Development of a Model to Investigate the Sustainability of Ontario's Future Electricity Supply Through a Dual Life Cycle Lens

by

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A thesis submitted to the
School of Graduate and Postdoctoral Studies in partial
fulfillment of the requirements for the degree of

Master of Applied Science in Mechanical Engineering

Department of Mechanical and Manufacturing Engineering in the
Faculty of Engineering and Applied Science

University of Ontario Institute of Technology (Ontario Tech University)

Oshawa, Ontario, Canada
October 2021

THESIS EXAMINATION INFORMATION

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Master of Applied Science in Mechanical Engineering

Thesis title: Development of a Model to Investigate the Sustainability of Ontario's Future Electricity Supply Through a Dual Life Cycle Lens

An oral defense of this thesis took place on April 5th, 2021, in front of the following examining committee:

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The above committee determined that the thesis is acceptable in form and content and that a satisfactory knowledge of the field covered by the thesis was demonstrated by the candidate during an oral examination. A signed copy of the Certificate of Approval is available from the School of Graduate and Postdoctoral Studies.

ABSTRACT

Since the turn of the century, greenhouse gas emissions and their climate related impacts have been studied with increased vigor. A tool that has gained popularity in supporting the reduction of emissions is life cycle assessment (LCA). This thesis proposes looking forward to using life cycle emissions and life cycle costs to determine which technologies can sustainably, both environmentally and economically, be used to meet Ontario's future electricity demand. A model was developed to calculate the life cycle impacts based on the installed capacity of each generation technology and its respective life cycle factors. The model was validated against historical results and then used to generate several alternative scenarios. A case study was performed, showing how a researcher could use the model to explore shutting down nuclear in Ontario. This model can now be used by researchers to assess life cycle impacts of electricity generation in Ontario and other jurisdictions.

Keywords: life cycle assessment; electricity forecast; energy; emissions; costs

AUTHOR'S DECLARATION

I hereby declare that this thesis consists of original work which I have authored. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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STATEMENT OF CONTRIBUTIONS

The part of the work described in Chapter 3 sub section 3.1 *Existing Research* draws directly on work done by Ryan Murphy-Snow and supervised by Jennifer McKellar. This was a modeling project in which energy flows were collected for several sectors in Ontario and converted to life cycle impacts. This work provided a baseline review of life cycle analysis for Ontario in 2014 and a basic user input scenario. I was responsible for verifying references used, updating values to align with temporal period of the model and completing tables where data was not previously found or available.

I hereby certify that I am the sole author of this thesis and that no part of this thesis has been published or submitted for publication. I have used standard referencing practices to acknowledge ideas, research techniques, or other materials that belong to others. Furthermore, I hereby certify that I am the sole source of the creative works and/or inventive knowledge described in this thesis.

ACKNOWLEDGEMENTS

I would like to thank my supervisors, both Dr. Jennifer McKellar and Dr. Marc A. Rosen, firstly for their patience with me, as I balanced both my masters and developments in my professional and personal life. I would also to thank them for their wisdom and guidance throughout my masters and for asking the hard questions to move my work forward.

I would like to acknowledge the Natural Sciences and Engineering Research Council of Canada (NSERC) for their financial support over my first two years. I would also like to thank Ontario Tech University for selecting me as one of the recipients of the TD Bank Financial Group Graduate Scholarship and the Nustadia Recreation Award in 2018.

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LIST OF ACRONYMS

CAD	Canadian Dollar
CERI	Canadian Energy Research Institute
CNA	Canadian Nuclear Association
CO_2e	Carbon Dioxide Equivalent
COP	Conference of the Parties
EIA	Energy Information Administration
FIT	Feed-in Tariff
GEA	Green Energy Act
GHG	Greenhouse Gas
HEPCO	Hydro-Electric Power Commission of Ontario
IESO	Independent Electricity System Operator
IPCC	IntergovernmentalPanel on Climate Change
INDC	Intended Nationally Determined Contributions
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LRP	Large Renewable Procurement
LTEP	Long Term Energy Plan
MRI	Midwestern Research Institute
NEB	National Energy Board
NREL	National Renewable Energy Laboratory
OEB	Ontario Energy Board
OPA	Ontario Power Authority
OPG	Ontario Power Generation
OPO	Ontario Planning Outlook
SLCA	Social Life Cycle Assessment
UNFCCC	United Nations Framework Convention on Climate Change
VBA	Visual Basic for Applications

LIST OF NOMENCLATURE

Symbol	Units	Description
CF_t	%	Technology Specific Capacity Factor
C_t	$	Technology Specific Capital Cost
Em	kg CO_2e/MWh	Process Specific Life Cycle Emissions
E_t	MWh	Technology Specific Total Life Cycle Electricity Generated
$E_{t,yr}$	MWh	Technology Specific Yearly Electricity Generated
$FO\&M_t$	$	Technology Specific Fixed Operation and Maintenance Cost
LCC	$/MWh	Life Cycle Costs
LCE	kg CO_2e/MWh	Life Cycle Emissions
lt	years	Life Time
$P_{t,yr}$	MW	Technology Specific Yearly Installed Generation Capacity
r	%	Discount Rate
$VO\&M_t$	$	Technology Specific Variable Operation and Maintenance Cost

Chapter 1. Introduction

1.1 Background and Objective Motivation

In the past three decades, there have been large developments in energy generation technologies, from the introduction of large-scale electricity storage to efficiency improvements of existing electricity generation technologies, such as hydroelectric or gas turbines. This has led to a diversification of electricity supply around the world. As more options for electricity generation become available, more factors can be considered, when comparing and selecting a technology, such as the energy source, cost, environmental impact, and market conditions. All factors of electricity generation are interdependent, making selecting an energy technology to supply electricity to meet future demand difficult for systems managers. These factors are also changing as innovation drives improvement of existing technologies and development of new technologies. In recent years, a decline in fossil fuels and an increase in renewable technologies can be observed [1] due to developments in renewable energy technologies and environmental concerns related to fossil fuel use.

