

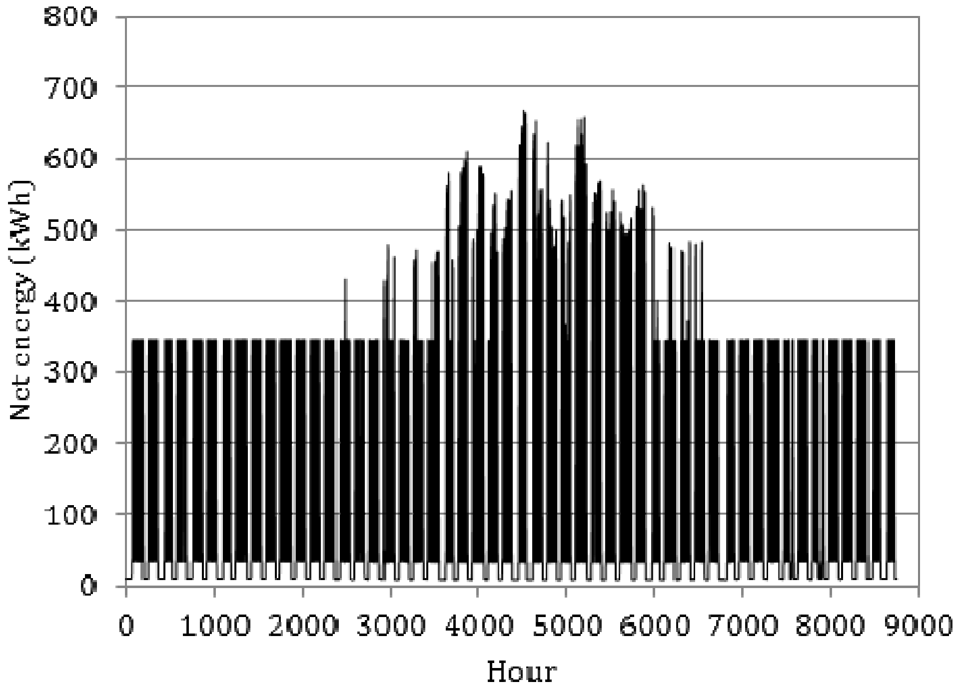


Figure 7-15: Base case: electricity consumed by buildings (whole year)

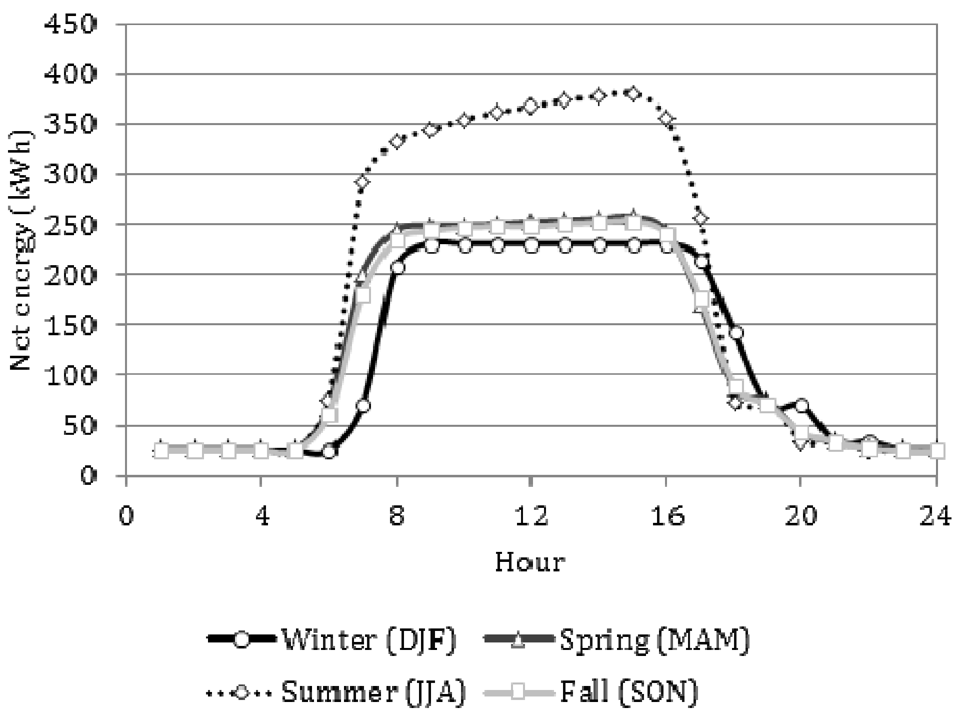


Figure 7-16: Base case: electricity consumed by buildings (daily profile, by season)

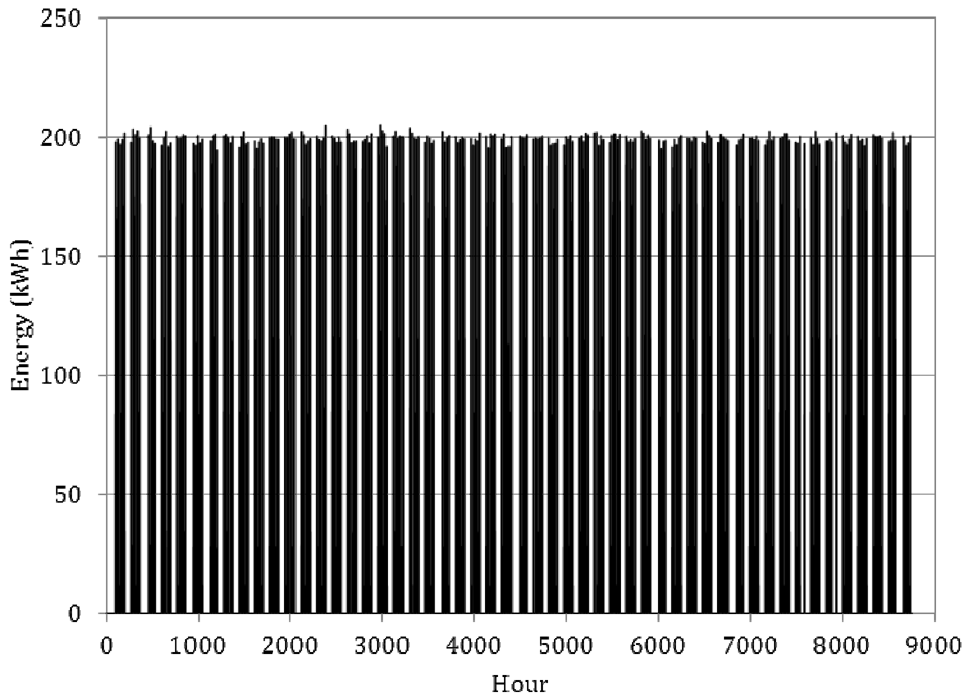


Figure 7-17: Base case: electricity consumed by fleet (whole year)

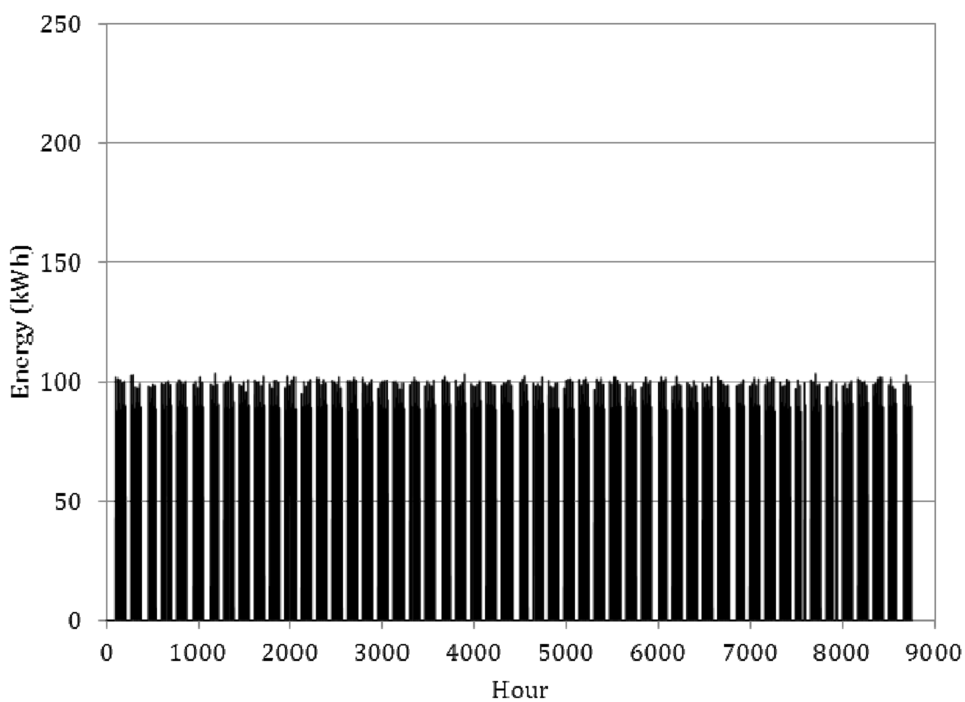


Figure 7-18: Alternate case: electricity consumed by fleet (whole year)

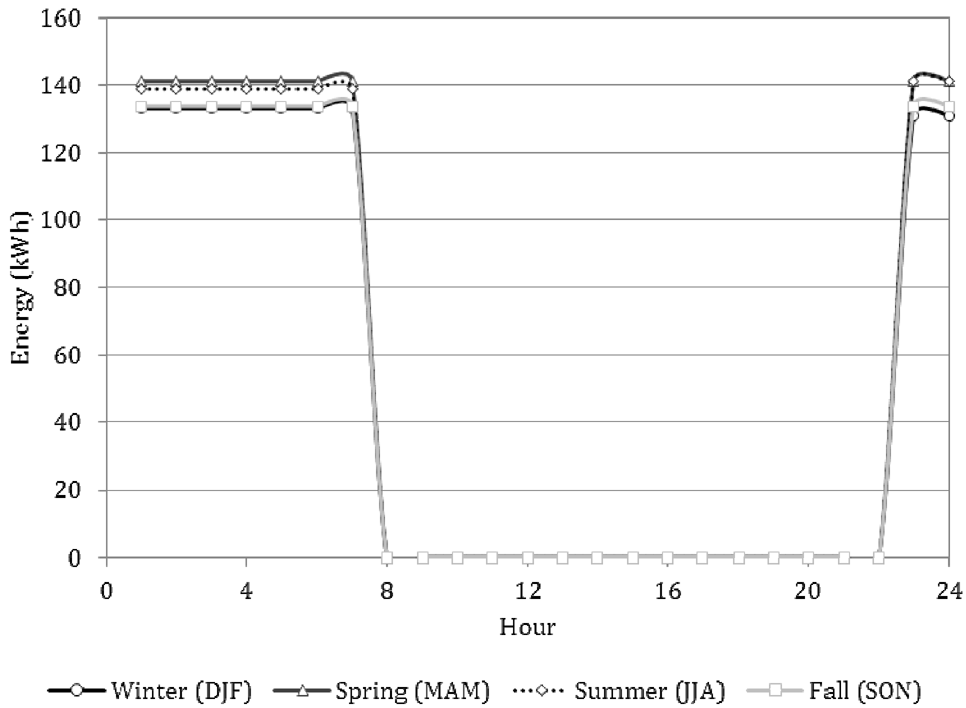


Figure 7-19: Base case: electricity consumed by fleet (daily profile, by season)

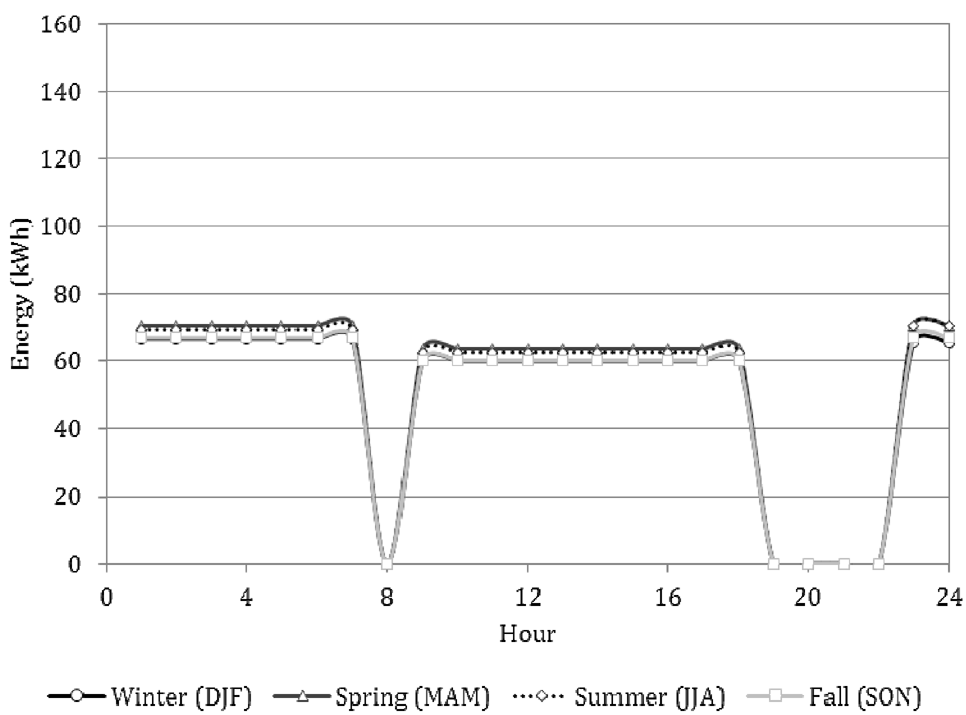


Figure 7-20: Alternate case: electricity consumed by fleet (daily profile, by season)

Figure 7-21 and Figure 7-22 show the whole year plots for the hydrogen consumed by the fleet for the base case and alternate case respectively. Figure 7-23 and Figure 7-24 show the daily profile plots for the hydrogen consumed by the fleet for the base case and alternate case respectively. The difference between the base case and alternate case is noticeable in both the whole year plots and the daily profile plots. In the whole year plots, the maximum hydrogen demand from the fleet at any time in the base case is always higher than in the alternate case. This is due to the lower number of vehicles refuelling simultaneously in the alternate case. The daily plots indicate both the timing of the refuelling period(s) and the ratio of vehicles refuelling between cases. The maximum hydrogen demand from the fleet in the base case is higher than in the alternate case, whereas the total duration of hydrogen demand is longer in the alternate case than in the base case. This is due to the difference in charging periods and number of vehicles refuelling simultaneously between the two cases.

Figure 7-25 and Figure 7-26 show the whole year plots for the hydrogen generated by the electrolyzers for the base case and alternate case respectively. Figure 7-27 and Figure 7-28 show the daily profile plots for the hydrogen generated by the electrolyzers for the base case and alternate case respectively. The changing of the charging schedule does not make a significant change in the whole year plot of hydrogen generated by the electrolyzers. This is because the electrolyzer logic is designed to always operate the electrolyzers at maximum capacity. Therefore, the hydrogen generated by electrolyzers will be equal to the electrolyzer's hydrogen generation capacity in most cases (with the exception of nearly full storage tanks). The effect of changing the charging schedule of the fleet is readily apparent in the daily profile plots. The base case has only one hydrogen generation event whereas the alternate case has two. This is due to the multiple refuelling periods in the alternate case. As the hydrogen is consumed by the fleet, the electrolyzers begin generating more hydrogen to refill the storage tanks. The time taken to refuel the storage tanks is the time it takes for the electrolyzer generation to decrease to zero. The time to refill the storage tanks is greater in the base case than in the alternate case. This is because the hydrogen demanded per refuelling period is higher in the base case than in the alternate case due to the greater number of vehicles refuelling simultaneously.

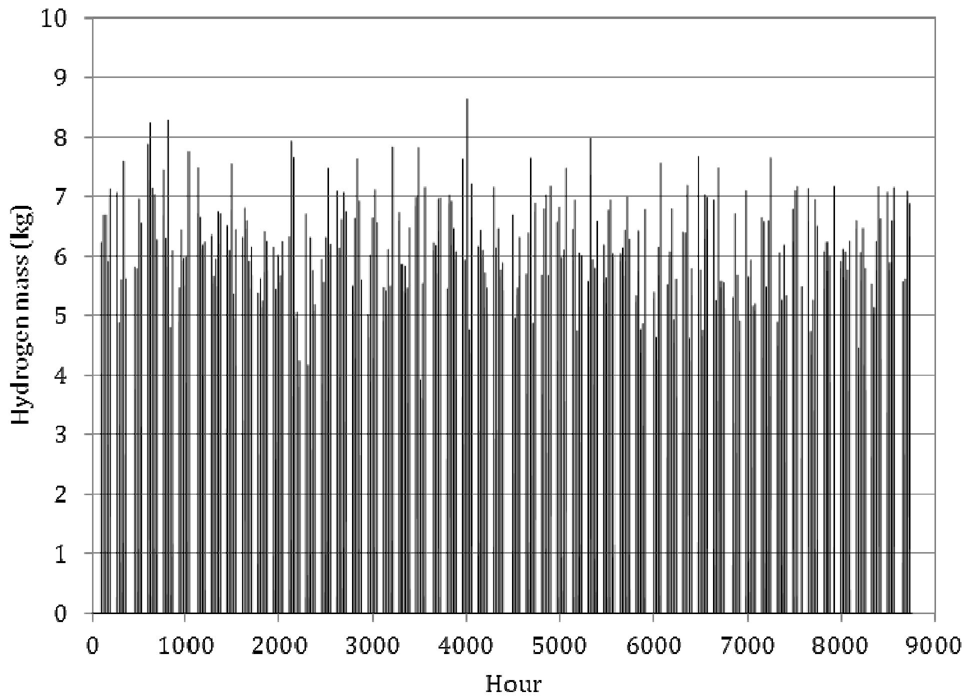


Figure 7-21: Base case: hydrogen consumed by fleet (whole year)

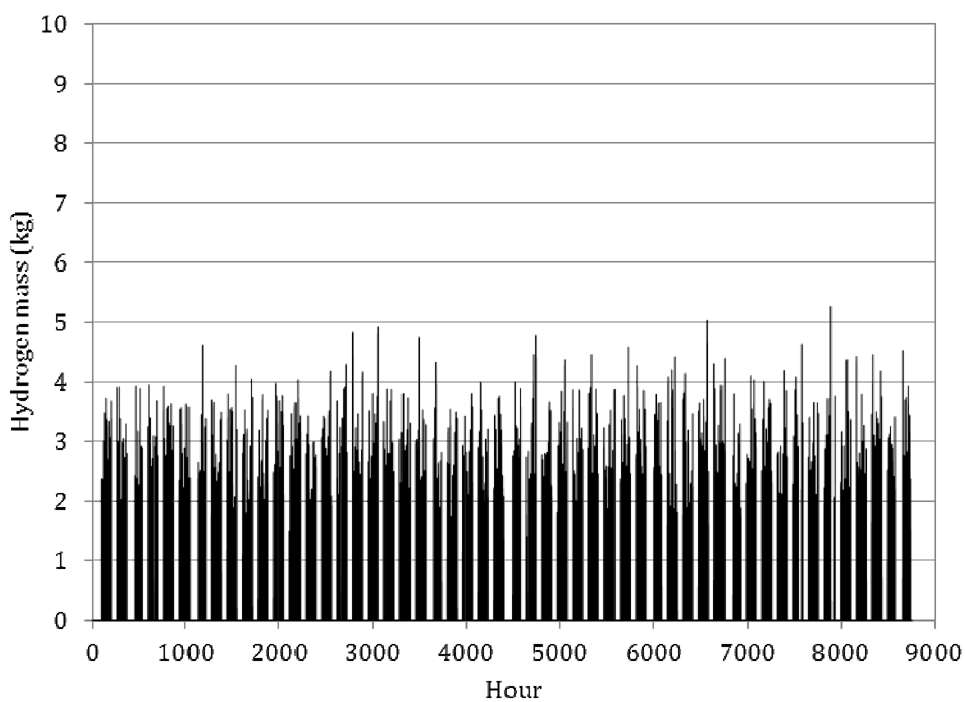


Figure 7-22: Alternate case: hydrogen consumed by fleet (whole year)

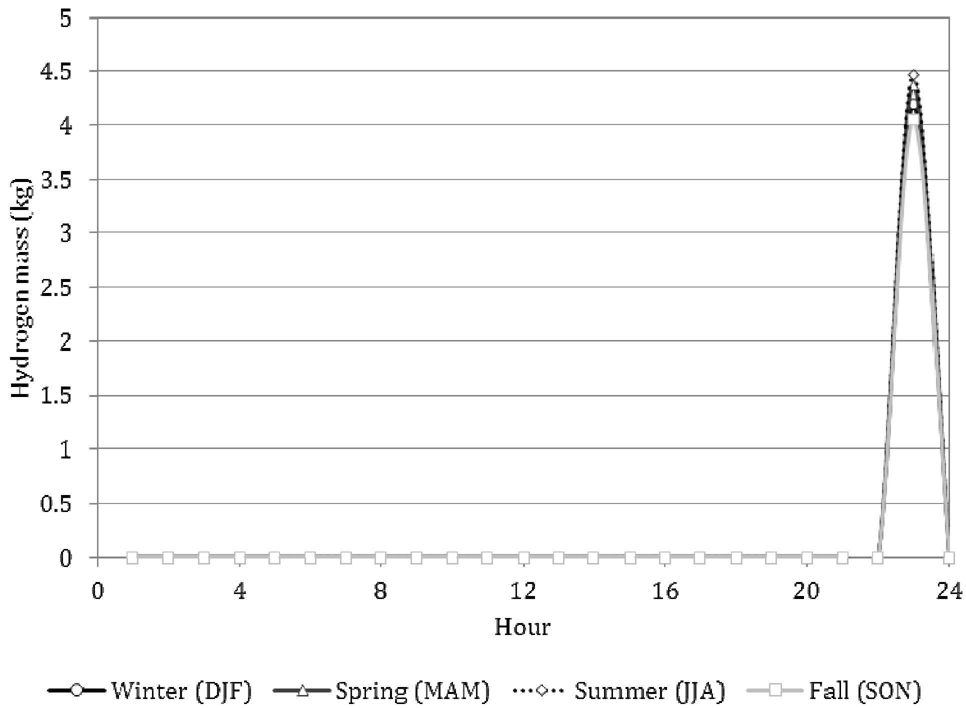


Figure 7-23: Base case: hydrogen consumed by fleet (daily profile, by season)

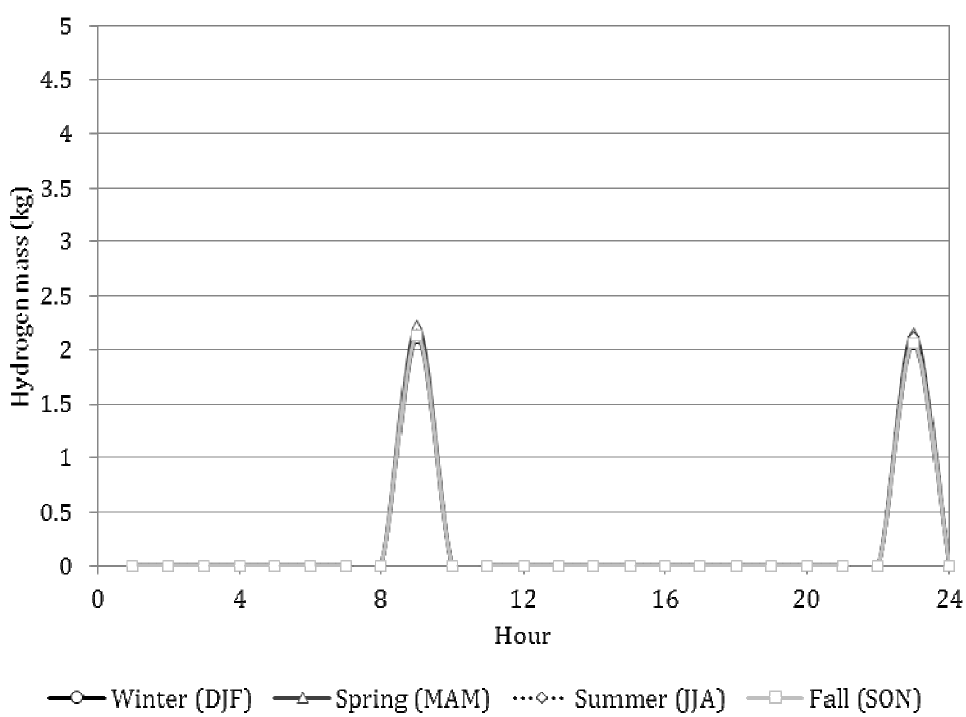


Figure 7-24: Alternate case: hydrogen consumed by fleet (daily profile, by season)

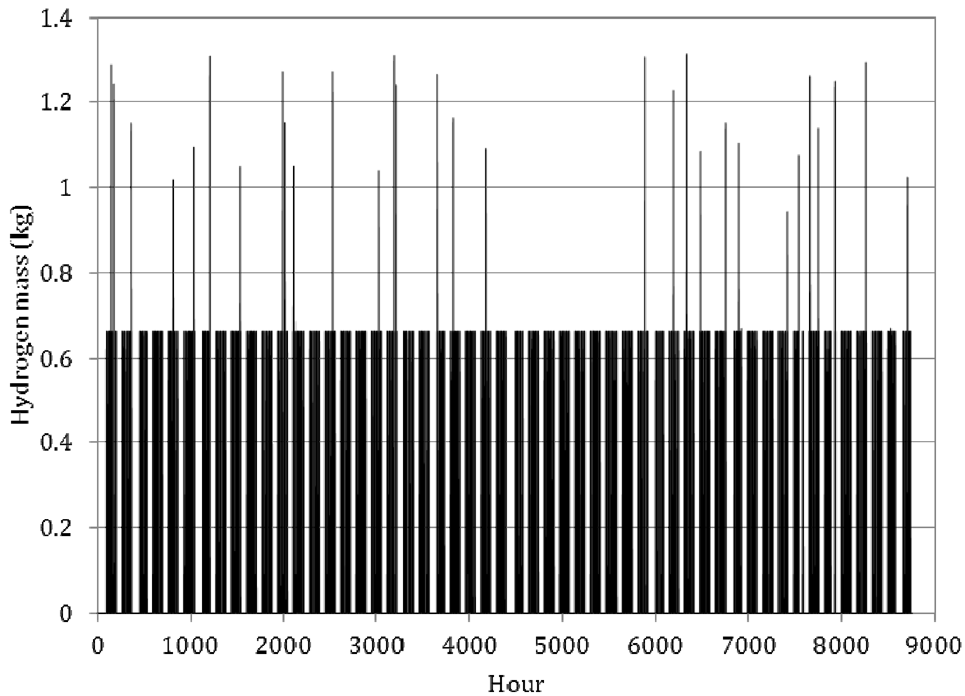


Figure 7-25: Base case: hydrogen generated by electrolyzers (whole year)

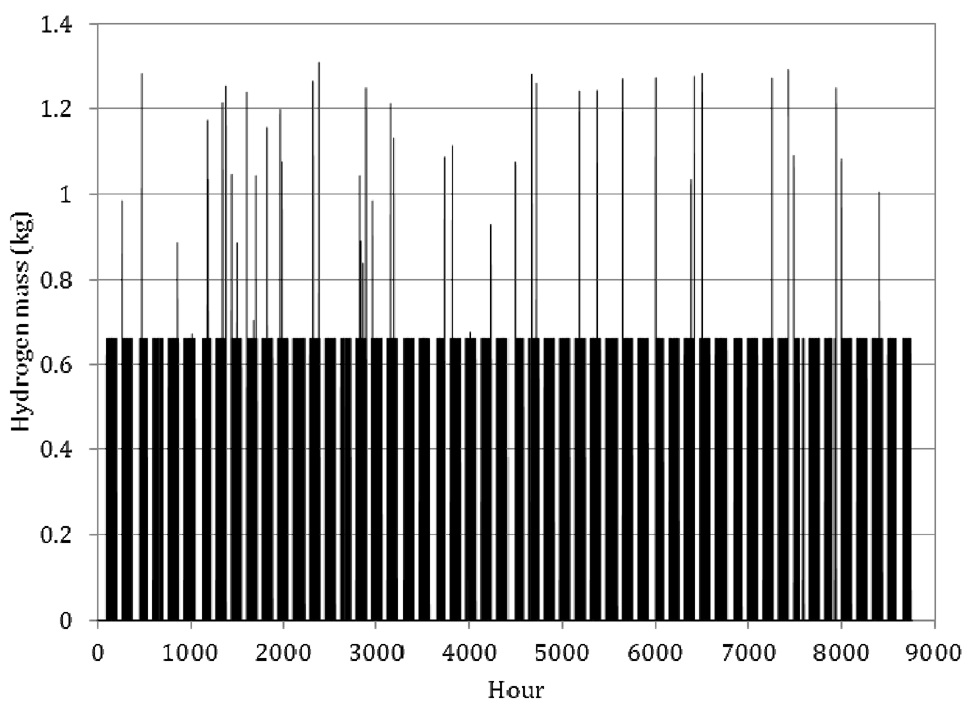


Figure 7-26: Alternate case: hydrogen generated by electrolyzers (whole year)

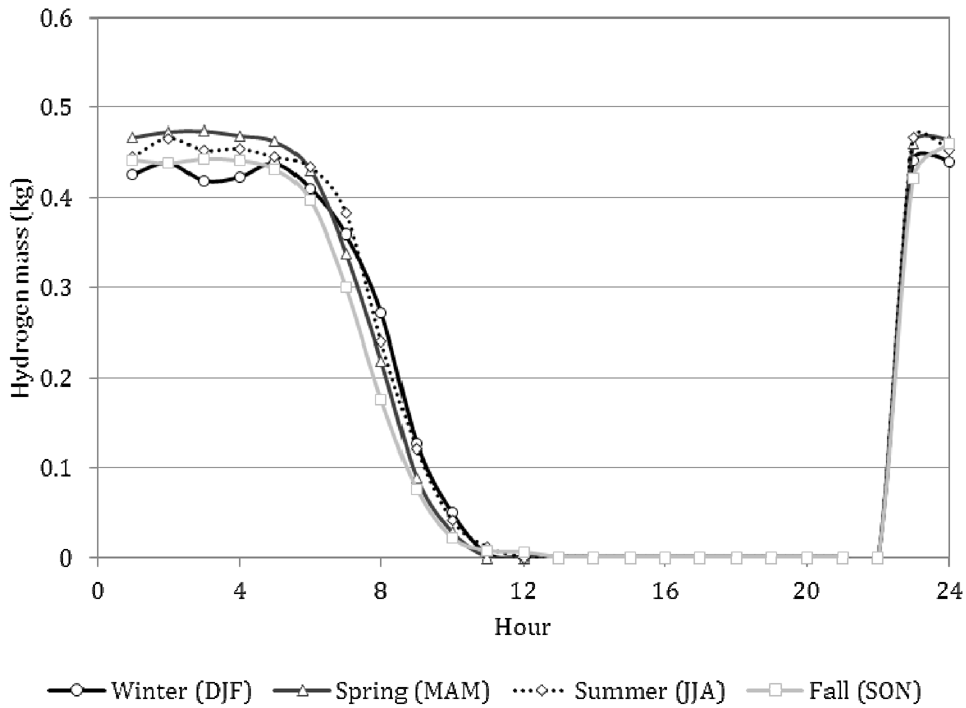


Figure 7-27: Base case: hydrogen generated by electrolyzers (daily profile, by season)

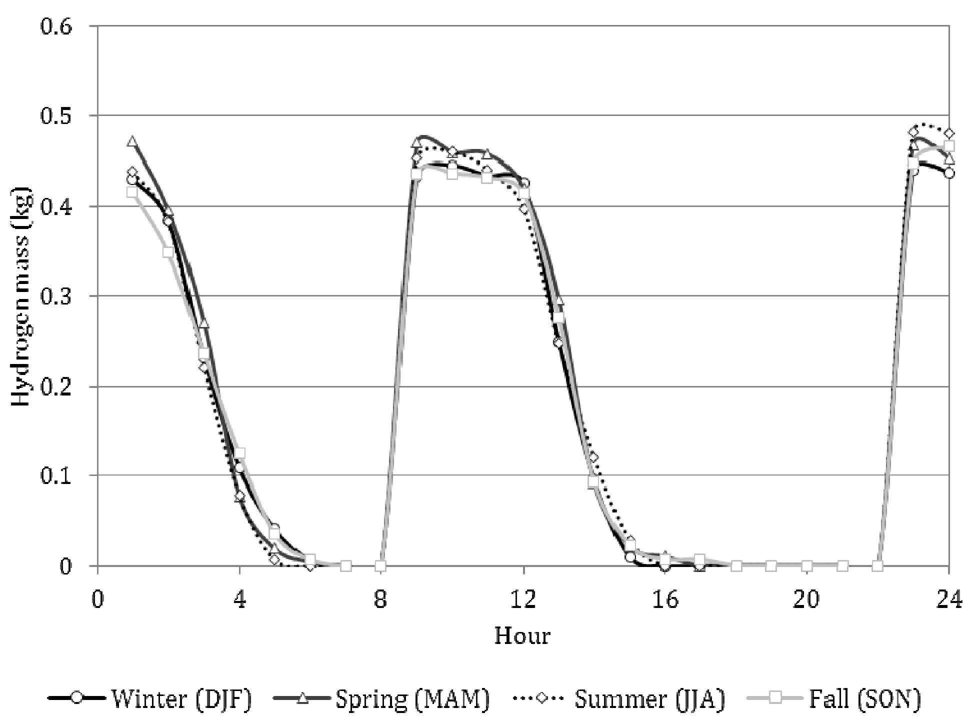


Figure 7-28: Alternate case: hydrogen generated by electrolyzers (daily profile, by season)

Figure 7-29 and Figure 7-30 show the whole year plots for the hydrogen stored in the storage tanks for the base case and alternate case respectively. Figure 7-31 and Figure 7-32 show the daily profile plots for the hydrogen added or withdrawn from the storage tanks for the base case and alternate case respectively. Note that Figures 7-31 and 7-32 are normalized to show the difference between the amount of hydrogen stored between the current hour and the start of the day; a positive value indicates a net hydrogen addition and a negative value indicates a net hydrogen withdrawal. The difference between the base case and alternate case is noticeable in both the whole year plots and the daily profile plots. In the whole year plots, the minimum hydrogen stored in the tanks is lower in the base case than in the alternate case. This is due to the greater hydrogen demand during refuelling in the base case, as a greater number of vehicles are refuelling. The daily profile plots show a noticeable difference between the base case and the alternate case. In the base case, hydrogen is added to the storage tank once (immediately after a refuelling event) and withdrawn once (at a refuelling event), whereas in the alternate case hydrogen is added and withdrawn twice, due to the multiple refuelling events. The amount of hydrogen added or withdrawn at any refuelling event is greater in the base case than in the alternate case due to the greater number of vehicles refuelling in the base case.

Figure 7-33 and Figure 7-34 show the whole year plots for the kilometers travelled per vehicle by fleet for the base case and alternate case respectively. Figure 7-35 and Figure 7-36 show the daily profile plots for the kilometers travelled per vehicle by fleet for the base case and alternate case respectively. Since changing the charging schedule does not affect the mean travel distance, and therefore the travel distribution (Figure 7-37), there is no noticeable difference between the whole year plots for the base case and the alternate case. The daily profile plots of the base case and alternate case simply indicate travel events (immediately at the end of a charging/refuelling event), and show that the alternate case (Figure 7-36) has two travel events whereas the base case has one, hence the two peaks in the alternate case.

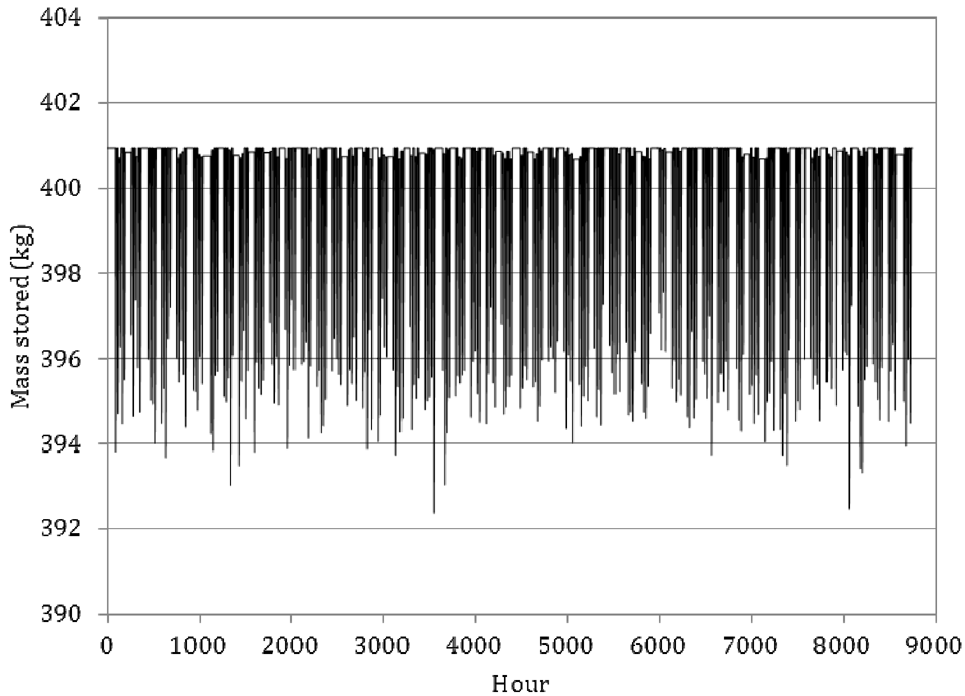


Figure 7-29: Base case: hydrogen stored in tanks (whole year)

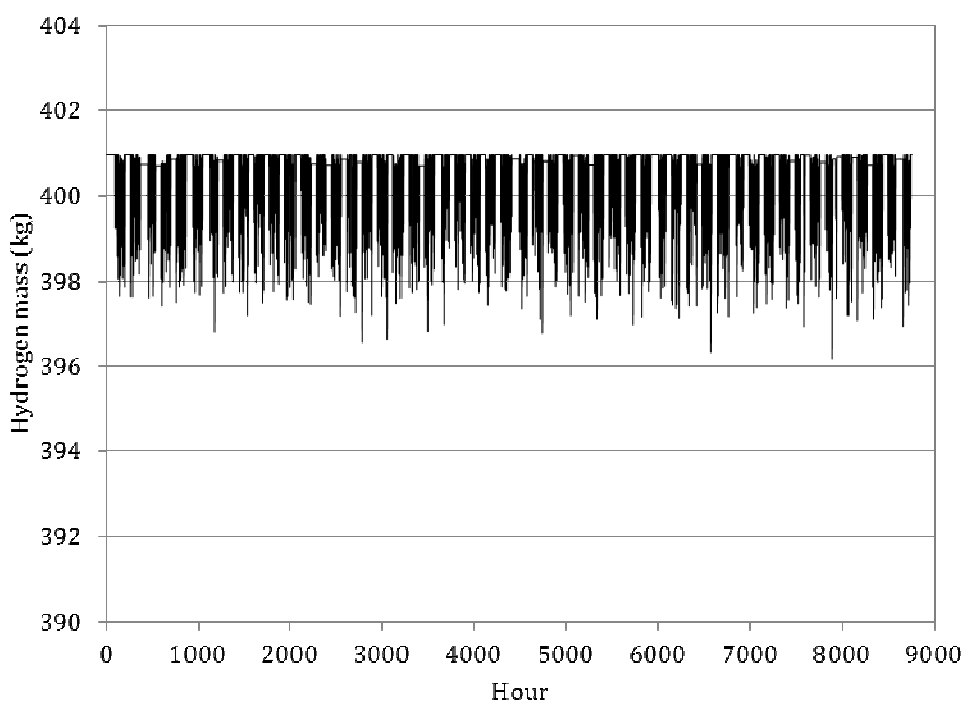


Figure 7-30: Alternate case: hydrogen stored in tanks (whole year)