In 1988, the Intergovernmental Panel on Climate Change (IPCC) was established by the United Nations and tasked with reviewing the state of knowledge of the science of climate change, as well as the social and economic impacts and potential response strategies [2]. The IPCC has been responsible for dozens of climate change related reports, which have been discussed annually at the United Nations Climate Change conferences often referred to as the Conference of the Parties (COP). These conferences have also created meaningful agreements with goals of reducing greenhouse gas (GHG) emissions such as the Kyoto Protocol in 1997 [3], the Copenhagen Accord in 2009 [4], the Cancun Agreements in 2010 [5], and most recently the Paris Agreement in 2016 [6], which was a result of COP 21 in Paris France. The Paris Agreement was influenced by the Fifth Assessment Report released by the IPCC in 2014 [7]. The major finding of this report was that if global warming continues and creates a rise in global atmospheric temperature greater than 2°C, this will cause climate change impacts that will be severe and irreversible. Therefore, the main goal of the Paris Agreement is to limit global warming to below a 2°C increase in atmospheric temperature rise compared to pre-industrial levels and to aggressively pursue ways to limit global temperature rise to 1.5°C [6]. Canada ratified the agreement on October 6, 2016, and identified the unique challenges and the current progress that Canada has made in addressing climate change in their Intended Nationally Determined Contributions (INDC) report to the United Nations [8].

The most frequently quoted definition for sustainable development is found in *Our Common Future* [9] and is defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". With regards to electricity this means that the supply of electricity is secure for future generations, while not creating lasting impacts, such as emissions or costs, that will burden future generations. In this research, sustainability will be assessed as the levelness of life cycle emissions and life cycle costs of the electricity generation in Ontario over the observed time period. Although there are several other factors to sustainable development, such as resource availability, and socio-economic factors like population, poverty, and income, only emissions and costs of electricity generation are explored in the research. The goal is to reduce and level out these factors to enable sustainable development in the future.

In Canada's INDC report, they acknowledge that Canada is responsible for 1.6% of global GHG emissions and commit to reducing emissions to 30% below their 2005 levels by 2030 [8]. This is completed through increasing regulations and standards on emissions-heavy sectors such as transportation, oil and gas, and chemicals processing. Canada has also implemented a carbon tax in 2018 as a way to cut industry pollution and fund innovation [10]. It is noted in the INDC report, that 80% of Canada's electricity supply does not directly emit GHGs, which is double the G7 and G20 averages [8]. Canada's significantly less emissions from electricity generation have been achieved through harnessing the abundant amount of renewable energy sources, specifically hydroelectricity, creating world class nuclear generation facilities, as well as through strict emission standards and banning new construction of traditional coal plants [11]. Though Canada's electricity system is relatively clean, in terms of direct emissions, upstream and downstream processes, related to these technologies have environmental impacts. Activities such as resource extraction, construction, manufacturing and decommissioning still create emissions which can affect our long-term sustainability. Canada also plans to invest in more renewable electricity generation and development in clean technology such as electric vehicles [8].

In Ontario specifically, there have been a number of pushes towards utilizing more sustainable energy sources, a major one being the Green Energy and Green Economy Act (GEA), 2009 [12]. This act promoted the installation and utilization of renewable energy generation, as well as energy conservation within the province. The GEA also encouraged the installation of large capacities of renewable energy through the Large Renewable Procurement (LRP) and Feed-in Tariff (FIT) programs. Others [13]–[15] have identified that the energy supply mix of Ontario will change over the upcoming decades to create a more diverse, cost-effective and sustainable energy supply for the province.

When considering multiple options, sustainability can be considered by determining the total impacts of a product or process from cradle to grave; this is called Life Cycle Assessment (LCA). LCA was developed in the 1960's as concerns of energy availability, material scarcity and environmental pollution grew [16]. This advancement allowed decision makers to compare the impacts of different products or processes. A notable early LCA study was completed by the Midwest Research Institute (MRI) for the Coca Cola Company comparing resource requirements, emissions and waste created by different beverage container options. Although the results of the study were never published other authors have acknowledge it as one of the first LCA studies [17]–[19]. In 1997, the International Organization for Standardization (ISO) developed ISO 14040:1997 Environmental management – Life cycle assessment – Principles and framework [20]. The ISO standard has since been revised by the current standards ISO 14040:2006 Environmental management – Life cycle assessment – Principles and framework [21] and ISO 14044:2006 Environmental management – Life cycle assessment – Requirements and guidelines [22].

The objective of this thesis is to create a model that can be used as a tool to investigate future electricity supply scenarios using both life cycle costs and life cycle emissions and to use this model to assess the sustainability of Ontario's electricity generation. To achieve this overall objective the following sub-objectives are to be completed: (a) develop a model and validate it by using historical data as model imputs and then compare outputs against other recent studies; (b) evaluate each technology on its ability to meet Ontario's demand gap; (c) explore prioritizing life cycle factors when selecting new generation; and (d) generate a case study which observes a nuclear shutdown like other jurisdictions and determine the resulting supply mix changes and corresponding life cycle factor impacts.