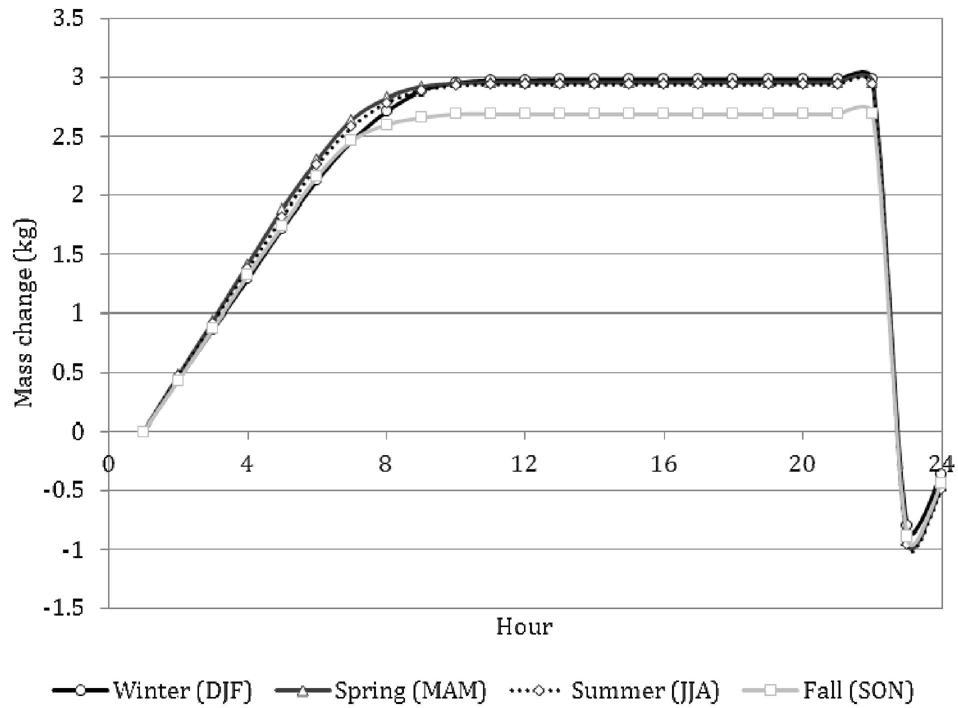


Figure 7-31: Base case: hydrogen stored in tanks (daily profile, by season)

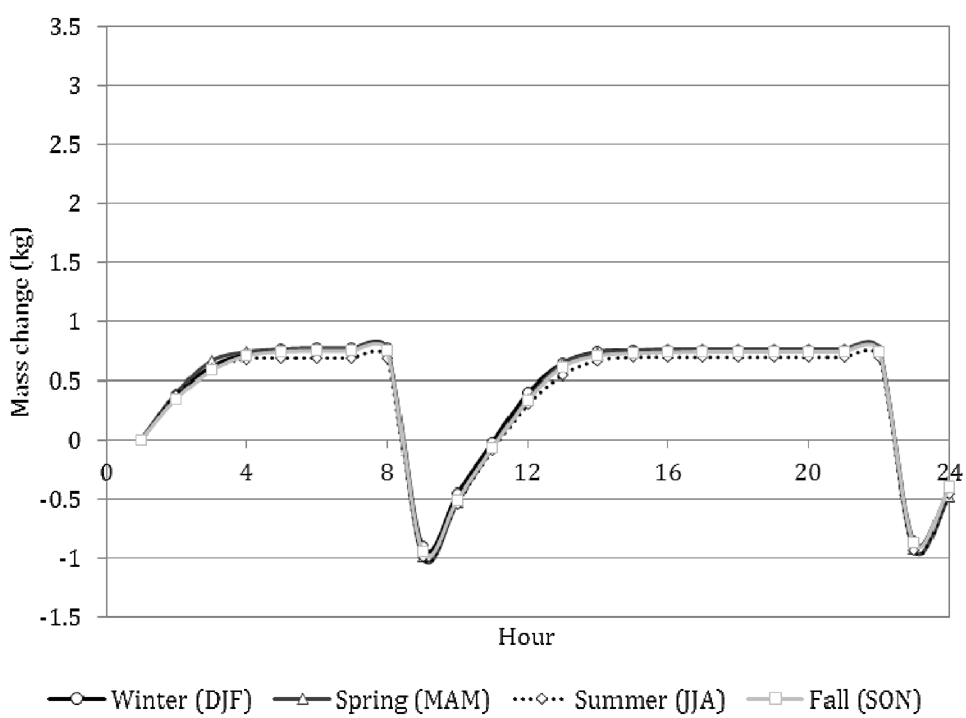


Figure 7-32: Alternate case: hydrogen stored in tanks (daily profile, by season)

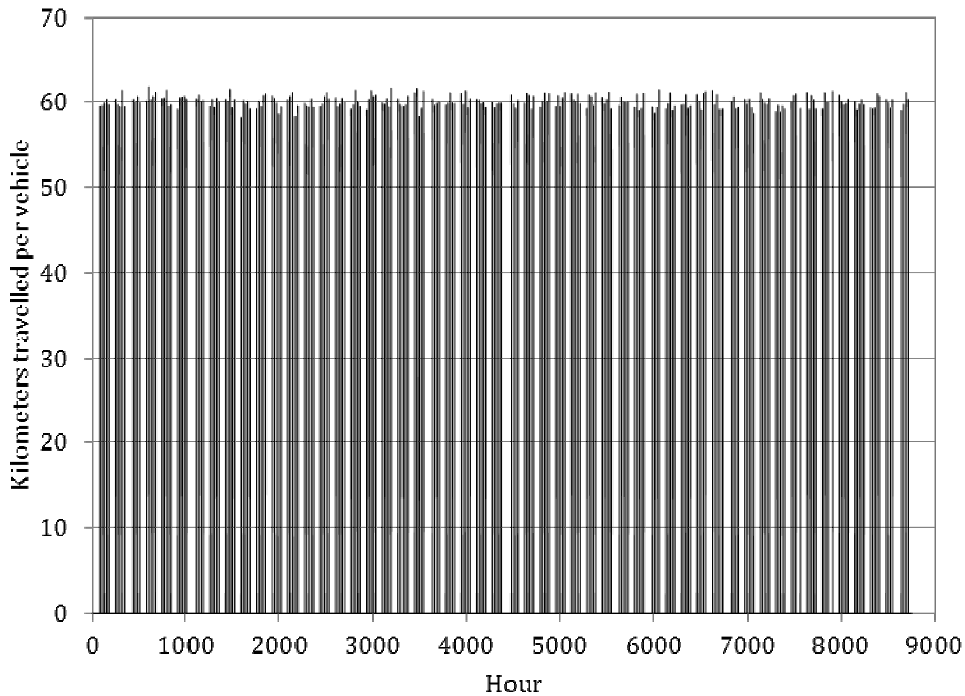


Figure 7-33: Base case: kilometers travelled per vehicle by fleet (whole year)

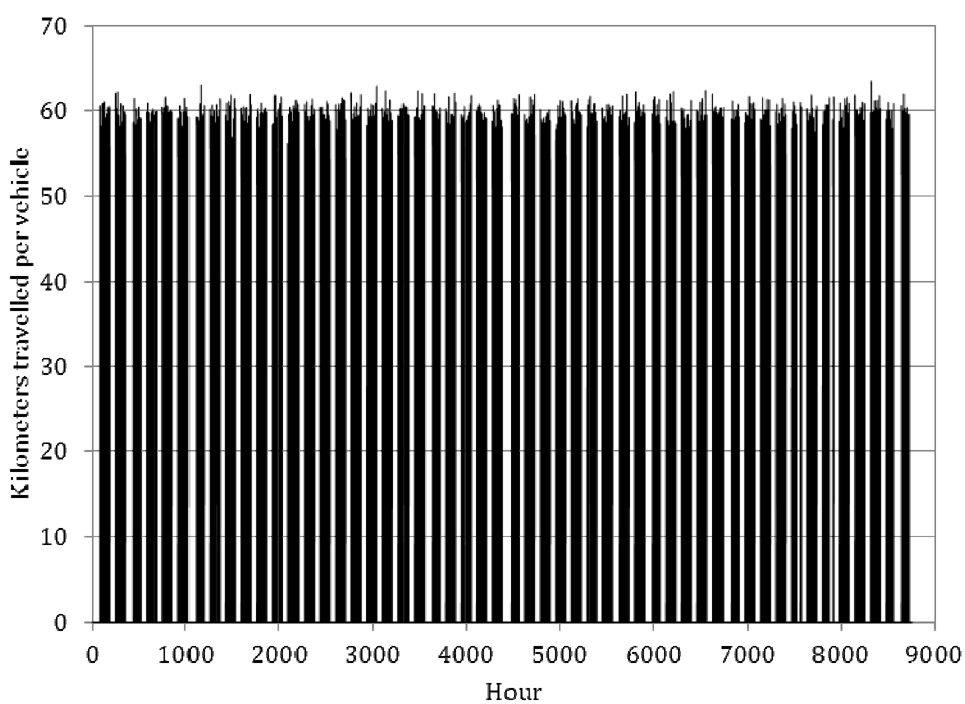


Figure 7-34: Alternate case: kilometers travelled per vehicle by fleet (whole year)

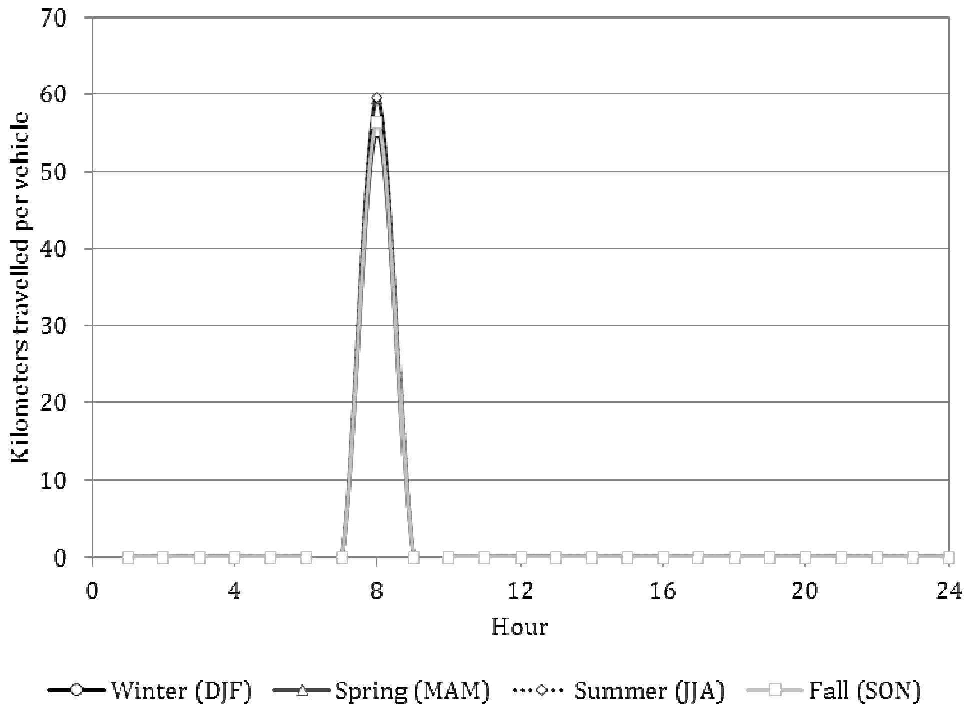


Figure 7-35: Base case: kilometers travelled per vehicle (daily profile, by season)

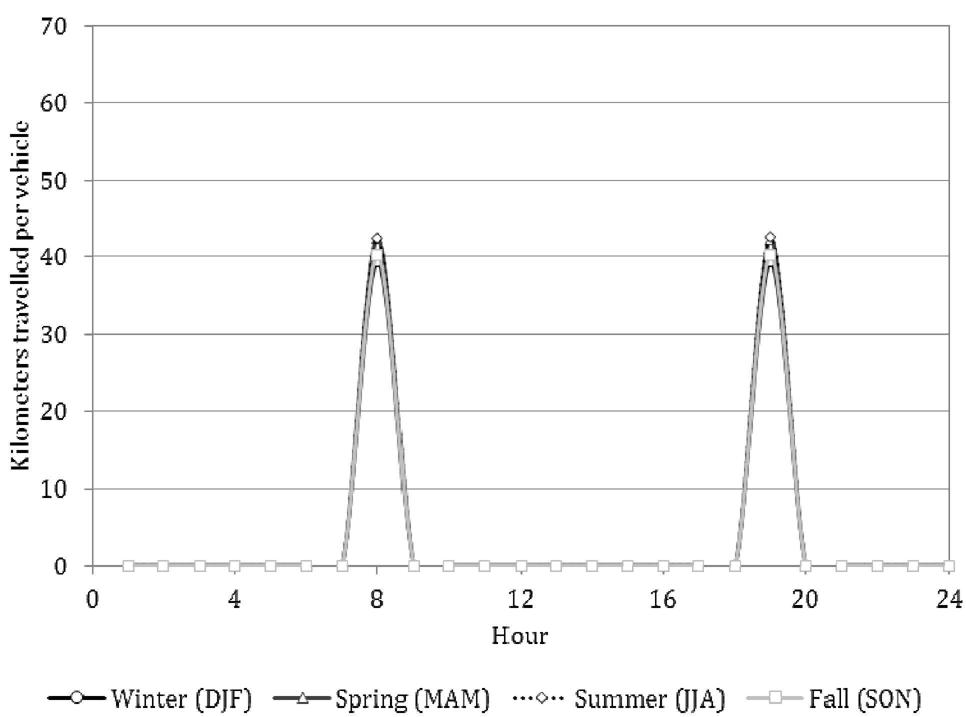


Figure 7-36: Alternate case: kilometers travelled per vehicle (daily profile, by season)

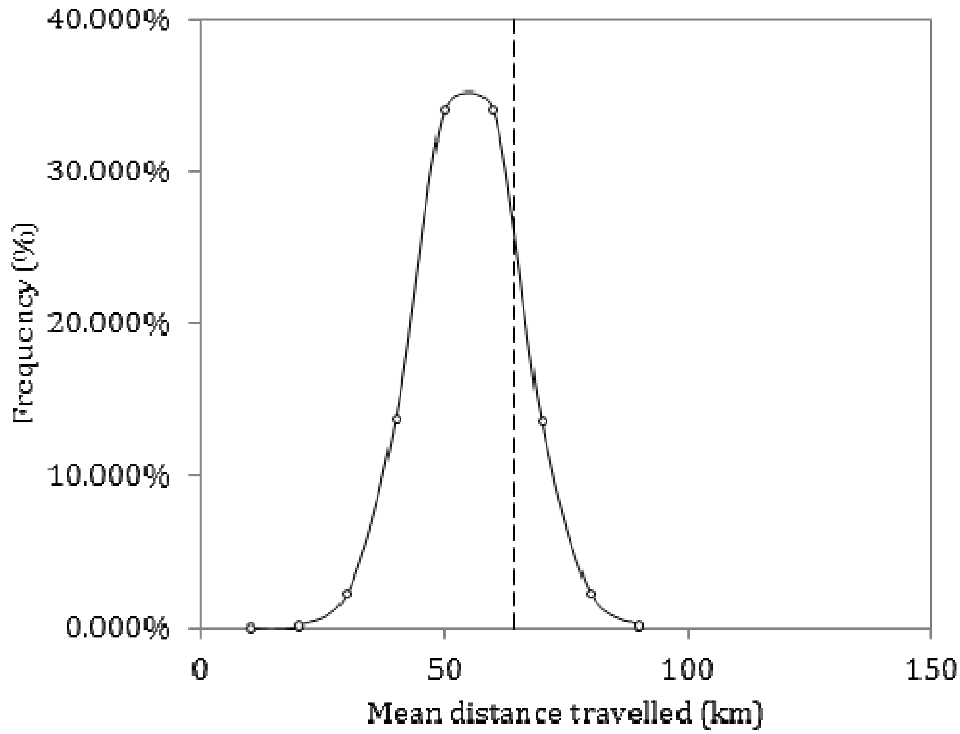


Figure 7-37: Base & alternate case: travel distance distribution by fleet

Tables 7-3 and 7-4 list the results of the cost modelling for the base case and alternate case respectively. The costs between the two cases are similar, with the exception of a greater grid electricity purchase cost in the alternate case. This is explained by the lack of available wind power supply during the second charging event, leading the a greater purchase of grid electricity. Overall, changing the charging schedule from overnight to split raises the price of electricity approximately \$5/MWh and the price of hydrogen approximately \$0.30/kg.

Table 7-3: Summary of results for base case

Parameter	Value
Cost components (revenue is positive, costs are negative)	
Wind turbines	-$239,750
Grid power sold	$73,569
Grid power purchased	-$62,735
Storage tanks	-$2,503
Electrolyzers	-$10,297
Emissions revenue	$43,392
Capacity factors	
Wind turbines	27.8%
Electrolyzers	26.9%
Calculated results	
Electricity price	$130.9/MWh
Hydrogen price	$14.67/kg
Total annual cost	$198,330
CO_2 emissions avoided	1,607,100 kg

Table 7-4: Summary of results for alternate case

Parameter	Value
Cost components (revenue is positive, costs are negative)	
Wind turbines	-$239,750
Grid power sold	$71,111
Grid power purchased	-$69,5245
Storage tanks	-$2,503
Electrolyzers	-$10,297
Emissions revenue	$43,411
Capacity factors	
Wind turbines	27.8%
Electrolyzers	27.0%
Calculated results	
Electricity price	$136.1/MWh
Hydrogen price	$14.91/kg
Total annual cost	$207,560
CO_2 emissions avoided	1,607,800 kg

7.2 On-grid scenarios

The experiment designed in the previous chapter was conducted, while the number of cases was reduced by completing the unreliable case analysis. The results of the on-grid analysis are presented in the sections below.

7.2.1 Minimizing price of electricity

Table 7-5 lists the cases with the lowest electricity price by the mean travel distance of the fleet. Figures 7-38, 7-39, 7-40, and 7-41 contain plots of the electricity price results, hydrogen price results, total annual costs and CO_2 emissions avoided for the best cases.