This tool will provide decision makers with a way to determine the long-term sustainability of Ontario's electricity supply across several scenarios. Across different demand scenarios and under varying technology preferences Ontario's future electricity supply will be explored through a dual life cycle lens of both life cycle costs and life cycle emissions. Through comparison of these life cycle metrics, across multiple scenarios, generation choices that lower the system life cycle cost or life cycle emissions will correlate across all scenarios and inform decision makers on potential methods to increase the long-term sustainability of Ontario's electricity generation. Reductions in system life cycle costs and life cycle emissions will aid in reaching provincial and national emission reduction goals while keeping electricity affordable for consumers. This project aims to aid policy and decision makers in understanding how to create a more sustainable electricity system for Ontario through investigating future life cycle impacts of different electricity supply scenarios.

1.2 Scope of Thesis

To fulfill the objective of this thesis, a model in Excel was created using Visual Basic for Applications (VBA) which utilized multiple future electricity demand scenarios for the province of Ontario, as well as life cycle cost and life cycle emissions for common electricity generation technologies. This data was utilized by the model to create several scenarios matching different electricity supply profiles, prioritizing specific factors and technological limits over the period from 2016 to 2035 with a temporal resolution of one year. The model balances the future electricity demands by assigning generation technologies according to scenario preferences. There are a multitude of scenarios that could be explored using the model, this thesis aims to explore some of the extreme potential scenarios, i.e., prioritizing a specific technology or prioritizing a life cycle factor when assigning new generation. This strategy will show how aggressive change could impact the environmental and economic sustainability of Ontario's electricity supply.

Both the demand and supply of the Ontario electricity system are constantly changing, no matter through which temporal scale the system is observed. The energy resources available at any given time can vary greatly depending on the weather and seasonal conditions. Even when all electricity generation sources are available the IESO’s market rules promote an efficient, competitive, and reliable electricity market, meaning that some generation sources will not be selected to produce electricity. When Ontario’s electricity system is observed at a high level, the variation that occurs on a smaller time scale such as hourly demand changes or weather variation each day can be approximated to a yearly average. Though this still leaves some variation in annual electricity generation and consumption, the model ensures that there will be adequate generating reserve to meet projected future peak demands.

For this model, the aspect of supply is the main variable of focus. Although several demand profiles from the IESO are considered along with their corresponding annual peak demands, the goal of the model is to select generation technologies based on the scenario criteria. This approach will ensure that the demand can be met and to observe the dual life cycle impacts of the selected generation.

1.3 Outline of Thesis

This thesis is divided into six chapters. Chapter 1 gives a brief background and motivation of the work. Chapter 2 presents a detailed literature review of life cycle analysis of electricity generation and how it is utilized to make decisions. This chapter also provides a brief history of electricity generation in Ontario. Chapter 3 provides the methodology used in the development of the model. Chapter 3 also explains the methodology and analysis that was performed in detail and provide a description of scenario specific criteria and how the model processes these equations and factors. Chapter 4 presents the results from the model and discusses the findings from the various scenarios. Chapter 5 summarizes the main findings of the thesis in the conclusion and includes recommendations for future use and development of the model.

Chapter 2. Literature Review

This chapter provides a brief overview of Ontario electricity generation and compares it in a national context, followed by a history of electricity generation and distribution for the province of Ontario and a review of the interaction of electricity and society in Ontario. Next LCA is explained and explored in an electricity generation context. Then previous LCA studies of Ontario's electricity system and its components are examined and followed by a brief overview of long-term energy forecasting with subsections pertaining specifically to Ontario. Finally, key findings and gaps in literature are summarized in the final chapter subsection.

The *National Inventory Report: Greenhouse Gas Sources and Sinks in Canada* [23] by the Government of Canada provides a sector level overview of greenhouse gas emissions. From this national perspective, Ontario is the second largest electricity generator of all the provinces and territories producing 151 TWh in 2016, second to Quebec which produced 183 TWh. This generation accounted for more than a quarter of Canada's electricity generation in 2016. A comparison of all provinces can be seen in Table 2.1. Ontario is a leader in nuclear generation both nationally and internationally, through the research and development of the Canada Deuterium Uranium (CANDU) reactor which lead to the installation of over 24 reactors across Canada in the second half of the twentieth century and an additional 12 implemented international. More recently in 2019, the province of Ontario, in collaboration with Natural Resources Canada (NRCan) and the provinces of New Brunswick and Saskatchewan, has committed to advancing the development and deployment of small modular reactors (SMRs) [24]. Currently Ontario has three nuclear generating stations producing 91 TWh in 2016, the largest of any province or territory. The province is also a leader in wind and solar, boasting 11.9 TWh of Other Renewables, such as wind and solar, in 2016, which was over a third of Canada's 28.9 TWh generated by Other Renewables that year.

Table 2.1: Regional and National 2016 Electricity Generation and Greenhouse Gas Emission Intensity [23]

Province/ Territory	Electricity Generation (TWh)	Percentage generated by:					GHG Intensity (g CO_2e /kWh)
		Hydro	Nuclear	Coal	Natural Gas	Other*	
Alberta	61.1	3.7	0	63.6	22.7	10.0	750
British Columbia	59.0	95.6	0	0	1.0	3.4	11
Manitoba	36.5	97.5	0	0**	0**	2.5	1.9
New Brunswick	14.6	21.5	31.1	14.8	16.1	16.5	320
Newfoundland & Labrador	40.8	94.6	0	0	0	5.4	37
Northwest Territories	0.351	72.6	0	0	4.0	23.4	200
Nova Scotia	9.45	9.1	0	50.9	13.1	26.9	700
Nunavut	0.189	0	0	0	0	100	740
Prince Edward Island	0.604	0	0	0	0	100	7
Ontario	151	23.1	60.2	0	8.5	8.2	37
Quebec	185	95.7	0	0	0	4.3	1.3
Saskatchewan	24.3	13.5	0	49.4	33.8	3.3	710
Yukon Territory	0.447	93.7	0	0	0	6.3	45
Canada	584	60.4	16.3	10.0	6.7	6.6	140

* Includes other combustion, biomass, other renewables: wind, tidal, and solar, and any other generation that falls under NAICS category 221119

** Generation from this fuel type within province is less than 10^{-3} percentage of annual provincial generation

This report [23] also noted the GHG intensity, which was calculated by dividing the total annual reported emissions from all generation facilities divided by the total electricity generated by all facilities. Although this document does not fully consider life cycle emissions related to upstream and downstream impacts of generation facilities such as material sourcing and decommissioning, it does give an annual snapshot of emissions from emitting generation sources. It also allows comparison between various provinces and territories, as well as to the weighted national average, with respect to their selected technologies and the annual emissions and GHG intensity. Based on reported emissions, Canada's electricity generation sector was responsible for 81 megatonnes (Mt) of carbon dioxide equivalent (CO_2e) emissions in 2016. Of this national total, Ontario was responsible for less than seven percent, reporting 5.5 Mt CO_2e emissions from their electricity generation facilities in 2016. The 2016 emissions show a reduction of almost 88% from Ontario's reported electricity generation emissions in 2000 of 44.2 Mt CO_2e [23].

From a provincial perspective, in 2018 the electricity generation sector produced the lowest emissions compared to the other economic sectors: transportation; industry;

buildings; agriculture; and waste. Figure 2.1 shows a comparison of all sector emissions from 2018, the most recent year for which data was recorded in the national inventory report [23]. Although GHG emissions from the electricity generation sector are relatively low, electrification of other sectors such as transportation, industry or buildings could increase electricity demand. This increase would likely require additional generation capacity to be installed. Therefore, the selection of low emission generation technologies will be required to reduce the annual emissions of the province, rather than transferring emissions from one sector to another.

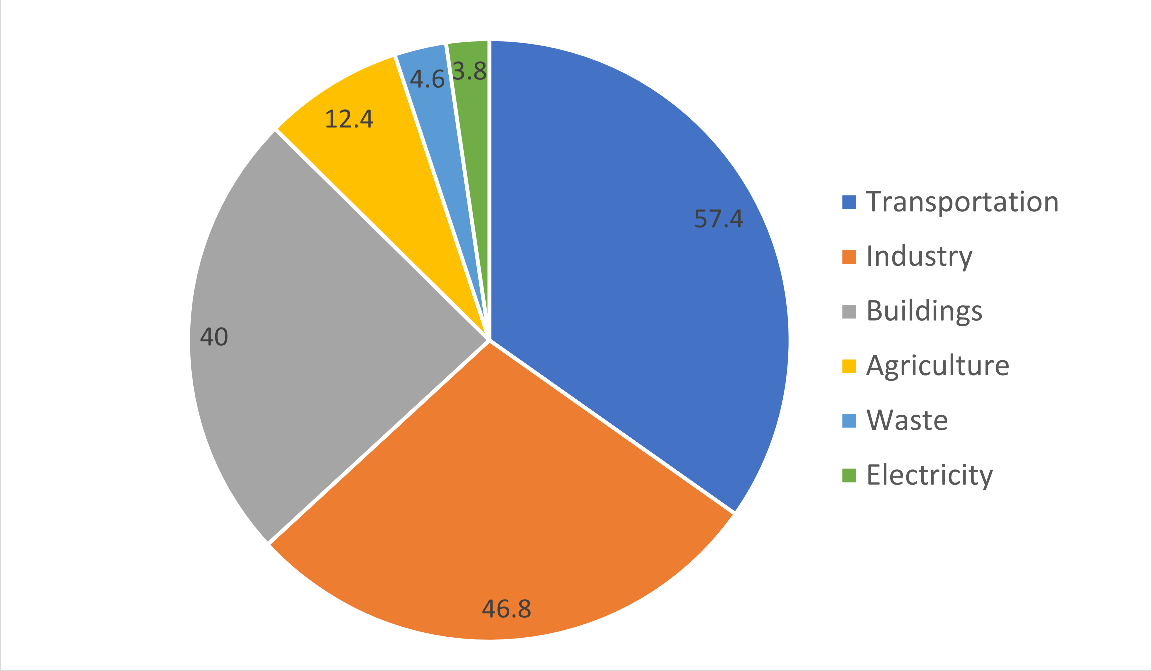


Figure 2.1:2018 GHG Emissions (Mt CO_2e) for Ontario by Economic Sector[23]

2.1 Electricity Generation & Distribution in Ontario

Before the future of electricity generation in Ontario can be explored, the history of generation in Ontario needs to be understood. In 2014, Rosenbloom and Meadowcroft published *The journey towards decarbonisation: Exploring socio-technical transitions in the electricity sector in the province of Ontario (1885-2013) and potential low-carbon pathways* [25], which provides a history of electricity generation in Ontario and the social and political drivers that created the system that the province has today. The following is a brief overview of the article, which encompasses up until the Green Energy and Economy Act and Feed-in Tariff (FIT) program. This is followed by a summary of modern developments in Ontario beyond the previous scope.