Table 7-5: On-grid optimized cases for minimum electricity price

Factor	Meaning	20km	40km	60km	80km	100km
A	Number of 1MW wind turbines	0	0	0	0	0
B	Number of 15 Nm^3/hr electrolyzers	0	1	1	2	4
C	Number of 400.95 kg compressed hydrogen storage tanks	0	1	1	1	2
D	Charging schedule of the fleet	Overnight	Overnight	Overnight	Overnight	Overnight
E	Mean travel distance (km)	20	40	60	80	100
F	Grid connection enabled	Yes	Yes	Yes	Yes	Yes

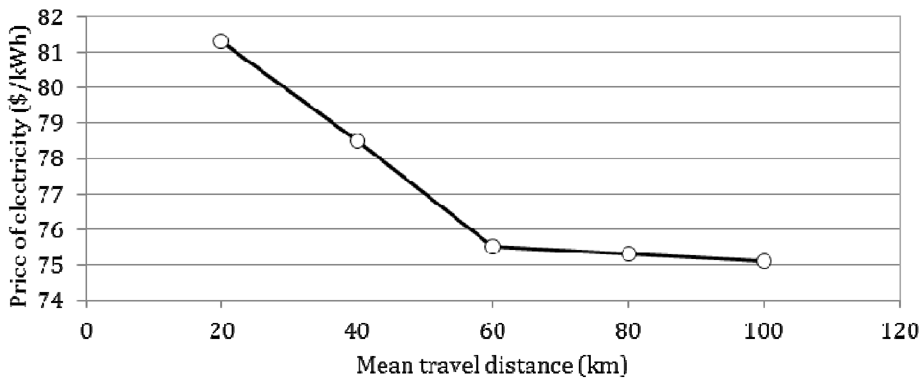


Figure 7-38: Electricity price results for minimum electricity price optimization

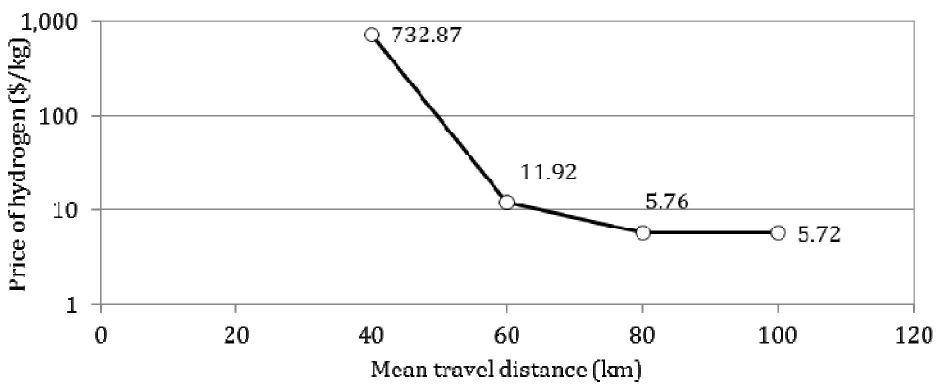


Figure 7-39: Hydrogen price results for minimum electricity price optimization

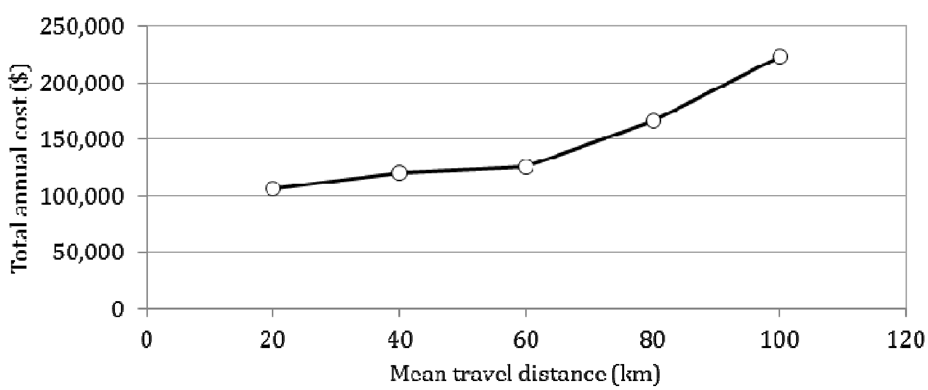


Figure 7-40: Total annual cost results for minimum electricity price optimization

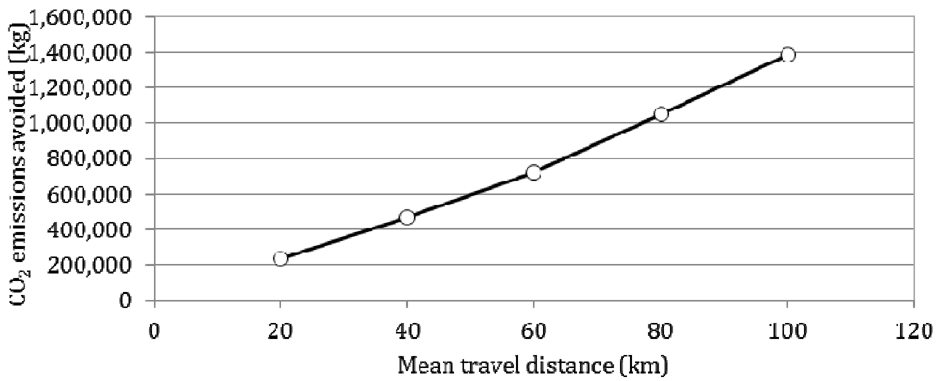


Figure 7-41: CO_2 emissions avoided results for minimum electricity price optimization

Wind turbines were not favoured when optimizing for the price of electricity; the cases contain zero wind turbines and drew electricity from the grid. This indicates that the price of electricity generated with the wind turbines is higher than the grid, despite the revenues earned from the sale of excess electricity to the grid and the CO_2 emissions avoided.

Multiple levels of the number of electrolyzers and compressed hydrogen storage tanks were not tried – they were chosen according to the previous unreliable case analysis presented earlier, in order to ensure that the hydrogen levels in the storage tanks were able to return to their starting levels at the beginning of each year. This allows the fleet to have a reliable source of hydrogen throughout the lifetime of the entire system.

The results of the optimization confirm the previous analysis on the effect of changing the charging schedule of the fleet. Overnight charging of the fleet was favoured over the split charging of the fleet. This is due to the lower price of electricity during the first charging period, which occurs during off-peak hours. The second charging period occurs during peak hours, when the price of electricity is significantly higher, raising the average price of electricity.

The transition between 40km and 60km of mean travel distance results in a marked difference in the behaviour of the electricity and hydrogen price results. The rate of decrease in prices between 20km and 60km of mean travel distance is higher than the rate of price decrease with mean travel distances above 60km. This behaviour is not observed however in the total annual cost results or the CO_2 emissions avoided results. The steep decrease in prices between 20km and 60km of mean travel distance is likely due to the low amounts of hydrogen consumed by the fleet at 20km and 40km of mean travel distance. The low consumption results in a low capacity utilization of the electrolyzers and hydrogen storage tanks, and recovering their capital costs from the amount of hydrogen produced results in a high hydrogen and electricity price. In such cases it would instead be preferable to purchase hydrogen from an external supplier, negating the cost of the electrolyzer.

Table 7-6: Summary of results for minimum electricity price optimization

Parameter	20km	40km	60km	80km	100km
Cost components (revenue is positive, costs are negative)					
Wind turbines	$0	$0	$0	$0	$0
Grid power sold	$0	$0	$0	$0	$0
Grid power purchased	-$112,200	-$120,440	-$131,920	-$171,410	-$214,300
Storage tanks	$0	-$2,503	-$2,503	-$2,503	-$5,006
Electrolyzers	$0	-$10,297	-$10,297	-$20,593	-$41,186
Emissions revenue	$6336	$12,644	$19,357	$28,355	$37,412
Capacity factors					
Wind turbines	N/A	N/A	N/A	N/A	N/A
Electrolyzers	N/A	29.3%	26.4%	97.0%	98.9%
Calculated results					
Electricity price	$81.3/MWh	$78.5/MWh	$75.5/MWh	$75.3/MWh	$75.1/MWh
Hydrogen price	N/A	$732.87/kg	$11.92/kg	$5.77/kg	$5.72/kg
Total annual cost	$105,860	$120,590	$125,360	$166,150	$223,080
CO_2 emissions avoided	234,680 kg	468,310 kg	716,90 kg	1,050,200kg	1,385,600 kg

7.2.2 *Minimizing total annual costs*

Table 7-7 lists the cases with the lowest total annual costs by the mean travel distance of the fleet. Figures 7-42, 7-43, 7-44 and 7-45 contain plots of the electricity price results, hydrogen price results, total annual costs and CO_2 emissions avoided for the best cases.

Table 7-7: On-grid optimized cases for minimum total annual costs

Factor	Meaning	20km	40km	60km	80km	100km
A	Number of 1MW wind turbines	0	0	0	0	0
B	Number of 15 Nm^3/hr electrolyzers	0	1	1	2	4
C	Number of 400.95 kg compressed hydrogen storage tanks	0	1	1	1	2
D	Charging schedule of the fleet	Overnight	Overnight	Overnight	Overnight	Overnight
E	Mean travel distance (km)	20	40	60	80	100
F	Grid connection enabled	Yes	Yes	Yes	Yes	Yes

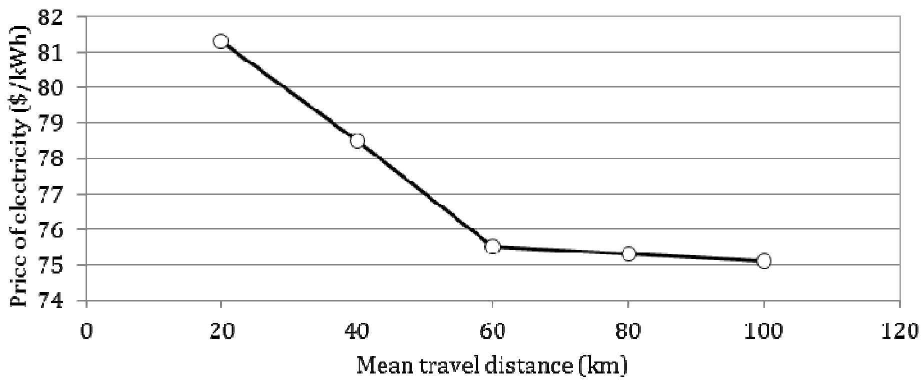


Figure 7-42: Electricity price results for minimum total annual cost optimization

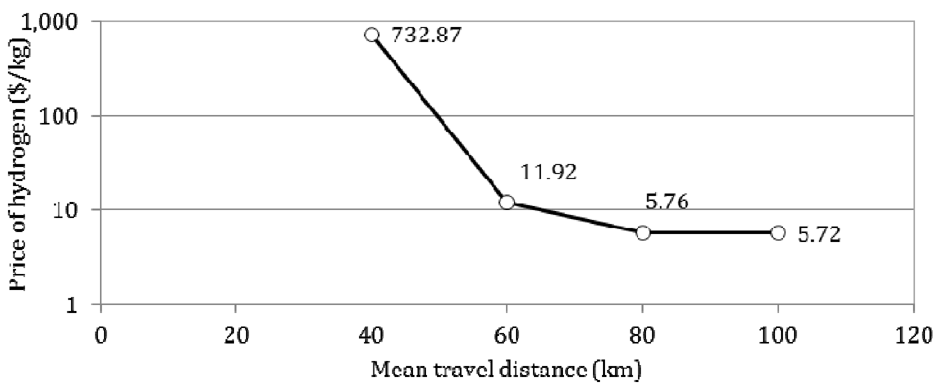


Figure 7-43: Hydrogen price results for minimum total annual cost optimization

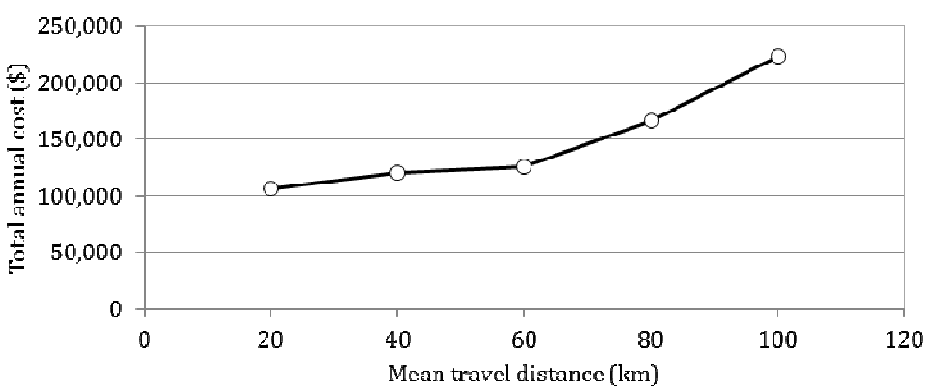


Figure 7-44: Total annual cost results for minimum total annual cost optimization

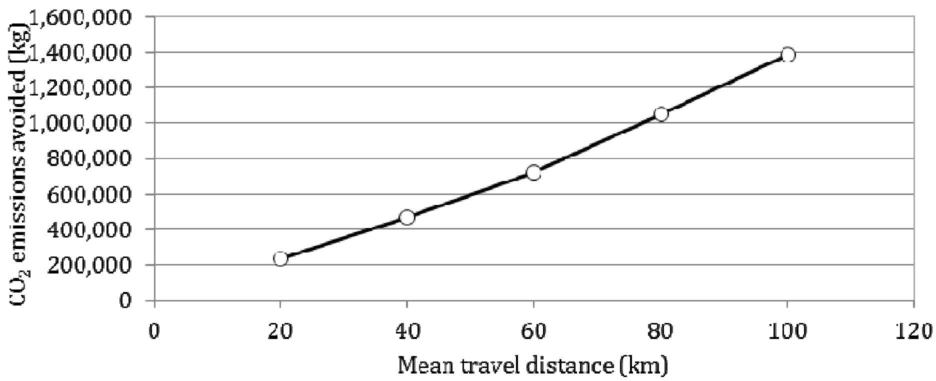


Figure 7-45: CO_2 emissions avoided results for total annual cost optimization

The case results for minimum total annual costs match the case results for minimum electricity price. This indicates a strong link between electricity price and total annual costs.

Table 7-8: Summary of results for total annual cost optimization

Parameter	20km	40km	60km	80km	100km
Cost components (revenue is positive, costs are negative)					
Wind turbines	$0	$0	$0	$0	$0
Grid power sold	$0	$0	$0	$0	$0
Grid power purchased	-$112,200	-$120,440	-$131,920	-$171,410	-$214,300
Storage tanks	$0	-$2,503	-$2,503	-$2,503	-$5,006
Electrolyzers	$0	-$10,297	-$10,297	-$20,593	-$41,186
Emissions revenue	$6336	$12,644	$19,357	$28,355	$37,412
Capacity factors					
Wind turbines	N/A	N/A	N/A	N/A	N/A
Electrolyzers	N/A	29.3%	26.4%	97.0%	98.9%
Calculated results					
Electricity price	$81.3/MWh	$78.5/MWh	$75.5/MWh	$75.3/MWh	$75.1/MWh
Hydrogen price	N/A	$732.87/kg	$11.92/kg	$5.77/kg	$5.72/kg
Total annual cost	$105,860	$120,590	$125,360	$166,150	$223,080
CO_2 emissions avoided	234,680 kg	468,310 kg	716,90 kg	1,050,200kg	1,385,600 kg

7.2.3 *Maximizing CO_2 emissions avoided*

Table 7-9 lists the cases with the highest CO_2 emissions avoided by the mean travel distance of the fleet. Figures 7-46, 7-47, 7-48 and 7-49 contain plots of the electricity price results, hydrogen price results, total annual costs and CO_2 emissions avoided for the best cases.

Table 7-9: On-grid optimized cases for maximum CO_2 emissions avoided

Factor	Meaning	20km	40km	60km	80km	100km
A	Number of 1MW wind turbines	2	2	2	2	2
B	Number of 15 Nm^3/hr electrolyzers	0	1	1	2	4
C	Number of 400.95 kg compressed hydrogen storage tanks	0	1	1	1	2
D	Charging schedule of the fleet	Overnight	Overnight	Overnight	Overnight	Overnight
E	Mean travel distance (km)	20	40	60	80	100
F	Grid connection enabled	Yes	Yes	Yes	Yes	Yes

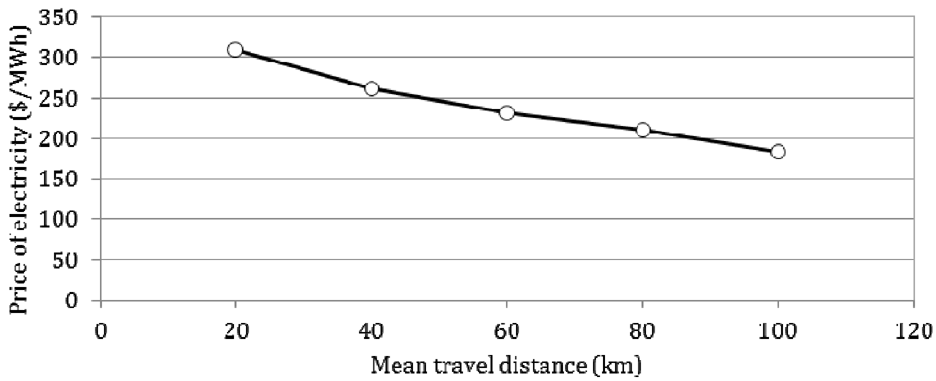


Figure 7-46: Electricity price results for maximum CO_2 emissions avoided optimization

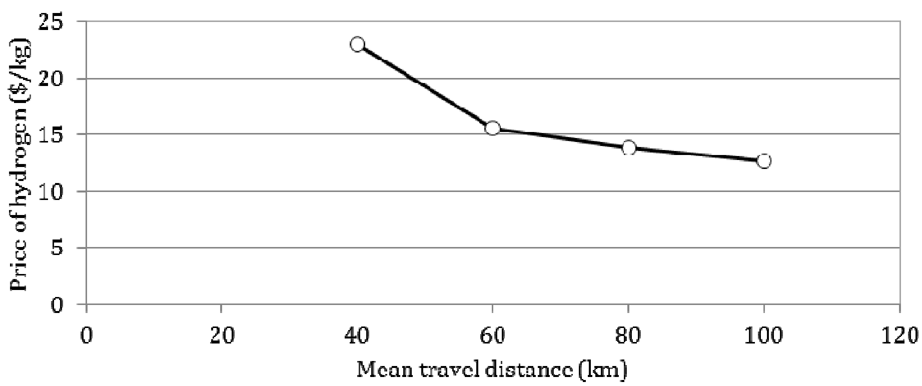


Figure 7-47: Hydrogen price results for maximum CO_2 emissions avoided optimization

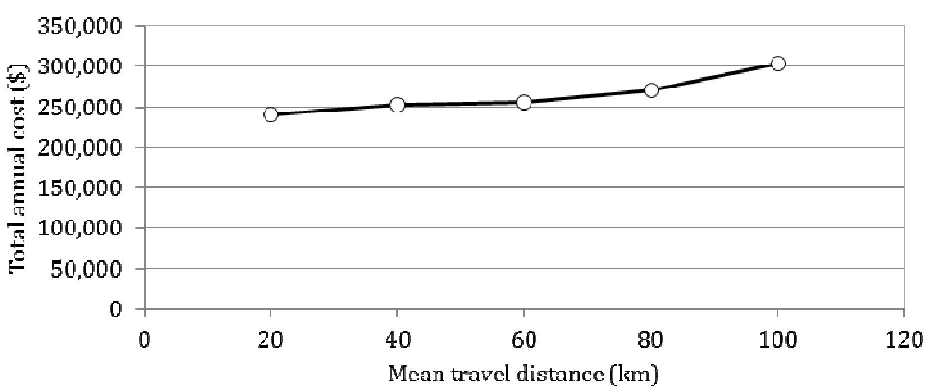


Figure 7-48: Total annual cost results for maximum CO_2 emissions avoided optimization

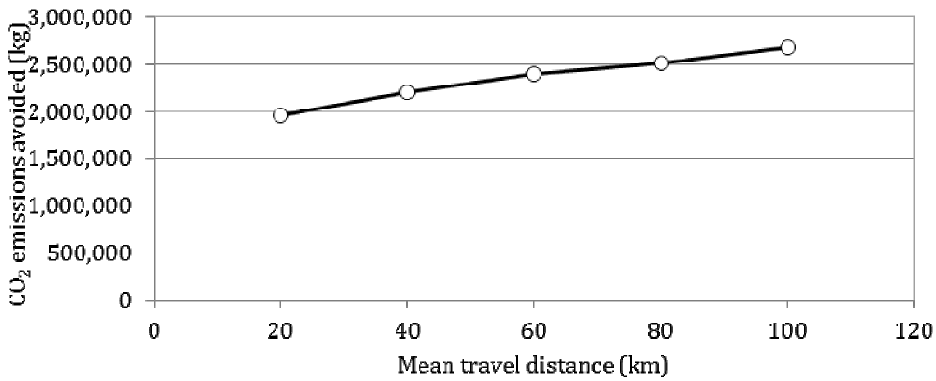


Figure 7-49: CO_2 emissions avoided results for maximum CO_2 emissions avoided optimization

Optimizing the system for the maximum CO_2 emissions avoided heavily favours wind turbines over grid electricity, and each best case has two wind turbines. This is due to the positive emissions avoided by each kWh of wind turbine electricity. As a result, the best case is the case which utilizes wind electricity as much as possible.

Maximizing wind to maximize CO_2 emissions avoided results in a large increase in the prices and total annual costs. The addition of two wind turbines results in an electricity price increase that ranges from $218/MWh at 20km of mean travel distance (a 253.5% increase) to $100/MWh at 100km of mean travel distance (a 133% increase). Similarly, the hydrogen price increase is approximately $7/kg of hydrogen for all mean travel distances except for 40km, where there is a sharp price decrease due to an increase amount of hydrogen produced. The total annual costs also increase due to the addition of two wind turbines from $100,000 to $250,000 for a 20km mean travel distance (150% increase), and from $250,000 to $300,000 for a 100km mean travel distance (20% increase).

Table 7-10: Summary of results for maximum CO_2 emissions avoided optimization

Parameter	20km	40km	60km	80km	100km
Cost components (revenue is positive, costs are negative)					
Wind turbines	-$479,510	-$479,510	-$479,510	-$479,510	-$479,510
Grid power sold	$188,390	$185,450	$181,740	$166,171	$150,900
Grid power purchased	-$39,845	-$42,840	-$47,937	-$64,166	-$86,482
Storage tanks	$0	-$2,503	-$2,503	-$2,503	-$5,006
Electrolyzers	$0	-$10,297	-$10,297	-$20,593	-$41,186
Emissions revenue	$54,368	$60,625	$67,407	$76,398	$85,966
Capacity factors					
Wind turbines	27.8%	27.8%	27.8%	27.8%	27.8%
Electrolyzers	N/A	0.3%	26.8%	97.5%	99.9%
Calculated results					
Electricity price	$239.8/MWh	$219.6/MWh	$197.6/MWh	$165.7/MWh	$143.6/MWh
Hydrogen price	N/A	$698.52/kg	$18.00/kg	$10.22/kg	$9.03/kg
Total annual cost	$276,600	$289,070	$291,090	$324,210	$375,320
CO_2 emissions avoided	2,013,600 kg	2,245,400 kg	2,496,600 kg	2,829,500 kg	3,183,900 kg

7.3 Off-grid scenarios

The results of the off-grid analysis are presented in the sections below.