In the late 19th century, privately owned coal generation developed as part of the industrial revolution and was followed shortly afterward by hydroelectric generation due to coal strikes in the early 20th century. These private generators and distributors had strong control over the industrial and municipal electricity markets, while consumers had to contend with high-priced and unreliable electricity. In 1906, a commission led by Adam Beck recommended that the province move to a public electricity system and support the public electricity system by creating the Hydro-Electric Power Commission of Ontario (HEPCO), later renamed Ontario Hydro in 1974. This led to the creation of a province-wide grid which focused on transmitting electricity from large generation sites, such as Niagara Falls, to both municipal distributors and large industrial consumers.

Over the next seventy-five years, the Ontario electricity system was in a state of endless expansion [25], supported by political circumstances and spending, as well as provincial economic growth [26]. This led to a number of campaigns such as 'Live Better Electrically' to increase electricity consumption in the post-war decades [27]. As residential consumption grew through the 1960s, HEPCO predicted that the province would require 90,000 MW of installed capacity by the year 2000 [26]. In comparison, the annual electricity demand of 2000 was 147 TWh [28], supplied by 28,224 MW of installed capacity [29]. This discrepancy is likely caused by the conservation efforts and increases in technology efficiency both on the generation side, improving power output and on the demand side, reducing end user consumption. Under the previous assumption of needing 90 GW of generation to meet future demand, HEPCO moved to large capacity coal and nuclear generating stations instead of chasing the remaining lower capacity hydro sites in the province. This mindset gained further support when the 1973 oil crisis occurred [26]. Unfortunately, nuclear projects have been notorious for running behind schedule and over budget; and ultimately their construction did not decrease the cost of electricity as predicted [30].

In 1997, the Independent and Integrated Performance Assessment Report, initiated by the president of Ontario Hydro, prompted the dispersion of Ontario Hydro into more specific entities. In 1998, the Energy Competition Act divided Ontario Hydro into: Hydro One, responsible for the transmission and distribution of electricity; Ontario Power Generation (OPG), responsible for managing electricity generation assets; and the

Electrical Safety Authority, which administers safety regulations. It also created the Independent Market Operator, which later became the Independent Electricity System Operator (IESO) to manage the market and balance the electricity system. Further entities were later added; the Ontario Energy Board was utilized to regulate local utilities and the Ontario Power Authority, which was responsible for planning future electricity generation. The Ontario Power Authority would later be absorbed by the IESO as their roles evolved and became similar.

In 2009, Bill 150, the Green Energy and Green Economy Act, later simplified to the Green Energy Act (GEA)[12], was legislated with the main goals of phasing out coal-fired generation, increasing conservation programs and introducing renewable generation through a Feed-in Tariff (FIT) program. All these pursuits were to reduce the province's GHG emissions and create a green energy industry within the province. The Ministry of Energy was able to increase the amount of renewable electricity generation in the sector through specific directives to its underlying agencies, IESO, OPG and OEB [31]–[33]. The FIT and microFIT programs through several procurement periods from 2009 to 2017 resulted in an addition of 4410 MW of installed renewable capacity by 2020. This capacity when broken down by generation technology equates to 50 MW of bioenergy, 70 MW of hydroelectric, 1780 MW of solar and 2510 MW of wind. It is worth noting that although these programs procured more renewable generation for Ontario and established a renewable industry within the province, early phases were criticized for raising electricity prices due to the high fixed subsidies provided by the programs. Insufficient communication with the public about the programs resulted in a lack of public support [34].

In 2016, the Government of Ontario passed Bill 172, *Climate Change Mitigation and Low-carbon Economy Act*, in which the operation of a Cap and Trade system was laid out, along with emission reduction targets for Ontario, based on the province's 1990 emissions. These targets were set for 2020, 2030 and 2050, with reductions of 15, 37 and 80 per cent, respectively [35]. The Cap and Trade system had large carbon emitters bid on carbon allowances; the second auction of carbon allowances took place in June of 2017 and the allowances sold at just over $18 Canadian Dollar (CAD) per tonne of carbon dioxide equivalent (t CO_2e) [36]. Similarly to the FIT program, Cap and Trade has been criticized for the increased cost to consumers and not communicating the function and benefits of the program to the general populous [37].

Shortly after the proclamation of Ontario's provincial Bill 172, the National Energy Board (NEB) and the IESO both released energy projection reports [15], [38], which included electricity capacity forecasts for Ontario broken down by energy source. Both reports identified that increases in energy conservation, efficiency and renewable market share are required to meet both the future energy demand and the emission goals. They also provided alternate scenarios which primarily revolved around the volatility of the crude oil and natural gas markets. Although the data for multiple scenarios based on future fuel costs are available on the NEB website [39] the scenarios were not described in their report. Similarly, the IESO document only determined the energy demands for each scenario; it did not determine the associated GHG emissions. Neither report discussed the economics of renewables versus fossil fuel electricity generation.

Most recently in Ontario, after 15 years of a Liberal government, the province shifted to a Conservative provincial majority. The newly-formed government worked quickly to enact its own policies by repealing both the Climate Change Mitigation and Low-Carbon Economy Act and the Green Energy Act on November 14, 2018 [35] and January 1, 2019, [40] respectively. This legislation eliminated the Cap and Trade system which was replaced by *A Made-in-Ontario Environment Plan* [41] released on November 28, 2018 by the Ministry of Environment, Conservation and Parks. This plan aims to reduce Ontario's emissions by 30% below 2005 levels by 2030 to align with Canada's target as part of the Paris Agreement [8]. Ontario had already reached a reduction of more than 20% by 2016 [42]. In the recent provincial environment plan, supporting actions are listed that are intended to ensure the province meets their 2030 emissions goal. Although it is not clear how much these initiatives will reduce the provincial emissions, in theory they support the goal and will reduce emissions if implemented [43].

From a federal perspective, Canada signed the Paris Agreement on October 5th, 2016, and the agreement was ratified November 4th, 2016. The agreement aims to strengthen the effort to limit global average temperature rise well below 2°C and pursue initiatives to limit the increase to 1.5°C [44]. In Canada's INDC submission to the United Nations Framework Convention on Climate Change (UNFCCC) [8], Canada plans to reduce GHG emissions economy wide by 30% below 2005 levels by 2030. Canada aims to achieve this through increased regulation of both emission and efficiency standards as well as through investment in clean energy technologies. On June 21, 2018, Canada adopted the *Greenhouse Gas Pollution Pricing Act*, which implemented a regulatory charge on fossil fuels and an output-based pricing system for large industry. Revenue generated by this program will be returned to the jurisdiction in which it was generated through Climate Action Incentive payments, through tax breaks for individuals and families as well as investing in green initiatives [45].

Both the provincial and federal governments plan to reduce GHG emissions to meet the Paris agreement by 2030. Ontario's Ministry of Energy, Northern Developments and Mines could create regulation and support programs through its agencies and will therefore be a key stakeholder in reducing the provincial emissions. Observing Ontario's electricity system through a life cycle lens will show an aspect of the long-term sustainability of the system, specifically the emissions and cost, allowing decision makers to make informed decisions in selecting which technologies can be most beneficial in reaching their goals.

2.2 Electricity and Society

Although the social impact on energy development is not analyzed in this thesis, it still has an impact on how and where energy technologies are implemented within the province. In Ontario, changes to energy production are driven by both market conditions of energy resources, as well as social and political factors. Even if an energy technology is cost-effective and has a low impact on the environment, the project can be delayed by government policy or community resistance.

A notable example of this is the public's perception of wind energy development in Ontario. Songsore and Buzzelli [46] performed a study of articles found in the top ten circulated newspapers in Ontario over an eight year span from January 1, 2002 to September 16, 2010. The study found that a lack of community level engagement from both government and wind energy developers as well as the coverage of potential health risks and environmental concerns led to an increase in public resistance to wind energy development in Ontario. This resistance led to delay or cancellation of wind projects as community and environmental impacts were investigated further. The study suggested that both government and energy developers should take a more transparent approach when implementing energy technologies in communities. Songsore and Buzzelli [46] also noted that the Green Energy and Green Economy Act made developers responsible for assessing health and safety risks prior to installation; however, they suggested that this be amended so that an independent party must complete an environmental and health assessment before a project begins.

Similarly, Fast *et al.* [47] examined the issue from a policy perspective. The article examined four issues that arose from policy changes that were meant to accelerate the development of wind energy within Ontario. The first issue was the public's concern of health impacts, which initially were often dismissed due to lack of evidence and supporting science. The authors suggest that wind developers should seek to gain support for their project from surrounding residents and the municipality to reduce frustration and opposition from the community due to lack of information. The second issue explored was the distribution of financial benefits to the communities from wind developers. Typically, in Ontario, this comes in the form of a voluntary contribution from the wind developers to the municipality as well as a compensation to residents who lease a parcel of their land as a site for a wind turbine. Again, the authors suggest greater community engagement prior to construction to determine appropriate and transparent compensation, whether through cooperatives, fixed or voluntary contribution agreements. The third issue the authors noted was the basic level of community engagement. As the Ontario government attempted to streamline approvals of wind projects community engagement became a 'tick box' on the to do list of developers. This step also did not need to be completed until after the developer had secured a FIT contract. Finally, the authors discussed the issue of wind turbines changing the landscape and community identity, while not taking the opinions of the community seriously. In summary, future wind developments could gain more community support and reduce resistance by engaging the community at every step of the development process.

These examples show the impact that society can have on electricity generation projects. Although this thesis aims to forecast how future electricity demand could be met in a sustainable way, what type of technology and the location of implementation may incur some resistance from the community if proper site assessment and community engagement are not implemented or achieved. This thesis looks at electricity supply at a provincial level, therefore specific community implementation and potential public resistance to these power projects is not considered but would require investigation prior to implementation.

2.3 Electricity LCA

Life Cycle Assessment is an increasingly popular tool used by industry, government, and academia to compare multiple options or identify impacts of a specific product or process over its entire life cycle, from raw material to end of life, in terms of environmental performance. LCAs have a standardized framework and requirements set out by the ISO in ISO14040:2006 [21] and ISO14044:2006 [22]. These standards allow for LCA studies to be compared because they provide guidelines so that LCA studies are completed similarly and any differences in assumptions or data used are stated. LCA can be used alongside life cycle costing (LCC) or social life cycle assessment (SLCA) [48], which examine financial and social impacts, respectively, of a product or process. LCA is a valuable tool for this thesis as it normalizes all environmental impacts to a common functional unit which allows for energy technologies to be compared against one another.