7.3.1 Minimizing price of electricity

Table 7-11 lists the cases with the lowest electricity price by the mean travel distance of the fleet. Figures 7-50, 7-51, 7-52 and 7-53 contain plots of the electricity price results, hydrogen price results, total annual costs and CO_2 emissions avoided for the best cases.

Table 7-11: Off-grid optimized cases for minimum electricity price

Factor	Meaning	20km	40km	60km	80km	100km
A	Number of 1MW wind turbines	2	2	2	2	2
B	Number of 15 Nm^3/hr electrolyzers	0	1	1	2	4
C	Number of 400.95 kg compressed hydrogen storage tanks	0	1	1	1	2
D	Charging schedule of the fleet	Overnight	Overnight	Overnight	Overnight	Overnight
E	Mean travel distance (km)	20	40	60	80	100
F	Grid connection enabled	No	No	No	No	No

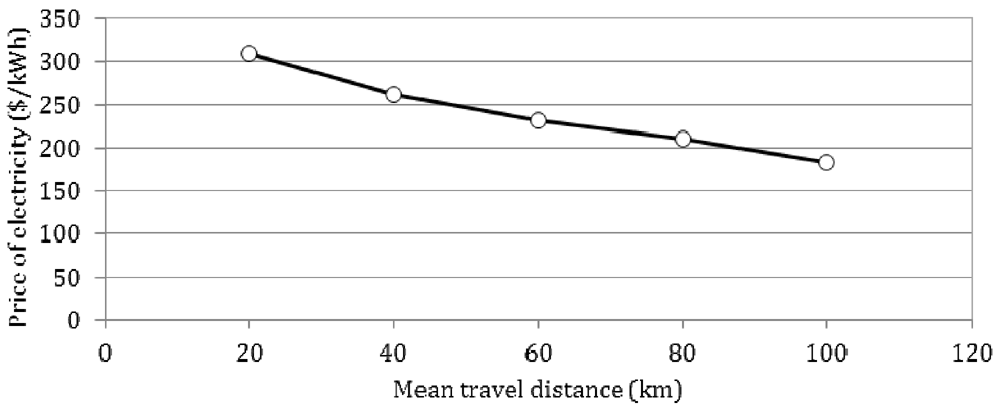


Figure 7-50: Electricity price results for minimum electricity price optimization

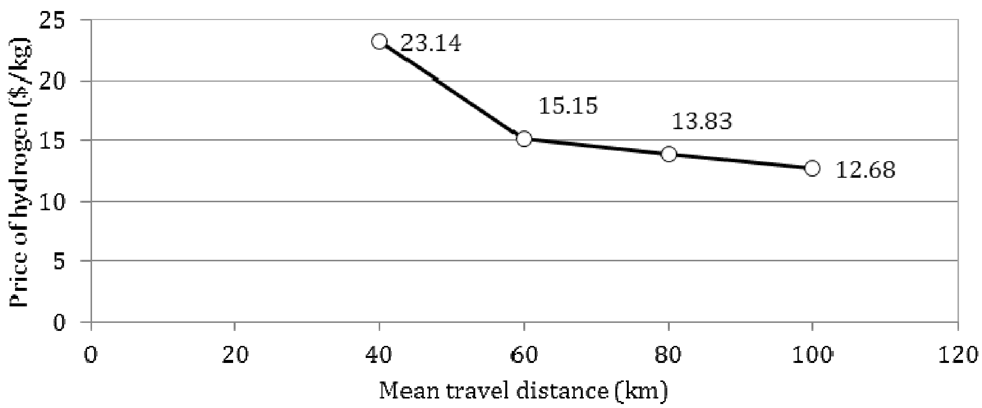


Figure 7-51: Hydrogen price results for minimum electricity price optimization

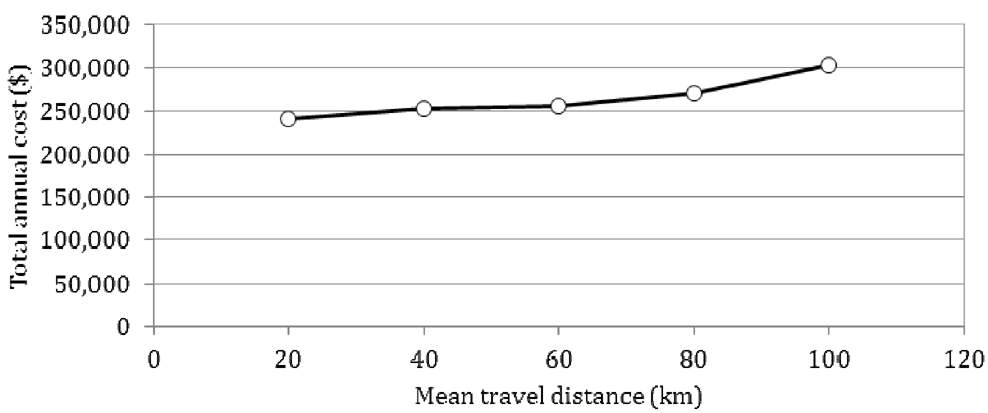


Figure 7-52: Total annual cost results for minimum electricity price optimization

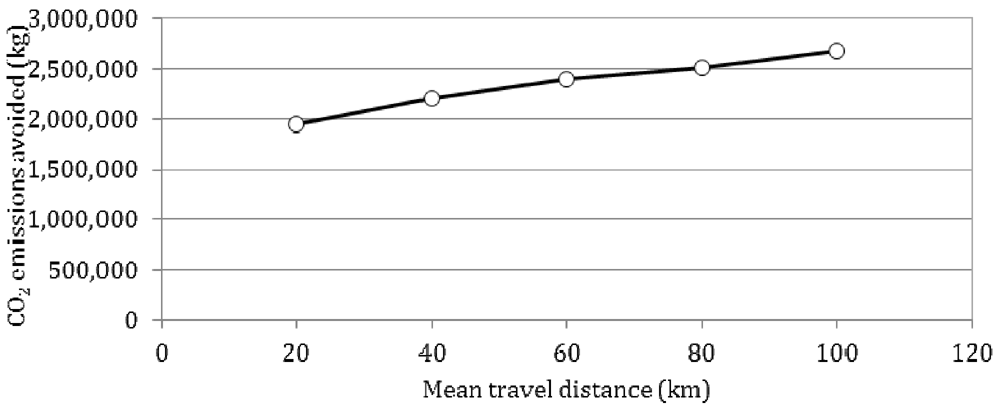


Figure 7-53: CO_2 emissions avoided results for minimum electricity price optimization

As a result of disabling the grid connection for the off-grid scenarios, the optimization favoured two wind turbines in order to meet as much electricity demand from the buildings and fleet as possible. However, since the wind turbine output occasionally decreases to zero, a completely off-grid scenario is unable to guarantee reliable electricity supply throughout the year. In this case, electricity generation in the facility via a stationary fuel cell, battery energy storage, or vehicle to grid could be considered, but would increase the capital cost dramatically. These scenarios are beyond the scope of this specific work.

The prices and total costs in an off-grid scenario are generally higher than a corresponding on-grid scenario, due to the addition of two wind turbines (which are more expensive year-to-year than purchasing grid electricity). For example, the electricity price for a 60km mean travel distance in the off-grid scenario is approximately $240/Mwh, and the corresponding electricity price in the on-grid scenario is $75.5/MWh (a 215% increase). The hydrogen price for a 60km mean travel distance in the off-grid scenario is $15.15/kg, whereas the hydrogen price in the corresponding on-grid scenario is $11.92. The percentage increase in the hydrogen price is much less than the percentage increase in the electricity price, even though the price of electricity is used to calculate the price of hydrogen. This indicates that the costs associated with the electrolyzers and storage tanks far outweigh the costs of electricity used in generating hydrogen, and lessen the impact of an increase.

Table 7-12: Summary of results for minimum electricity price optimization

Parameter	20km	40km	60km	80km	100km
Cost components (revenue is positive, costs are negative)					
Wind turbines	-$479,510	-$479,510	-$479,510	-$479,510	-$479,510
Grid power sold	$0	$0	$0	$0	$0
Grid power purchased	$0	$0	$0	$0	$0
Storage tanks	$0	-$2,503	-$2,503	-$2,503	-$5,006
Electrolyzers	$0	-$10,297	-$10,297	-$20,593	-$41,186
Emissions revenue	$52,766	$59,484	$64,681	$67,658	$72,787
Capacity factors					
Wind turbines	27.8%	27.8%	27.8%	27.8%	27.8%
Electrolyzers	N/A	21.7%	58.8%	57.3%	54.8%
Calculated results					
Electricity price	$506.6/MWh	$417.3/MWh	$360.5/MWh	$318.9/MWh	$266.1/MWh
Hydrogen price	$14.67/kg	$23.14/kg	$15.15/kg	$13.83/kg	$12.68/kg
Total annual cost	$426,740	$432,820	$427,630	$434,940	$453,410
CO_2 emissions avoided	1,954,300 kg	2,203,200 kg	2,395,600 kg	2,505,900 kg	2,677,300 kg

7.3.2 Minimizing total annual costs

Table 7-13 lists the cases with the lowest total annual costs by the mean travel distance of the fleet. Figures 7-54, 7-55, 7-56 and 7-57 contain plots of the electricity price results, hydrogen price results, total annual costs and CO_2 emissions avoided for the best cases.

Table 7-13: Off-grid optimized cases for minimum electricity price

Factor	Meaning	20km	40km	60km	80km	100km
A	Number of 1MW wind turbines	2	2	2	2	2
B	Number of 15 Nm^3/hr electrolyzers	0	1	1	2	4
C	Number of 400.95 kg compressed hydrogen storage tanks	0	1	1	1	2
D	Charging schedule of the fleet	Overnight	Overnight	Overnight	Overnight	Overnight
E	Mean travel distance (km)	20	40	60	80	100
F	Grid connection enabled	No	No	No	No	No

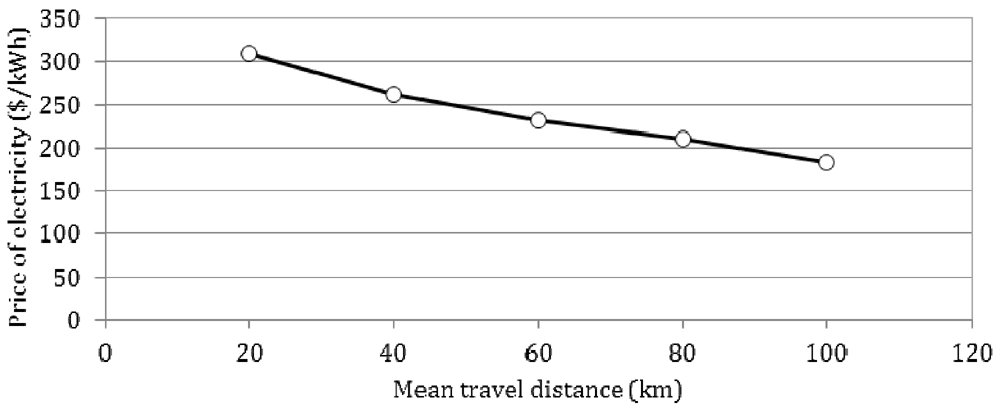


Figure 7-54: Electricity price results for minimum total annual cost optimization

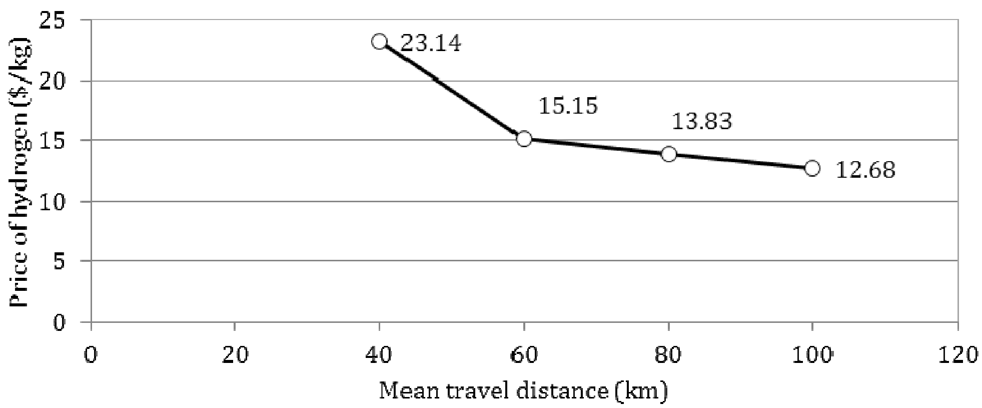


Figure 7-55: Hydrogen price results for minimum total annual cost optimization

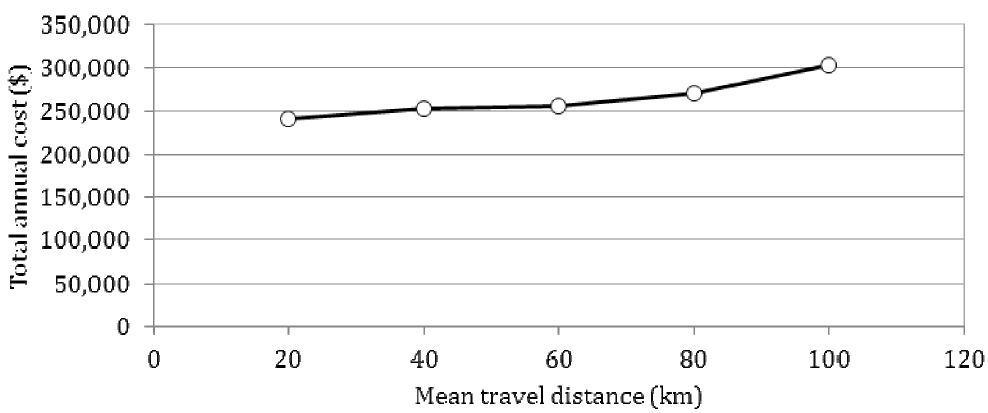


Figure 7-56: Total annual cost results for minimum total annual cost optimization

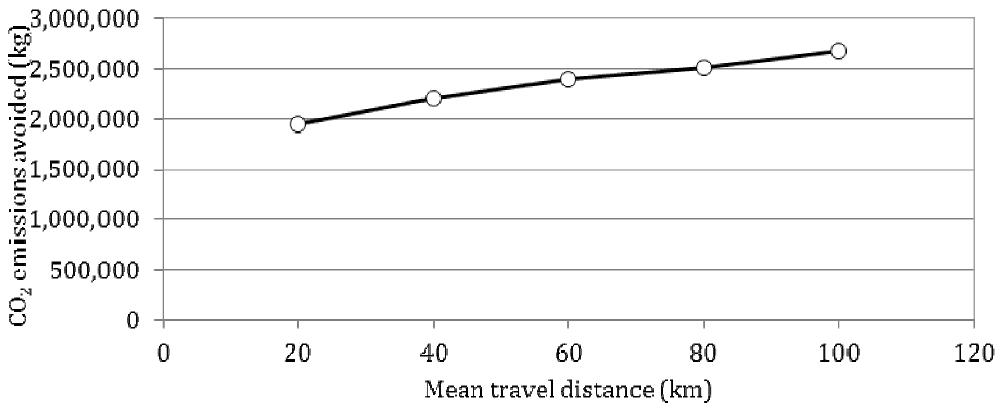


Figure 7-57: CO_2 emissions avoided results for minimum total annual cost optimization

The results for the total annual cost optimization match the results for the electricity price optimization, as in the on-grid scenarios. This is expected due to the strong link between electricity prices and total annual costs in the cost modelling.

Table 7-14: Summary of results for total annual cost optimization

Parameter	20km	40km	60km	80km	100km
Cost components (revenue is positive, costs are negative)					
Wind turbines	-$479,510	-$479,510	-$479,510	-$479,510	-$479,510
Grid power sold	$0	$0	$0	$0	$0
Grid power purchased	$0	$0	$0	$0	$0
Storage tanks	$0	-$2,503	-$2,503	-$2,503	-$5,006
Electrolyzers	$0	-$10,297	-$10,297	-$20,593	-$41,186
Emissions revenue	$52,766	$59,484	$64,681	$67,658	$72,787
Capacity factors					
Wind turbines	27.8%	27.8%	27.8%	27.8%	27.8%
Electrolyzers	N/A	21.7%	58.8%	57.3%	54.8%
Calculated results					
Electricity price	$506.6/MWh	$417.3/MWh	$360.5/MWh	$318.9/MWh	$266.1/MWh
Hydrogen price	$14.67/kg	$23.14/kg	$15.15/kg	$13.83/kg	$12.68/kg
Total annual cost	$426,740	$432,820	$427,630	$434,940	$453,410
CO_2 emissions avoided	1,954,300 kg	2,203,200 kg	2,395,600 kg	2,505,900 kg	2,677,300 kg

7.3.3 Maximizing CO_2 emissions avoided

Table 7-15 lists the cases with the highest CO_2 emissions avoided by the mean travel distance of the fleet. Figures 7-58, 7-59, 7-60 and 7-61 contain plots of the electricity price results, hydrogen price results, total annual costs and CO_2 emissions avoided for the best cases.