Figure 2.2 gives a high-level visualization of the life cycle of an electricity generation facility. The main processes include Construction, Fuel Processing, Generation and Decommissioning, which are completed using energy, materials, and financial resources to produce electricity. These processes that are required for a facility to generate electricity also produce emissions which are converted to carbon dioxide equivalent (CO_2e). For some electricity generation technologies various processes are considered to have negligible impacts, such as fuel for wind or solar technologies, since wind and solar energy have no associated cost or emissions. Conversely, technologies like natural gas and nuclear utilize fuels which require mining, refinement and transportation which increases the environmental impact of the technology even before any electricity is generated. The dashed line box in Figure 2.2 encompasses the general processes associated electricity generation facilities, while the arrows to the left and right of the dashed box show the inputs and outputs of the system, respectively. This dashed line is considered the boundary of the study. In some cases, LCA studies will alter the boundary, if data is unavailable for specific processes or if these processes are considered negligible, then the author may choose to adjust the boundary accordingly to exclude said process. The arrows to the left and right of the boundary represent the system inputs and outputs, respectively. The boxes within the boundary represent the processes, each of which utilize the inputs to generate both the desired output(s) and other corollary products.

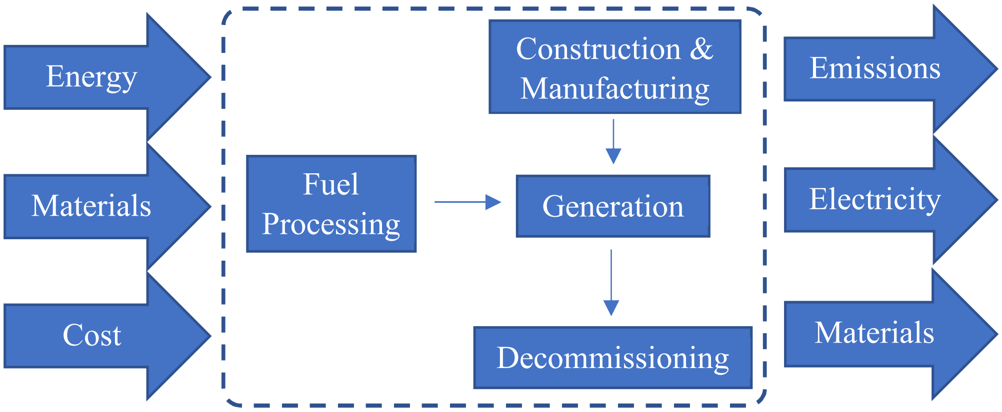


Figure 2.2: High Level Life Cycle of Electricity Generation Technology, Including Flows

One of the main challenges of LCA is accounting for time [49]. Traditionally, LCAs assume temporal boundaries in which processes related to the acquisition of materials, fuels and other market factors remain constant. Levasseur et al. [49] described a dynamic LCA as one where "the temporal profiles of emissions are considered so that the life cycle inventory (LCI) results for each emission is a function of time rather than a single number." Studies [49]–[51] have shown that the dynamic LCA of renewable technologies, especially over large time periods, showed reduced life cycle emissions relative to static LCAs due to improved manufacturing methods and technology development of renewable generation technologies. Levasseur *et al.* [49] used a dynamic LCA and integrated absolute global warming potentials, to show that when renewable fuels are evaluated on a longer time horizon, 50 to 100 years, the dynamic life cycle emissions are much less than the traditional static LCA approach. While Pehnt [51] in comparison, assumed that emissions related to production of renewable technologies would decrease as manufacturing methods improve to incorporate more recycled materials and technology development would improve the lifetime energy generated further reducing to total life cycle emissions of the technology. Since Ontario has begun integrating more renewable technologies into their electricity system, dynamic LCA is expected to capture the long-term performance more accurately. Although this analysis is attractive for assessing future options for Ontario's electricity supply, it would require a high resolution of data. Specifically, for renewables, when most emissions occur in the early life cycle stages of resource extraction, manufacturing and construction, these emissions would need to be accounted for in the life cycle inventory so that time dependant equations could determine the future global warming potential of those emissions over the technology's life cycle. This analysis would also require the back tracking of existing generation to determine the system's impacts and carry these impacts forward until the generation source's end of life as part of the future scenarios. Although this thesis looks at the future of Ontario's electricity supply, it would not be considered dynamic LCA as none of the inputs used by the model are a function of time.

The definition of scope is a common problem in comparing LCA studies and can be caused by a lack of available data related to the specific scope of the study. Several authors [52]–[54] have discussed the difficulties of performing LCAs related to electricity generation due to the lack of publicly available data, variance in electricity demand and uncertainty of future energy requirements. From these studies [52]–[54], all agree that transparency of data, reproducibility of studies and consistency in boundary determination are key to progressing electricity generation LCAs and gaining a stronger understanding of the temporal dynamics of future electricity. With respect to this study, some technologies are still being developed and improved upon and, therefore, all aspects of their life cycle may not have sufficient data to support this project. Specific examples for this thesis include end of life impacts of solar or electricity storage as these technologies do not have large capacities reaching end of life to provide the necessary insight. Another example of downstream impacts is the dismantling, recycling, and end of life of wind turbines in Ontario and its associated impacts are relatively unstudied. For these areas where life cycle data is still being developed, this model was created in such a way to allow for future alterations to inputs as new data become available, increasing the accuracy of the results.

2.4 LCA Forecasting

LCA is often used as a tool for assessing several options of products or processes for future implementation. Using LCA to assess all the future impacts of processes becomes more complicated as future data for all inputs within the scope of the study is required, but there is an inherent uncertainty with how the inputs will change in the future. Therefore, when analyzing life cycle impacts of future scenarios, it is common to keep the factors static assuming that any future implementation will be at current standards or with reduced impacts [55]–[57].