Table 7-15: Off-grid optimized cases for minimum electricity price

Factor	Meaning	20km	40km	60km	80km	100km
A	Number of 1MW wind turbines	2	2	2	2	2
B	Number of 15 Nm^3/hr electrolyzers	0	1	1	2	4
C	Number of 400.95 kg compressed hydrogen storage tanks	0	1	1	1	2
D	Charging schedule of the fleet	Overnight	Overnight	Overnight	Overnight	Overnight
E	Mean travel distance (km)	20	40	60	80	100
F	Grid connection enabled	No	No	No	No	No

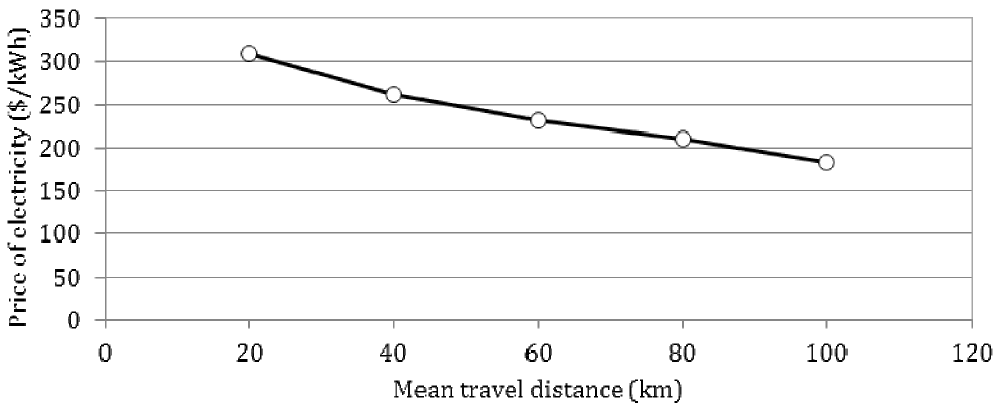


Figure 7-58: Electricity price results for maximum CO_2 emissions avoided optimization

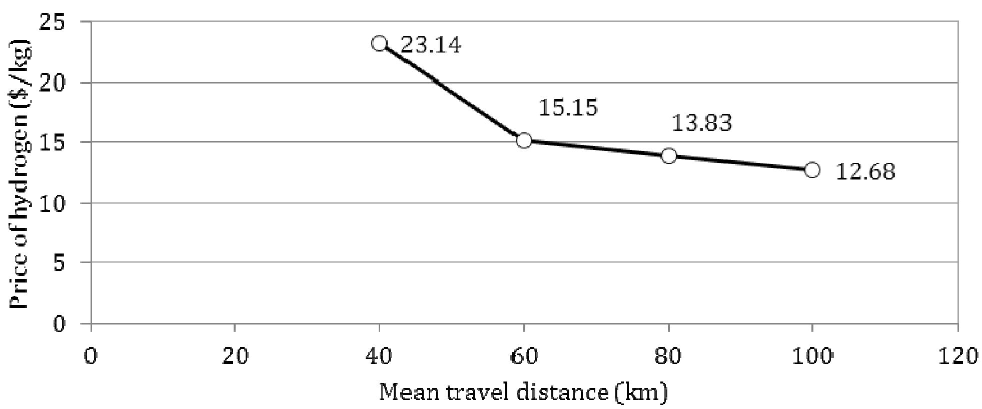


Figure 7-59: Hydrogen price results for maximum CO_2 emissions avoided optimization

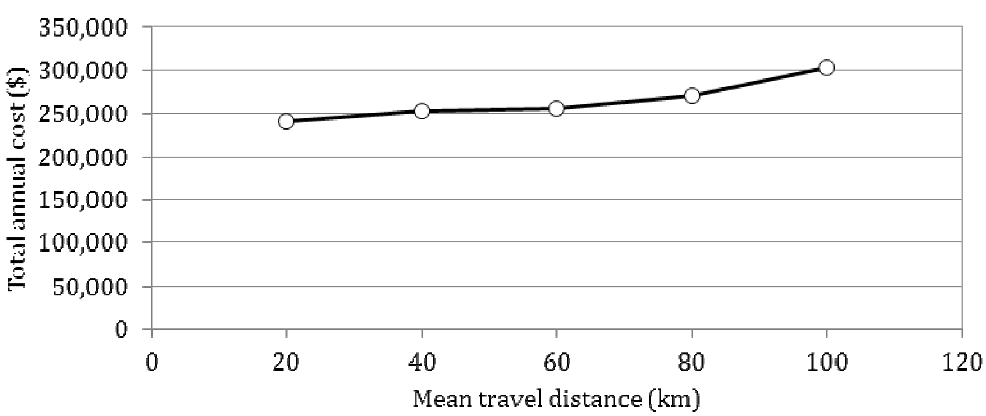


Figure 7-60: Total annual cost results for maximum CO_2 emissions avoided optimization

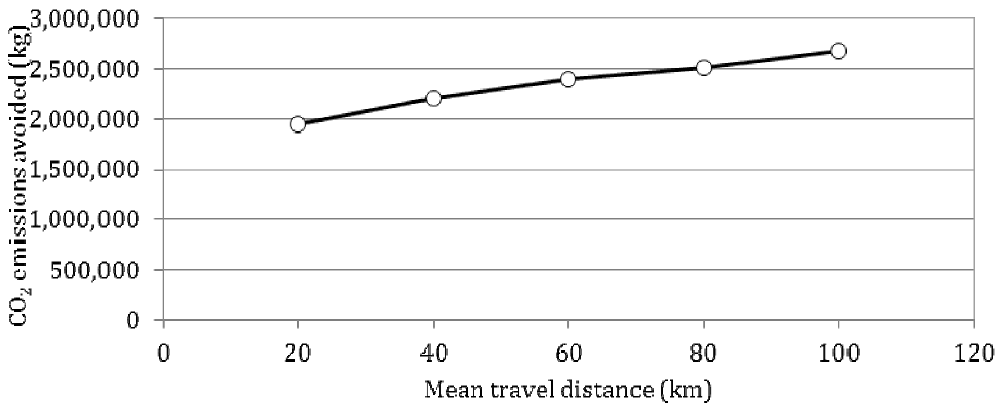


Figure 7-61: CO_2 emissions avoided results for maximum CO_2 emissions avoided optimization

The results for the CO_2 emissions avoided optimization match the results for the electricity price optimization. This is due to the reduced number of factors available for optimization while ensuring a reliable electricity supply. In the on-grid scenarios, the emissions avoided were increased by increasing the number of wind turbines, and thereby increasing the amount of grid electricity displaced. This is not possible in the off-grid scenarios. Due to the lack of grid connection, the optimization pre-emptively selects two wind turbines for all cases to ensure a reliable electricity supply. The number of wind turbines cannot be increased due to the design of experiment.

Table 7-16: Summary of results for maximum CO_2 emissions avoided optimization

Parameter	20km	40km	60km	80km	100km
Cost components (revenue is positive, costs are negative)					
Wind turbines	-$479,510	-$479,510	-$479,510	-$479,510	-$479,510
Grid power sold	$0	$0	$0	$0	$0
Grid power purchased	$0	$0	$0	$0	$0
Storage tanks	$0	-$2,503	-$2,503	-$2,503	-$5,006
Electrolyzers	$0	-$10,297	-$10,297	-$20,593	-$41,186
Emissions revenue	$52,766	$59,484	$64,681	$67,658	$72,787
Capacity factors					
Wind turbines	27.8%	27.8%	27.8%	27.8%	27.8%
Electrolyzers	N/A	21.7%	58.8%	57.3%	54.8%
Calculated results					
Electricity price	$506.6/MWh	$417.3/MWh	$360.5/MWh	$318.9/MWh	$266.1/MWh
Hydrogen price	$14.67/kg	$23.14/kg	$15.15/kg	$13.83/kg	$12.68/kg
Total annual cost	$426,740	$432,820	$427,630	$434,940	$453,410
CO_2 emissions avoided	1,954,300 kg	2,203,200 kg	2,395,600 kg	2,505,900 kg	2,677,300 kg

Chapter 8

Conclusions & Future Work

8.1 Conclusions

A model for a clean energy hub operating in the context of a hydrogen economy was developed and analyzed. In this model, an energy hub provides an interface between energy supply and energy demand components. The purpose of the modelling was to investigate the interactions between a single energy hub and novel components such as a plug-in fuel cell vehicle fleet. The energy supply consists of wind turbines, as well as a connection to the electricity grid. The energy demand consists of a commercial building and a fleet of light duty plug-in fuel cell vehicles. The energy demand model for a commercial building was created using the building energy simulation software eQuest, and was created using an approach found in literature. The PFCV is a consumer of both electricity and hydrogen. An individual vehicle model was built and this model was replicated for a number of vehicles in the fleet. The fleet was able to charge at-once overnight or in a split configuration (half overnight, and half in the afternoon). The energy hub also interfaces with hydrogen demand components, namely the vehicle fleet. The energy hub is not connected to a hydrogen supply component, but it allows for conversion of electricity to hydrogen through electrolyzers on site. The electrolyzers are able to consume electricity to generate hydrogen, which in turn is stored in storage tanks on site.

An economic analysis was performed to obtain the price of electricity and hydrogen produced by the energy hub, as well as its total annual costs and the CO_2 emissions avoided. Analysis of a number of different senarios were performed for the following criteria: minimizing the price of electricity, minimizing the total annual costs, and maximizing the CO_2 emissions avoided. Both on-grid and off-grid scenarios were considered. On-grid scenarios represent an energy hub close to transmission lines or urban areas, whereas off-grid scenarios represent energy hubs in remote locations.

It was observed that the connection of the energy hub to the broader electricity grid was the most significant factor affecting the results collected. Grid electricity was found to be generally cheaper than electricity produced by wind turbines, and scenarios for minimizing costs heavily favoured grid electricity. However, wind turbines were found to avoid CO_2 emissions over the use of grid electricity, and scenarios for maximizing emissions avoided heavily favoured wind turbine electricity. In one case, removing the grid connection resulted in the price of electricity increasing from $82/MWh to $300/MWh.

The mean travel distance of the fleet was another important factor affecting the cost modelling of the energy hub. The hub's performance was simulated over a range of mean travel distances (20km to 100km), and the results varied greatly within the range. This is because the mean travel distance directly affects the quantities of electricity and hydrogen consumed by the fleet, a large consumer of energy within the hub. Other factors, such as the output of the wind turbines, or the consumption of the commercial building, are largely fixed by the size of the infrastructure and generation capacity of the available turbines. A key sensitivity was discovered within this range; the results were 'better' (lower costs and higher emissions avoided) when the mean travel distance exceeded the electric travel range of the fleet. This effect was more noticeable in the on-grid analysis. This sensitivity is due to the underutilization of the hydrogen systems within the hub at lower mean travel distances; the greater the mean travel distance, the greater the utilization of the electrolyzers and storage tanks. At lower mean travel distances, the utilization of the electrolyzers ranged from 25% to 30%, whereas at higher mean travel distances it ranged from 97% to 99%. At higher utilization factors the price of hydrogen is reduced, since the cost recovery is spread amongst a larger quantity of hydrogen that is used over the greater number of kilometres travels with the use of hydrogen.

8.2 Future Work

The current implementation of travel modelling is a key limitation that prevents more detailed study of advanced charging strategies. In the current implementation, travel is modelled as a discrete event rather than a continuous event; it is not possible to implement trip based behaviour in the current model. Specifically the vehicle is only charged at key descrite times that it interactes with the energy hub. A key recommendation is to improve the model to implement trip-based behaviour based on drive cycles such as the UDDS and HWFET. With this energy use could be allocated over the trip based on the type of energy that would be available at the hub.

More sophisticated charging options could be considered. In the current implementation, the fleet may only charge with an overnight or split charging period strategy with no consideration towards the hourly electricity price. A more sophisticated charging strategy could consider the change in peak periods between seasons and adjust the charging periods accordingly. Rapid charging could also be a consideration, but the impact on vehicle battery durability must be within this evaluation. Ultimately a charging and hydrogen generation production schedule (and thus interaction with the grid) should consider sensitivity to electricity price schedule, and the potential possibility that components of the fleet may be able to charge during multiple periods in a day.

A detailed analysis could be performed to determine the sensitivity of the results to the differences in price between off-peak, mid-peak and on-peak price levels for electricity. This would possibly have interactions with the charging schedule of the fleet. Overnight fleet charging takes advantage of lower off-peak electricity prices and is always expected to be cheaper. Adjusting electricity price levels may also affect the economic viability of wind turbines. At a certain point the price of electricity produced by both wind turbines and the grid will be equal, and this may lead to the best cases which contain wind turbines.

A further analysis could be performed to determine the level of subsidy or the level of emissions credits necessary to allow wind turbines to become an economically viable option. Wind turbines represent a significant capital investment, and the price of the electricity produced by the turbines will not match the price of electricity from the grid (even after environmental rebates are applied). Therefore, if the objective of the analysis is to determine scenarios in which the price of electricity is minimized then any number of wind turbines will always move the network farther from the best scenario. Since hydrogen is produced solely through electricity, the price of hydrogen will be higher in scenarios which contain wind turbines.

Vehicle-to-grid (V2G) options could also be considered for the energy hub. The batteries in the fleet vehicles could be used for load levelling of the building energy demand, reducing the overall cost of electricity produced by the wind turbines. Further to this, the use and 'repurposing' of used batteries as energy storage within the energy hub could be evaluated.

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Appendix A
MATLAB Energy Model

```
Hub code
%% Run initialization code
% Initialize RANDN to a different state each time.
randn('state', sum(100*clock))

%% SIMULATION PARAMETERS

% Debug mode flag - does not clear simhub_electricitysystem and
simhub_hydrogensystem after a
% run
init.sim.debug = false;

% Set output suppression to false
% init.sim.suppression is what a custom tool would use to suppress
% interaction with the user, e.g. dialog and input boxes
init.sim.suppression = true;

% Set custom supply module combine flag
% If set to false, then the core will revert to executing each file on its
% own, rather than combining using simhub_supply_cominemodules
% Default is true for much faster execution. This flag is here so that
% execution times can be tested with more custom supply modules in the
% future, to determine the effectiveness of the precombine method.
init.sim.supply_combinemodules = true;

% Define simulation month and days
init.sim.month_hours = 24 * cumsum([0 31 28 31 30 31 30 31 31 30 31 30 31]) +
1;
init.sim.month = 1;
init.sim.days = 365;

% load day types. days 1 - 5 are weekdays,  & 7 are weekends and 8 are
% holidays. cars will have different weekday/weekend behaviour
load day_types % the variable being loaded is called dummy
init.sim.day_type = dummy;
clear dummy

% Set workflow mode
% mode = 1: initialization phase
% mode = 2: simulation phase
% mode = 3: termination phase
mode = 1;

%% GRID PARAMETERS

% Run grid initialization file
grid_initialize

%% SUPPLY PARAMETERS
```

```
% POWER AVAILABLE AT CHARGING STATION
% Based on 110 V, 15 A
init.supply.charging_station_power = 110 * 15 / 1000; % [kW]

% Run supply initialization file
wind_initialize

%% STORAGE PARAMETERS

% Run storage initialization file
storage_initialize

%% FLEET PARAMETERS

% Run fleet initialization file
fleet_initialize

%% BUILDING PARAMETERS

% Run building initialization file
building_initialize

%% Run footer code

% Inform user the initialization has fixed
fprintf ('Hub initialization finished\n');

%% Pre simulation code
% This is the best place for the following code. The define/save case
% functionality means that the waitbar can't be in the initialization file.

% Show waitbar
if ~init.sim.suppression
    my_waitbar = waitbar(0,'Running simulation. Please wait...');
end

% Declare simulation start and end times
init.sim.start_time = init.sim.month_hours(init.sim.month); % must always be
>= 1
init.sim.end_time = init.sim.start_time + 24 * init.sim.days - 1;

% Declare the and current_hour variable
current_hour = mod(init.sim.start_time,24);
% check to make sure current_hour is valid
if current_hour == 0
    current_hour = 24;
end
current_day = 0;

%% GRID DECLARATION

% Declare the grid
simhub_electricitysystem = ElectricitySystem();

%% FLEET DECLARAION
```

```
% Run the demand declaration file
fleet_declare

%% STORAGE DECLARATION

% Run storage initialization file
simhub_hydrogensystem = HydrogenSystem( ...
    init.storage.capacity, ...
    init.storage.mass, ...
    init.storage.h2_from_power_efficiency, ...
    init.storage.power_from_h2_efficiency, ...
    init.storage.h2_from_power_ratio, ...
    init.storage.h2_generation_max, ...
    init.storage.h2_consumption_max, ...
    init.storage.num_electrolyzers ...
    );

%% Data Logger Declaration

% Run the data logger declaration file
logging_declare

%% Run footer code
% Inform user the initialization has fixed
fprintf ('Hub declaration finished\n');

% Set workflow mode
% mode = 1: initialization phase
% mode = 2: calculation & simulation phase
% mode = 3: termination phase
mode = 2;

% Start time loop
for sim_hour = init.sim.start_time:init.sim.end_time % for each hour

    % Run hour updating calculations
    hub_updatehour

    %% CALCULATE
    % Every module will be making interaction.I.request at this stage.

    % Run wind calculations
    wind_calculate

    % Run building calculations
    building_calculate

    % Run fleet calculations
    fleet_calculate

    %% ALLOCATE
    % Time to take the requests and assign to interaction.I.allowance

    % Take whatever wind power we get
    wind.interaction.power.allowance = wind.interaction.power.request;

    % Supply the building with whatever it needs
```

```
    building.interaction.power.allowance =
building.interaction.power.request;

    % Supply the fleet with whatever it needs
    fleet.interaction.power.allowance = fleet.interaction.power.request;
    fleet.interaction.hydrogen.allowance =
fleet.interaction.hydrogen.request;

    %% SIMULATE

    % Run wind simulation
    wind_simulate

    % Run building simulation
    building_simulate

    % Run fleet simulation
    fleet_simulate

    %% BALANCE

    hub_balance

    % Call the data logger to update records
    logging_update
end % sim_hour

% Inform user the simulation has fixed
fprintf ('Hub simulation finished\n');

% this file can only be used in loop with a counter variable called counter
% 1 and running from init.sim.start_time to init.sim.end_time

% update current_hour counter
current_hour = mod(sim_hour,24);
if current_hour == 0
    current_hour = 24;
end

if current_hour == 1
    current_day = current_day + 1;
end

% update waitbar
if ~init.sim.suppression
    waitbar((sim_hour - init.sim.start_time) / (init.sim.end_time -
init.sim.start_time),my_waitbar);
end

%% Run termination code
% Set workflow mode
% mode = 1: initialization phase
% mode = 2: simulation phase
% mode = 3: termination phase
mode = 3;

% Close waitbar and clear dummy variables
```

```
if ~init.sim.suppression
    close(my_waitbar)
end

% Clear minor core variables
clear sim_hour ...
    current_hour ...
    my_waitbar ...
    excess_power ...
    h2_system_power ...
    grid_power_building ...
    grid_power_fleet ...
    electricitysystem_power_building ...
    electricitysystem_power_fleet ...
    mode ...
    current_day

if ~ init.sim.debug
    clear simhub_electricitysystem ...
        simhub_hydrogensystem
end

% Clear minor fleet variables
clear travel_flag ...
    charge_power_allocated ...
    charge_power_delivered ...
    charge_power_consumed ...
    travel_distance_desired ...
    travel_distance_actual ...
    ess_distance_max ...
    hss_distance_max ...
    total_distance_max ...
    hydrogen_needed

clear ans

% Inform user the termination has fixed
fprintf ('Hub termination finished\n');

classdef ElectricitySystem < handle
    % ELECTRICITYSYSTEM Class object for simulation of an electricity
    % system
    %   G  = ELECTRICITYSYSTEM() returns a ElectricitySystem class object.

    properties %(SetAccess = private)
        hourly_holding         % hourly holding of power [kWh]
    end

    methods
        function g = ElectricitySystem()
            % initialize the grid in the constructor
            g.hourly_holding = 0;
        end % g

        function power_available = poweravailable(g)
            % return all power available
```

```
            power_available = g.hourly_holding;
        end % poweravailable

        function supply(g,power_supplied)
            % adds power to the grid for one hour

            g.hourly_holding = g.hourly_holding + power_supplied;
        end % supply

        function power_delivered = demand(g,power_demanded)
            % when you receive a power request

            if power_demanded <= g.hourly_holding
                power_delivered = power_demanded;
                g.hourly_holding = g.hourly_holding - power_demanded;
            else
                power_delivered = g.hourly_holding;
                g.hourly_holding = 0;
            end
        end % demand
    end % methods
end % classdef

%% Output key simulation parameters

% print the report if init.sim.supression is false

if ~ init.sim.suppression
    fprintf('-------------------\n');
    fprintf('simHub QUICK REPORT\n');
    fprintf('-------------------\n\n');

    % Print simulation parameters
    if init.sim.debug == true
        a = 'true';
    else
        a = 'false';
    end
    fprintf('Simulation parameters: <a href="matlab:
edit(''simhub_core_initialize.m'')">[edit]</a>\n\n');
    fprintf('Start time:    %d\n', init.sim.start_time);
    fprintf('Stop time:     %d\n', init.sim.end_time);
    fprintf('Debug mode:    %s\n', a);
    fprintf('\n');
    clear a

    % Print supply modules used
    fprintf('Supply modules (%d):\n\n',1);
    fprintf('* Only wind is being used\n\n');

    % Print storage parameters
    fprintf('Storage parameters: <a href="matlab:
edit(''simhub_storage_initialize.m'')">[edit]</a>\n\n');

    fprintf('Capacity [kg]:                %1.2f\n', init.storage.capacity);
    fprintf('Max. power input [kW]:        %1.2f\n',
simhub_hydrogensystem.power_consumption_max);
```

```
    fprintf('Max. power output [kW]:        %1.2f\n',
simhub_hydrogensystem.power_generation_max);
    fprintf('Round trip efficiency [%%]:    %1.2f\n',
100*simhub_hydrogensystem.h2_from_power_efficiency *
simhub_hydrogensystem.power_from_h2_efficiency);
    fprintf('\n');

    % Print demand parameters
    fprintf('Fleet parameters: <a href="matlab:
edit(''simhub_fleetHE_initialize.m'')">[edit]</a>\n\n');
    fprintf('Fleet count:    %d\n', init.fleet.population);
    fprintf('\n');

    fprintf('-------------------\n\n');
end

Building code
% ELECTRICITY DEMAND PROFILE [kW]

% This data is from eQuest for a MOB in Toronto, 2008.
load building_data_power

% check for validity of init.building.electricity_demand_profile
building.data.power(building.data.power < 0) = 0;

% Number of buildings
init.building.count = 2;

% going to output building power request to hub
building.interaction.power.request = -1 * ...
    building.data.power(sim_hour) * ...
    init.building.count;

building.interaction.hydrogen.request = 0;

% Note: this is an electricity demand module.
% Power will always be negative
% Hydrogen will always be zero

% Make sure the allowance is less than the request
building.interaction.power.allowance = min(...
    building.interaction.power.allowance, ...
    building.interaction.power.request);

% BEHAVIOUR: depends on init.grid.enabled. No fuel cells

% Check for exceeding electricity system limitations and scale allowance &
% distribution accordingly
if simhub_electricitysystem.poweravailable  < (-1 *
building.interaction.power.allowance) && init.grid.purchase_enabled == 0 %
exceeding limitations and no grid!
    building.interaction.power.allowance = -1 *
simhub_electricitysystem.poweravailable;
end

% Decide to meet the allowance, since this is a simple module.
building.interaction.power.actual = building.interaction.power.allowance;
```

```
% Supply building with power
electricitysystem_power_building = simhub_electricitysystem.demand(-1 *
building.interaction.power.actual);

% add deficit electricity to grid_power. if grid is disabled then this will
% be zero anyway
grid_power_building = (-1 * building.interaction.power.actual) -
electricitysystem_power_building;

% Hydrogen is always zero
building.interaction.hydrogen.actual = 0; %kg

Electrolyzer and Hydrogen storage code
%% Define parameters

% HYDROGEN STORAGE CAPACITY
% Single tank according to Maniyali
init.storage.capacity = 400.95; % [kg]

% INITIAL HYDROGEN STORAGE
init.storage.mass = init.storage.capacity; % [kg]
init.storage.target_mass = 60; % [kg]

% HYDROGEN FROM ELECTRICITY ENERGY EFFICIENCY
% Based on Hydrogenics product spec sheet
init.storage.h2_from_power_efficiency = 0.799425; % [0-1]

% ELECTRICITY FROM HYDROGEN ENERGY EFFICIENCY
% Based on a hypothetical fuel cell system
init.storage.power_from_h2_efficiency = 0.5; % [0-1]

% IDEAL INTERCONVERSION ENERGY REQUIRED
% At 100% efficiency, what is the energy required for interconversion
% of hydrogen and power?
% Based on HHV of hydrogen
init.storage.h2_from_power_ratio = 1/39.4; % [kg/kWh]

% MAXIMUM HYDROGEN GENERATION RATE
% This value is from the HyStat A series electrolyzer
% It corresponds to 15 Nm3/hr production of Hydrogen
% Relates to the size of the electrolysis units.
init.storage.h2_generation_max = 5.3567/4; % [kg/h]

% MAXIMUM HYDROGEN CONSUMPTION RATE
% This is a dummy value right now. Will fill in later from Hydrogenics
% values.
% Relates to the size of the conversion equipment (likely fuel cells)
init.storage.h2_consumption_max = 0; % [kg/h]

% NUMBER OF ELECTROLYZERS
% Relates to the number of the electrolyzers
init.storage.num_electrolyzers = 2; % [positive integer]

classdef HydrogenSystem < handle
    % HydrogenSystem Class object for simulation of an electricity grid
    %   S  = HydrogenSystem(...
```

```
    %             capacity, ...
    %             mass, ...
    %             h2_from_power_efficiency, ...
    %             power_from_h2_efficiency, ...
    %             h2_from_power_ratio, ...
    %             h2_generation_max, ...
    %             h2_consumption_max, ...
    %             num_electrolyzers ...
    %             )
    % returns a HydrogenSystem class object.

    properties %(SetAccess = private)
        capacity % [kg]
        mass % [kg]

        h2_from_power_efficiency % [0-1]
        power_from_h2_efficiency % [0-1]

        h2_from_power_ratio % [kg/kWh]
        power_from_h2_ratio % [kWh/kg]


        h2_generation_max % [kg/h]
        h2_consumption_max % [kg/h]

        power_consumption_max % [kW]
        power_generation_max % [kW]

        num_electrolyzers % [positive integer]
    end

    methods
        function s = HydrogenSystem(...
                capacity, ...
                mass, ...
                h2_from_power_efficiency, ...
                power_from_h2_efficiency, ...
                h2_from_power_ratio, ...
                h2_generation_max, ...
                h2_consumption_max, ...
                num_electrolyzers ...
                )
            % initialize the storage in the constructor

            % check to make sure mass <= capacity
            if mass > capacity
                error('Error: mass assigned to HydrogenSystem class object 
greater than capacity assigned');
            end

            % assign properties passed in arguments
            s.capacity = capacity;
            s.mass = mass;
            s.h2_from_power_efficiency = h2_from_power_efficiency;
            s.power_from_h2_efficiency = power_from_h2_efficiency;
            s.h2_from_power_ratio = h2_from_power_ratio;
            s.h2_generation_max = h2_generation_max;
```

```
            s.h2_consumption_max = h2_consumption_max;
            s.num_electrolyzers = num_electrolyzers;

            % calculate other derivative properties
            s.power_from_h2_ratio = 1 / h2_from_power_ratio;
            s.power_consumption_max = s.num_electrolyzers *
s.h2_generation_max ...
                * s.power_from_h2_ratio / h2_from_power_efficiency;
            s.power_generation_max = h2_consumption_max ...
                * s.power_from_h2_ratio * power_from_h2_efficiency;
        end % s

        function power_available = poweravailable(s)
            % return all power available

            power_available = min(s.mass,s.h2_consumption_max) *
s.power_from_h2_ratio * s.power_from_h2_efficiency;
        end % poweravailable

        function power_accepted = deposit(s, power_supplied)
            % when you receive a power supply

            % calculate maximum power the storage can accept right now
            max_power_dummy = ...
                min((s.capacity - s.mass), ...
                s.num_electrolyzers * s.h2_generation_max) * ...
                s.power_from_h2_ratio / s.h2_from_power_efficiency;

            % check to see if power is within storage limitations
            if power_supplied > max_power_dummy
                power_supplied = max_power_dummy;
            end
            clear max_power_dummy

            new_mass_dummy = power_supplied * s.h2_from_power_ratio ...
                * s.h2_from_power_efficiency;

            % check to see whether the power is too low (40% of generation
            % capacity)
            if new_mass_dummy < 0.4 * s.h2_generation_max
                new_mass_dummy = 0;
                power_supplied = 0; % reject the power
            end

            % now must translate power_supplied into h2
            s.mass = s.mass + new_mass_dummy;
            clear new_mass_dummy

            power_accepted = power_supplied;
        end % deposit

        function power_delivered = withdraw(s, power_requested)
            % when you receive a power request

            % check to see if power is within storage limitations
            max_power_dummy = s.poweravailable;
            if power_requested > max_power_dummy
```

```
                power_requested = max_power_dummy;
            end
            clear max_power_dummy

            % now must translate power_requested into h2
            s.mass = s.mass - power_requested * s.h2_from_power_ratio ...
                / s.power_from_h2_efficiency;

            power_delivered = power_requested;
        end % withdraw
    end % methods
end % classdef
```

```
Fleet code
%% Define fleet parameters

% NUMBER OF VEHICLES IN FLEET
% Demand can consist of cars, either PHEVs or H2FCVs, or both
% For now I will consider an EV fleet
init.fleet.population = 200;   % Number of vehicles in fleet

% CHARGING TIMES DURING THE DAY
% Currently from 10 PM to 6 AM
% 1 indicates charging, 0 indicates no charging
init.fleet.charging_period = [1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1
1]; % [hour of day]

% CHARGING STRATEGY
% 1 indicates equal charge power to every vehicle - uncontrolled
% 2 indicates minimum charge power to every vehicle - controlled
init.fleet.charging_strategy = 2;

% DAILY TRAVEL DISTANCE PER VEHICLE
% Right now it's a constant, later will work into a distribution based
% model
init.fleet.daily_travel_distance = 75; % Daily travel distance [km]
% Need to update this for city/hwy driving

%% Define vehicle parameters

% Model future plans:
% Incorporate degradation
% Incorporate variability in performance and capacity
% Incorporate time based consumption
% Integrate multiple fleets ... i.e. cities

% ENERGY STORAGE SYSTEM: ENERGY CAPACITY
% Battery Capacity. This value comes from reported Volt figures of the
% total usable battery capacity
init.fleet.ess_capacity = 10; % [kWh]

% ENERGY STORAGE SYSTEM: INITIAL STATE OF CHARGE
% All vehicles have a half charged ESS initially
init.fleet.ess_soc_initial = 1; % (0-1)

% ENERGY STORAGE SYSTEM: KILOMETERS PER ENERGY CONSUMED
% This value comes from reported Volt figures
```

```
init.fleet.ess_performance = 6.44; % [km/kWh]

% HYDROGEN STORAGE SYSTEM: HYDROGEN CAPACITY
% Currently a dummy value
init.fleet.hss_capacity = 4; % [kg]

% HYDROGEN STORAGE SYSTEM: INITIAL HYDROGEN STORED
% All vehicles have a fully charged HSS initially
init.fleet.hss_mass_initial = init.fleet.hss_capacity; % [kg]

% HYDROGEN STORAGE SYSTEM: KILOMETERS PER HYDROGEN CONSUMED
% Currently a dummy value, this section will be beefed up with PSAT
% work
init.fleet.hss_performance = 70; % [km/kg]

%% DEMAND DECLARAION

% Declare the vehicles in the fleet
init.fleet.vehicle = ones(init.fleet.population,6);

% ESS declarations
init.fleet.vehicle(:,1) = init.fleet.ess_capacity;
init.fleet.vehicle(:,2) = init.fleet.ess_soc_initial;
init.fleet.vehicle(:,3) = init.fleet.ess_performance;

% HSS declarations
init.fleet.vehicle(:,4) = init.fleet.hss_capacity;
init.fleet.vehicle(:,5) = init.fleet.hss_mass_initial;
init.fleet.vehicle(:,6) = init.fleet.hss_performance;

%% Module code

% Note: this is an electricity/hydrogen demand module.
% Power will always be negative
% Hydrogen will always be negative

travel_distance_actual = zeros(init.fleet.population,1);
charge_power_allocated = zeros(init.fleet.population,1);
charge_power_consumed = zeros(init.fleet.population,1);
hydrogen_needed = zeros(init.fleet.population,1);

fleet.interaction.power.request = 0;
fleet.interaction.hydrogen.request = 0;

% make sure it's a weekday
if init.sim.day_type(sim_hour) < 6
    % Run travel flag calculation
    travel_flag = fleet_checktravel(current_hour,init.fleet.charging_period);

    if travel_flag == 1 % time to travel

        %% TRAVEL

        % simple random travel demand generation
        travel_distance_desired = ones(init.fleet.population,1) ...
            * init.fleet.daily_travel_distance ...
```

```
            + randn(init.fleet.population,1) * 15; % standard deviation of 15
km

        % fix negative travel values
        travel_distance_desired(travel_distance_desired < 0) = 0;

        % run travel calculations
        fleet_travel

    elseif init.fleet.charging_period(current_hour) == 1 % time to charge

        %% CHARGE/REFILL

        % determine power delivered to each vehicle
        switch init.fleet.charging_strategy

            case 1 % distribute grid power to all vehicles equally

                % run charge division calculations
                fleet_allocate_equal

            case 2 % charge all vehicles by the end of the charging period

                % run charge division calculations
                fleet_allocate_timed

        end

        % Calculate power request
        fleet.interaction.power.request = -1 * sum(charge_power_allocated);

        % Calculate hydrogen request
        % Calculate total hydrogen mass needed by fleet for a fillup
        hydrogen_needed = max(0,(init.fleet.vehicle(:,4) -
init.fleet.vehicle(:,5)));
        fleet.interaction.hydrogen.request = -1 * sum(hydrogen_needed);
    end
end

function travel_flag = fleet_checktravel(current_hour,charging_period)
% travel flag calculation

% returns 1 for first hour of travel, and -1 for first hour of charging

if current_hour > 1
    travel_flag = ...
        charging_period(current_hour - 1) ...
        - charging_period(current_hour);
else
    travel_flag = ...
        charging_period(24) ...
        - charging_period(current_hour);
end % travel flag calculation has been tested to work correctly
end

%% Calculate new ESS and HSS storage and travel_distance_actual
```

```
% check for validity of travel_distance_desired
if min(travel_distance_desired) <0
    error ('Error: travel_distance_desired has negative values');
end

% Calculate how much distance each vehicle can cover in charge depleting
% mode
ess_distance_max = init.fleet.vehicle(:,2) ...
    .* init.fleet.vehicle(:,1) .* init.fleet.vehicle(:,3);

% Calculate how much distance each vehicle can cover in charge sustaining
% mode
hss_distance_max = init.fleet.vehicle(:,5) .* init.fleet.vehicle(:,6);

% Calculate how much distance each vehicle can cover in total
total_distance_max = ess_distance_max + hss_distance_max;

% Assume all distance travelled, prior to calculations
travel_distance_actual = travel_distance_desired;

% Where travel_distance_desired is less than ess_distance_max, deduct from
% ESS
index_dummy = travel_distance_desired < ess_distance_max;
init.fleet.vehicle(index_dummy,2) = init.fleet.vehicle(index_dummy,2) ...
    .* (ess_distance_max(index_dummy) - travel_distance_desired(index_dummy))
...
    ./ ess_distance_max(index_dummy); % deduct from ESS

% Where travel_distance_desired is more than ess_distance_max, but less
% than total_distance_max, deplete the ESS and deduct from HSS
index_dummy = logical((travel_distance_desired >= ess_distance_max) ...
    .* (travel_distance_desired < total_distance_max));
init.fleet.vehicle(index_dummy,2) = 0; % deplete the ESS
init.fleet.vehicle(index_dummy,5) = init.fleet.vehicle(index_dummy,5) ...
    .* (total_distance_max(index_dummy) -
travel_distance_desired(index_dummy)) ...
    ./ hss_distance_max(index_dummy); % deduct from HSS

% Where travel_distance_desired is more than total_distance_max, deplete
% ESS and HSS, and correct travel_distance_actual assumption made above
index_dummy = travel_distance_desired >= total_distance_max;
init.fleet.vehicle(index_dummy,2) = 0; % deplete the ESS
init.fleet.vehicle(index_dummy,5) = 0; % deplete the HSS
travel_distance_actual(index_dummy) = total_distance_max(index_dummy);

travel_distance_actual(travel_distance_actual < 1e-4) = 0; % fix really small
numbers to 0

clear index_dummy

%% Module code

% Note: this is an electricity/hydrogen demand module.
% Power will always be negative
% Hydrogen will always be negative

% Create some variables for later
```

```
electricitysystem_power_fleet = 0;
grid_power_fleet = 0;

if init.fleet.charging_period(current_hour) == 1 % time to charge

    % Make sure the allowance is less than the request
    fleet.interaction.power.allowance = max(...
        fleet.interaction.power.allowance, ...
        fleet.interaction.power.request);
    fleet.interaction.hydrogen.allowance = max(...
        fleet.interaction.hydrogen.allowance, ...
        fleet.interaction.hydrogen.request);

    %% ELECTRICITY

    % BEHAVIOUR: depends on init.grid.enabled. No fuel cells

    % Check for exceeding electricity system limitations and scale allowance
& distribution accordingly
    fleet.interaction.power.correction_factor =
simhub_electricitysystem.poweravailable / (-1 *
fleet.interaction.power.allowance);
    if fleet.interaction.power.correction_factor < 1 &&
init.grid.purchase_enabled == 0 % exceeding limitations and no grid!
        fleet.interaction.power.allowance =
fleet.interaction.power.correction_factor *
fleet.interaction.power.allowance;
        charge_power_allocated = fleet.interaction.power.correction_factor *
charge_power_allocated;
    end

    % Reference:
    % init.fleet.vehicle(:,1) - ess_capacity [kWh]
    % init.fleet.vehicle(:,2) - ess_soc
    % init.fleet.vehicle(:,3) - ess_performance [km/kWh]
    % init.fleet.vehicle(:,4) - hss_capacity [kg]
    % init.fleet.vehicle(:,5) - hss_mass [kg]
    % init.fleet.vehicle(:,6) - hss_performance [km/kg]

    % check for validity of charge_power_allocated
    if min(charge_power_allocated) < 0
        error ('Error: charge_power_allocated has negative values');
    end

    if sum(charge_power_allocated) ~= 0 % make sure fleet isn't fully charged
already
        % calculate new SOCs
        init.fleet.vehicle(:,2) = init.fleet.vehicle(:,2) ...
            + charge_power_allocated ./ init.fleet.vehicle(:,1);

        % assume all power consumed
        charge_power_consumed = charge_power_allocated;

        % correct over charging, if any
        index_dummy = init.fleet.vehicle(:,2) > 1;
        charge_power_consumed(index_dummy) = ...
            charge_power_consumed(index_dummy) ...
```

```
            - (init.fleet.vehicle(index_dummy,2) - 1) ...  % (SOC - 1) = %
overcharge
            .* init.fleet.vehicle(index_dummy,1);          % * capacity =
overcharge power [kWh]
        init.fleet.vehicle(index_dummy,2) = 1;
        charge_power_consumed(charge_power_consumed < 1e-4) = 0; % fix really
small numbers to 0

        % demand charge_power_consumed from grid
        % this is a safe way to do it becase we have already corrected for
        % demands higher than the hub can provide
        electricitysystem_power_fleet =
simhub_electricitysystem.demand(sum(charge_power_consumed));

        % add electricity shortfall to grid_power. If not needed, then this
        % should be zero anyway.
        grid_power_fleet = sum(charge_power_consumed) -
electricitysystem_power_fleet;

        fleet.interaction.power.actual = -1 * sum(charge_power_consumed);

        % remove the correction_factor on charge_power_allocated so we can
get an
        % idea of the original power requested
        if fleet.interaction.power.correction_factor < 1 &&
init.grid.purchase_enabled == 0 % if correction_factor was applied previously
            charge_power_allocated = charge_power_allocated /
fleet.interaction.power.correction_factor;
        end
        clear fleet.interaction.power.correction_factor
        clear index_dummy
    end

    %% HYDROGEN

    if fleet.interaction.hydrogen.request < 0

        % BEHAVIOUR: limits itself to hub storage

        % Adjust hydrogen_needed and allowance to account for hydrogen mass
in storage
        fleet.interaction.hydrogen.correction_factor =
simhub_hydrogensystem.mass / (-1 * fleet.interaction.hydrogen.allowance);
        if fleet.interaction.hydrogen.correction_factor < 1 % exceeding
limitations!
            fleet.interaction.hydrogen.allowance =
fleet.interaction.hydrogen.correction_factor *
fleet.interaction.hydrogen.allowance;
            [-1 sim_hour simhub_hydrogensystem.mass sum(hydrogen_needed)]
            hydrogen_needed = fleet.interaction.hydrogen.correction_factor *
hydrogen_needed;
        end

        % Refill all vehicles
        init.fleet.vehicle(:,5) = init.fleet.vehicle(:,5) + hydrogen_needed;

        % Deduct from storage
```

```
        simhub_hydrogensystem.mass = simhub_hydrogensystem.mass +
fleet.interaction.hydrogen.allowance;

        % Report back to hub
        fleet.interaction.hydrogen.actual =
fleet.interaction.hydrogen.allowance;

        % Revert hydrogen_needed
        if fleet.interaction.hydrogen.correction_factor < 1 % exceeding
limitations!
            hydrogen_needed =
hydrogen_needed/fleet.interaction.hydrogen.correction_factor;
        end

    end
end

% calculate time remaining till the end of the charging period
time_remaining = 1; % initialize as if this is the last hour
exit_loop_flag = 0;
while exit_loop_flag == 0
    % calculate the next hour
    current_hour_dummy = mod(sim_hour + time_remaining, 24); % this variable
will always be the NEXT hour
    if current_hour_dummy == 0
        current_hour_dummy = 24;
    end

    % if next hour is travel, stop
    if fleet_checktravel(current_hour_dummy, init.fleet.charging_period) == 1
        exit_loop_flag = 1;
    else
        time_remaining = time_remaining + 1;
    end
end
clear current_hour_dummy exit_loop_flag

% calculate charge power for full charge just before the end of the charging
period
% if time_remaining == 1
%     time_remaining = 2;
% end
charge_power_allocated = (ones(init.fleet.population,1) -
init.fleet.vehicle(:,2)) ...
    .* init.fleet.vehicle(:,1) / (time_remaining); % ((1-SOC) *
capacity)/time_remaining


% correct for over charging
charge_power_allocated = min(charge_power_allocated,
init.supply.charging_station_power);

clear index_dummy time_remaining

%% Module code

% Note: this is an electricity/hydrogen demand module.
```

```
% Power will always be negative
% Hydrogen will always be negative

% Create some variables for later
electricitysystem_power_fleet = 0;
grid_power_fleet = 0;

if init.fleet.charging_period(current_hour) == 1 % time to charge

    % Make sure the allowance is less than the request
    fleet.interaction.power.allowance = max(...
        fleet.interaction.power.allowance, ...
        fleet.interaction.power.request);
    fleet.interaction.hydrogen.allowance = max(...
        fleet.interaction.hydrogen.allowance, ...
        fleet.interaction.hydrogen.request);

    %% ELECTRICITY

    % BEHAVIOUR: depends on init.grid.enabled. No fuel cells

    % Check for exceeding electricity system limitations and scale allowance
& distribution accordingly
    fleet.interaction.power.correction_factor =
simhub_electricitysystem.poweravailable / (-1 *
fleet.interaction.power.allowance);
    if fleet.interaction.power.correction_factor < 1 &&
init.grid.purchase_enabled == 0 % exceeding limitations and no grid!
        fleet.interaction.power.allowance =
fleet.interaction.power.correction_factor *
fleet.interaction.power.allowance;
        charge_power_allocated = fleet.interaction.power.correction_factor *
charge_power_allocated;
    end

    % Reference:
    % init.fleet.vehicle(:,1) - ess_capacity [kWh]
    % init.fleet.vehicle(:,2) - ess_soc
    % init.fleet.vehicle(:,3) - ess_performance [km/kWh]
    % init.fleet.vehicle(:,4) - hss_capacity [kg]
    % init.fleet.vehicle(:,5) - hss_mass [kg]
    % init.fleet.vehicle(:,6) - hss_performance [km/kg]

    % check for validity of charge_power_allocated
    if min(charge_power_allocated) < 0
        error ('Error: charge_power_allocated has negative values');
    end

    if sum(charge_power_allocated) ~= 0 % make sure fleet isn't fully charged
already
        % calculate new SOCs
        init.fleet.vehicle(:,2) = init.fleet.vehicle(:,2) ...
            + charge_power_allocated ./ init.fleet.vehicle(:,1);

        % assume all power consumed
        charge_power_consumed = charge_power_allocated;
```

```
        % correct over charging, if any
        index_dummy = init.fleet.vehicle(:,2) > 1;
        charge_power_consumed(index_dummy) = ...
            charge_power_consumed(index_dummy) ...
            - (init.fleet.vehicle(index_dummy,2) - 1) ...  % (SOC - 1) = %
overcharge
            .* init.fleet.vehicle(index_dummy,1);          % * capacity =
overcharge power [kWh]
        init.fleet.vehicle(index_dummy,2) = 1;
        charge_power_consumed(charge_power_consumed < 1e-4) = 0; % fix really
small numbers to 0

        % demand charge_power_consumed from grid
        % this is a safe way to do it becase we have already corrected for
        % demands higher than the hub can provide
        electricitysystem_power_fleet =
simhub_electricitysystem.demand(sum(charge_power_consumed));

        % add electricity shortfall to grid_power. If not needed, then this
        % should be zero anyway.
        grid_power_fleet = sum(charge_power_consumed) -
electricitysystem_power_fleet;

        fleet.interaction.power.actual = -1 * sum(charge_power_consumed);

        % remove the correction_factor on charge_power_allocated so we can
get an
        % idea of the original power requested
        if fleet.interaction.power.correction_factor < 1 &&
init.grid.purchase_enabled == 0 % if correction_factor was applied previously
            charge_power_allocated = charge_power_allocated /
fleet.interaction.power.correction_factor;
        end
        clear fleet.interaction.power.correction_factor
        clear index_dummy
    end

    %% HYDROGEN

    if fleet.interaction.hydrogen.request < 0

        % BEHAVIOUR: limits itself to hub storage

        % Adjust hydrogen_needed and allowance to account for hydrogen mass
in storage
        fleet.interaction.hydrogen.correction_factor =
simhub_hydrogensystem.mass / (-1 * fleet.interaction.hydrogen.allowance);
        if fleet.interaction.hydrogen.correction_factor < 1 % exceeding
limitations!
            fleet.interaction.hydrogen.allowance =
fleet.interaction.hydrogen.correction_factor *
fleet.interaction.hydrogen.allowance;
            [-1 sim_hour simhub_hydrogensystem.mass sum(hydrogen_needed)]
            hydrogen_needed = fleet.interaction.hydrogen.correction_factor *
hydrogen_needed;
        end
```

```
        % Refill all vehicles
        init.fleet.vehicle(:,5) = init.fleet.vehicle(:,5) + hydrogen_needed;

        % Deduct from storage
        simhub_hydrogensystem.mass = simhub_hydrogensystem.mass +
fleet.interaction.hydrogen.allowance;

        % Report back to hub
        fleet.interaction.hydrogen.actual =
fleet.interaction.hydrogen.allowance;

        % Revert hydrogen_needed
        if fleet.interaction.hydrogen.correction_factor < 1 % exceeding
limitations!
            hydrogen_needed =
hydrogen_needed/fleet.interaction.hydrogen.correction_factor;
        end

    end
end

Grid code
%% Define grid parameters

init.grid.purchase_enabled = 1; % 0 if grid purchase is off, 1 if purchase is
on
init.grid.sale_enabled = 1; % 0 if grid selling is off, 1 if selling is on

% This data is from eQuest for a MOB in Toronto, 2008.
load grid_data_cost

% check for validity of init.building.electricity_demand_profile
grid.data.cost(grid.data.cost < 0) = 0; % $/kWh

Wind code
% Initialize monthly average wind speed
wind.speed.monthly_average = [3.1 3.4 3 3.3 3.3 2.7 2.3 1.9 1.7 2.1 2.6 3.3];

% Initialize hours in each month
wind.month.hours = 24 * cumsum([31 28 31 30 31 30 31 31 30 31 30 31]) + 1;

% Initialize season of month
% 1 = winter
% 2 = spring
% 3 = summer
% 4 = fall
wind.month.season = [1 1 2 2 2 3 3 3 4 4 4 1];

% Initialize seasonal wind profiles relative to monthly average
wind.speed.seasonal_profile = [
    1.159214 1.136335 1.113456 1.090576 1.067697 1.052444 1.037191 1.021939
1.0066860 0.960927 0.915169 0.869410 0.823652 0.827465 0.831278 0.835092
0.838905 0.899916 0.960927 1.021939 1.082950 1.143961 1.148842 1.154028; %
winter
    1.070476 1.123795 1.177114 1.230433 1.175966 1.121498 1.067031 1.012564
0.9580970 0.902317 0.908880 0.915442 0.922004 0.928567 0.935129 0.941691
```

```
0.951535 0.885912 0.907567 0.929223 0.950878 0.972534 0.994190 1.017158; %
spring
    1.109489 1.109489 1.109489 1.109489 1.036496 0.963504 0.890511 0.817518
0.8175180 0.817518 0.817518 0.887591 0.957664 1.027737 1.097810 1.167883
1.124088 1.080292 1.036496 0.992701 0.992701 0.992701 0.992701 1.051095; %
summer
    1.114551 1.086687 1.058824 1.030960 1.003096 1.003096 1.003096 1.003096
0.9695944 0.928793 0.928793 0.928793 0.928793 0.928793 0.928793 0.928793
0.891641 0.854489 0.965944 1.077399 1.095975 1.114551 1.114551 1.114551; %
fall
    ];

% Wind turbine parameters
wind.turbine.hub_height = 80;
wind.turbine.rotor_diameter = 80;
wind.turbine.capacity = 1000; % [kW]

% Field parameters
wind.turbine_count = 1; % number of wind turbines

% Check the month and season
wind.dummy.sim_hour = mod(sim_hour, 365*24);
if wind.dummy.sim_hour == 0
    wind.dummy.sim_hour = 365 * 24;
end

[wind.dummy.month, wind.dummy.month] =
histc(wind.dummy.sim_hour,wind.month.hours);
wind.dummy.month = wind.dummy.month + 1;

wind.dummy.season = wind.month.season(wind.dummy.month);

% Get windspeed
wind.dummy.windspeed = wind.speed.monthly_average(wind.dummy.month) *
wind.speed.seasonal_profile(wind.dummy.season, current_hour);

% windspeed is measured at 10 m,
% the turbine chosen for this region is Vestas V80 2000/80 Onshore that has a
hub height of 80 m and a
% rotor diameter of 80 m
% since data for windspeed is available at 10 m, actual wind speed can be
found by multiplying windspeed*(height difference)^(1/7)
% Power is in MW

% http://www.windfair.net/vestas/vestas-v-80-2.0mw.html

% Calculate actual wind speed
wind.dummy.actspeed = wind.dummy.windspeed*(wind.turbine.hub_height-
10)^(1/6.61);

if wind.dummy.actspeed <= 3
    wind.dummy.eff = 0;
elseif wind.dummy.actspeed > 3 && wind.dummy.actspeed <=4
    wind.dummy.eff = 0.02205;
elseif wind.dummy.actspeed > 4 && wind.dummy.actspeed <= 5
    wind.dummy.eff = 0.0675;
elseif wind.dummy.actspeed > 5 && wind.dummy.actspeed <= 6
```

```
    wind.dummy.eff = .1305;
elseif wind.dummy.actspeed > 6 && wind.dummy.actspeed <= 7
    wind.dummy.eff = .2185;
elseif wind.dummy.actspeed > 7 && wind.dummy.actspeed <= 8
    wind.dummy.eff = .3345;
elseif wind.dummy.actspeed > 8 && wind.dummy.actspeed <= 9
    wind.dummy.eff = .4785;
elseif wind.dummy.actspeed > 9 && wind.dummy.actspeed <= 10
    wind.dummy.eff = .6395;
elseif wind.dummy.actspeed > 10 && wind.dummy.actspeed <= 11
    wind.dummy.eff = .795;
elseif wind.dummy.actspeed > 11 && wind.dummy.actspeed <= 12
    wind.dummy.eff = .9115;
elseif wind.dummy.actspeed > 12 && wind.dummy.actspeed <= 13
    wind.dummy.eff = .9725;
elseif wind.dummy.actspeed > 13 && wind.dummy.actspeed <= 14
    wind.dummy.eff = .994;
elseif wind.dummy.actspeed > 14 && wind.dummy.actspeed <= 15
    wind.dummy.eff = .999;
elseif wind.dummy.actspeed > 15 && wind.dummy.actspeed <= 25
    wind.dummy.eff = 1;
else
    wind.dummy.eff = 0;
end

% Your code must end with an assignment to wind_power.
% This assignment is necessary to return the module's power back to
% the simHub grid.
wind.interaction.power.request = wind.turbine.capacity * wind.dummy.eff *
wind.turbine_count;
wind.interaction.hydrogen.request = 0;

% Note: this is an electricity supply module.
% Power will always be positive
% Hydrogen will always be zero

% Make sure the allowance is less than the request
wind.interaction.power.allowance = min(...
    wind.interaction.power.allowance, ...
    wind.interaction.power.request);

% Decide to meet the allowance, since this is a simple module.
wind.interaction.power.actual = wind.interaction.power.allowance;

% Supply wind power to hub
simhub_electricitysystem.supply(wind.interaction.power.actual);

% Send cost information to hub
wind.interaction.power.cost = 5; % $/kWh

% Hydrogen is always zero
wind.interaction.hydrogen.actual = 0; %kg

Cost modelling code
%% Header code
% Set workflow mode
% mode = 1: initialization phase
```

```
% mode = 2: calculation & simulation phase
% mode = 3: termination phase
% mode = 4: costing phase
mode = 4;

interestrate = 1 + 0.05;

USD_to_CAD = 1; % Conversion rate between USD and CAD

%% Electrolyzer

% Calculating electrolyzer annual cost

electrolyzer.cost.TICC = init.storage.num_electrolyzers * 15 / 485 * 3419479;
% $ - total installed capital cost (TICC)
electrolyzer.lifetime = 20; % year

electrolyzer.cost.TICC_annual = electrolyzer.cost.TICC * ... % TICC
annualized
    interestrate ^ (electrolyzer.lifetime * 0.46) / ...
    electrolyzer.lifetime; % $/year

electrolyzer.cost.RC_annual = 0.3 * electrolyzer.cost.TICC * ... %
refurbishment cost annualize
    interestrate ^ (10 * 0.46) / ...
    interestrate ^ (electrolyzer.lifetime * 0.46) / ...
    electrolyzer.lifetime; % $/year

electrolyzer.cost.OMC_annual = 0.09 * electrolyzer.cost.TICC; %
operating/maintenance costs

electrolyzer.cost.annual = ...
    electrolyzer.cost.TICC_annual + ...
    electrolyzer.cost.RC_annual + ...
    electrolyzer.cost.OMC_annual;

%% Hydrogen Storage
storage.cost.annual = 2503.23 * USD_to_CAD * ...
    init.storage.capacity / 400.95; % $ / year

%% Wind

% Two factors:
% - capacity installed
% - power generated

wind.lifetime = 20; % years

wind.cost.TICC_annual = wind.turbine_count * 1.0 * 2750000 * ...
    USD_to_CAD * ...
    interestrate ^ (wind.lifetime * 0.46) / ...
    wind.lifetime; % TICC $/year

wind.cost.OMC_unitized = 0.01 * USD_to_CAD; % $/kWh
wind.cost.OMC_annual = wind.cost.OMC_unitized * ...
    sum(results.electricity_system.supply_power); % $/year
```

```
wind.cost.annual = ...
    wind.cost.TICC_annual + ...
    wind.cost.OMC_annual;

%% Electricity cost & revenue

grid.cost.annual = sum(results.electricity_system.grid_power .*
grid.data.cost(init.sim.start_time:init.sim.end_time));

grid.revenue.annual = -1 * sum(results.electricity_system.excess_power .*
grid.data.cost(init.sim.start_time:init.sim.end_time));

%% Emissions revenue

% We earn $1.785248636/kg H2 that goes to cars

emissions.cost.annual = -1 * 1.785248636 *
sum(results.hydrogen_system.demand_h2);

%% Profit/loss

total_cost = emissions.cost.annual + ...
    grid.cost.annual + ...
    grid.revenue.annual + ...
    wind.cost.annual + ...
    storage.cost.annual + ...
    electrolyzer.cost.annual;

total_h2 = sum(results.hydrogen_system.demand_h2);

h2_cost = total_cost / total_h2;

revenue = [-1 * emissions.cost.annual ...
    -1 * grid.revenue.annual ...
    -1 * grid.cost.annual ...
    -1 * wind.cost.annual ...
    -1 * storage.cost.annual ...
    -1 * electrolyzer.cost.annual ...
    -1 * total_cost ...
    total_h2 ...
    h2_cost]';

% Inform user the costing has fixed
fprintf ('Cost calculation finished\n');

Data Logging Code
%% Declare Fleet variables

% declare charging period
results.vehicles.charging_period = zeros(init.sim.end_time,1);

% declare SOCs
results.vehicles.soc = zeros(init.fleet.population, init.sim.end_time);

% declare power consumption per vehicle
results.vehicles.power = zeros(init.fleet.population, init.sim.end_time);
```

```
% declare hydrogen consumption per vehicle
results.vehicles.h2_refilled = zeros(init.fleet.population,
init.sim.end_time);

% declare distance travelled per vehicle
results.vehicles.travel = zeros(init.fleet.population, init.sim.end_time);

%% Declare Electricity System data

% declare fleet power demand
results.electricity_system.fleet_power_request = zeros(init.sim.end_time,1);

% declare fleet power consumption (electricitysystem, grid)
results.electricity_system.fleet_power = zeros(init.sim.end_time, 2);

% declare building power demand
results.electricity_system.building_power_request =
zeros(init.sim.end_time,1);

% declare building power consumption (electricitysystem, grid)
results.electricity_system.building_power = zeros(init.sim.end_time,2);

% declare total demand power request
results.electricity_system.demand_power_request = zeros(init.sim.end_time,1);

% declare total demand power consumption
results.electricity_system.demand_power = zeros(init.sim.end_time,2);

% declare total supply power
results.electricity_system.supply_power = zeros(init.sim.end_time, 1);

% declare excess power sold to market
results.electricity_system.excess_power = zeros(init.sim.end_time, 1);

% declare power from hydrogen system ... positive is power in to ES
results.electricity_system.h2_power = zeros(init.sim.end_time, 2);

% declare power from electricity grid
results.electricity_system.grid_power = zeros(init.sim.end_time, 1);

%% Declare Hydrogen System variables

% declare hydrogen storage level
results.hydrogen_system.mass = zeros(init.sim.end_time, 1);

% declare hydrogen demand
results.hydrogen_system.demand_h2 = zeros(init.sim.end_time, 1);

%% Record fleet results

% record charging period
results.vehicles.charging_period(sim_hour,1) =
init.fleet.charging_period(current_hour);

% record SOCs
results.vehicles.soc(:, sim_hour) = init.fleet.vehicle(:,2);
```

```
% record power consumption per vehicle
results.vehicles.power(:, sim_hour) = charge_power_consumed;

% record hydrogen consumption per vehicle
results.vehicles.h2_refilled(:, sim_hour) = hydrogen_needed;

% record distance travelled per vehicle
results.vehicles.travel(:, sim_hour) = travel_distance_actual;

%% Record Electricity System data

% record fleet power demand
results.electricity_system.fleet_power_request(sim_hour,1) =
sum(charge_power_allocated);

% record fleet power consumption
results.electricity_system.fleet_power(sim_hour,:) =
[electricitysystem_power_fleet grid_power_fleet];

% record building power demand
results.electricity_system.building_power_request(sim_hour,1) = -1 *
building.interaction.power.request;

% record building power consumption
results.electricity_system.building_power(sim_hour,:) =
[electricitysystem_power_building grid_power_building];

% record total demand power request
results.electricity_system.demand_power_request(sim_hour,1) =
results.electricity_system.fleet_power_request(sim_hour,1) +
results.electricity_system.building_power_request(sim_hour,1);

% record total demand power consumption
results.electricity_system.demand_power(sim_hour,1) =
results.electricity_system.fleet_power(sim_hour,1) +
results.electricity_system.building_power(sim_hour,1);
results.electricity_system.demand_power(sim_hour,2) =
results.electricity_system.fleet_power(sim_hour,2) +
results.electricity_system.building_power(sim_hour,2);

% record total supply power
results.electricity_system.supply_power(sim_hour,1) =
wind.interaction.power.actual;

% record excess power sold to market
results.electricity_system.excess_power(sim_hour,1) = excess_power;

% record power from hydrogen system ... positive is power in to ES
results.electricity_system.h2_power(sim_hour,:) = [(-1*h2_system_power)
grid_power_h2];

% record power from electricity grid
results.electricity_system.grid_power(sim_hour,1) = grid_power_building +
grid_power_fleet + grid_power_h2;

%% Record Hydrogen System data
```

```
% record hydrogen storage level
results.hydrogen_system.mass(sim_hour) = simhub_hydrogensystem.mass;

% record hydrogen demand
results.hydrogen_system.demand_h2(sim_hour) = sum(hydrogen_needed);
```

Appendix B
MATLAB Emissions Code

```
% EMISSIONS Calculates the emissions avoided by each unit
%
% Author: Faraz Syed, University of Waterloo (f2syed@uwaterloo.ca)

%% Header code
% Set workflow mode
% mode = 1: initialization phase
% mode = 2: calculation & simulation phase
% mode = 3: termination phase
% mode = 4: post-processing phase
mode = 4;

%% Wind emissions avoided
% Wind displaces 0.365 kg CO2/kWh of grid electricity displaced
% In a off-grid scenario, the excess electricity does not displace grid
% electricity, and I must not earn emissions rebates for that
W.emissions_avoided = 0.365 * ...
    sum(results.electricity_system.supply_power) - ...
    sum(results.electricity_system.excess_power) * ...
    ~init.grid.purchase_enabled; % kg CO2

%% Fleet emissions avoided
% Fleet displaces 0.2342 kg CO2/km travelled by the fleet
if init.fleet.split_charging == true
    F.emissions_avoided = 0.2342 * ...
    (sum(results.vehicles.travel(:)) + sum(results.vehicles_B.travel(:))); %
kg CO2
else
    F.emissions_avoided = 0.2342 * ...
    sum(results.vehicles.travel(:)); % kg CO2
end

%% Electrolyzer emissions avoided

% Electrolyzers displace 10.158 kg CO2/kg H2 produced
E.emissions_avoided = 10.158 * sum(results.hydrogen_system.generated);

%% Footer code

results.emissions_avoided = ...
    W.emissions_avoided + ...
    F.emissions_avoided + ...
    E.emissions_avoided;
```