Looking to the future, Stamford & Azapagic [55] explored the life cycle sustainability assessment of future electricity scenarios for the UK with three separate carbon reduction goals (65%, 80% and 100%). Their article observed electricity grid mixes, electricity generation and yearly emissions at critical years 2009 (initial year), 2020, 2035, 2050 and 2070, instead of continuous annual analysis. This analysis allowed for the integration of specific emission targets for 2050. They also explored various other sustainability factors such as: land occupation; ozone layer depletion; and smog potential as well as socio-economic factors like total employment, radioactive waste to be stored, and human toxicity potential. The article found that in the 65% CO_2 reduction scenario, the UK would not reach their 2050 emission goal until 2070. Therefore, a more aggressive switch to carbon reducing technologies needs to be taken to meet their 2050 commitment.

Although future electricity supply LCAs have been completed in other jurisdictions e.g. [55], [58]–[60], Ontario's future electricity supply has not been observed through a dual sustainability lens of both life cycle emissions and life cycle costs for future electricity supply. This work aims to better understand Ontario's future electricity generation across several scenarios through a dual life cycle lens. This will aid decision makers in determining future electricity generation sources that will help to meet future electricity demand while being both environmentally and economically sustainable.

2.5 Electricity LCA in Ontario

There have been several studies that look at life cycle emissions of electricity generation in Ontario [14], [56], [61]–[64]. Mallia & Lewis [14] assessed facility specific life cycle GHG emissions of almost all types of electricity generation for 2008; however, cost was not considered. The other studies provided insight through comparative life cycle assessment of some, but not all technologies utilized in Ontario, which provides reference for technology specific data, but lacks the system level view that this thesis aims to provide.

As Ontario was transitioning away from coal-fired electricity generation, Zhang et al. [56] compared the life cycle operational costs of coal, wood pellet and natural gas-fired electricity generation in Ontario. The scope of the LCA focused on the operation of the plant and used static analysis for both cost and emission analysis. Zhang et al. [56]

performed a static comparison of Biomass, Natural Gas and cofiring of the two resources to determine which technology would be best suited, both economically and environmentally, to replace coal generation in Ontario. Although some consideration was given to the impact of refurbishment of the plants to convert them from coal to alternative fuels, the study focused on the yearly operation and fuel consumption. The study considered both GHG emissions and costs of coal, wood pellet, natural gas, and combined-cycle combustion. The study was not described as a dynamic LCA; however, three price points for natural gas (\$5/GJ, \$7/GJ, \$11/GJ) were analyzed to account for the uncertainty of future natural gas prices. Similarly, a high pellet cost was used during analysis, although the authors speculated that there were cheaper sources of biomass available, which would reduce the operating cost. The study is an example of a combined LCA/LCC which was able to determine the cost of GHG emission reduction (\$/t CO_2e) for varying fuel types at multiple price points. It can be noted that a dynamic LCC could utilize the variance in natural gas price to determine how many years the natural gas plant could remain feasible. As part of this study, Zhang et al. explored variation in Natural Gas pricing by assuming a low, medium and high cost to address future price uncertainty of natural gas, and the effects it would have on the life cycle costs of the system. Most notably, Zhang et al. explore the metric of cost-effectiveness of GHG reduction, which allowed them to compare several scenarios by combining emissions and costs into one metric. This equation is depicted below as equation 1. The cost effectiveness of GHG reduction is the negative ratio of the difference between the alternate scenario cost of electricity, $LCC_{alternate}$ and the reference life cycle cost of electricity, LCC_{ref}, over the difference of the alternate scenario life cycle emissions, $LCE_{alternate}$ and the reference life cycle emissions, LCE_{ref}.

$$Cost - effectiveness\ of\ GHG\ Reduction = -\frac{LCC_{alternate} - LCC_{ref}}{LCE_{alternate} - LCE_{ref}} \qquad (1)$$

In 2013, Mallia & Lewis [14] published a study in which life cycle emissions of all generation stations that produce more than 100,000 t CO_2e annually were normalized, based on power output and averaged to find a GHG intensity of 201 t CO_2e/GWh for the 2008 electricity grid. However, their study was done before Ontario removed coal from the provincial energy system, which was found to contribute 23 megatonnes of CO_2e [14] (or 1006 t CO_2e/GWh when in context of annual electricity generation) to Ontario's carbon footprint in 2008. Also, the minimum annual emissions reporting requirement meant that smaller scale plants that did not exceed the emission reporting threshold would not have been included in the study [14]. Since this study, the minimum emission reporting threshold has been reduced to 10,000 t CO_2e [65], which would encompass more generators and industry emissions. Their study [14], also did not consider cost, which is a prominent factor when determining how to expand the current energy system.

Richardson & Harvey [61] explored three successive scenarios of optimizing renewable energy, demand response and energy storage to replace conventional fuels in Ontario. Firstly, the displacement of fossil fuel electricity generation was considered, followed by the retirement of the Pickering Nuclear Generating Station and finally the electrification of vehicles. The scenarios resulted in increasing costs of electricity and while all reduced CO_2 emissions, grid-focused scenarios reduced emissions by 5-6%, whereas electrifying passenger transportation resulted in a 73% reduction. This work also provided valuable insight into capacity limits of renewable generation, noting that hydroelectricity could, at most, produce 38 TWh annually. Similarly, wind and solar were utilized the most in the third scenario, providing roughly 75 TWh and 30 TWh respectively. Biomass was utilized as a back-up and peak generation source and therefore only contributed between 3-11%, although the work suggested sustainable generation from biomass in Ontario could range from 14 TWh to 87 TWh. The scenarios explored are likely to occur over several decades; however, the study assumed instantaneous transition. These shifts in Ontario electricity system will likely take several years if implemented aggressively and over that time other changes could occur such as increases in both peak and annual demand, improvements in technology or development of new technologies.

More recently, in 2017, Siddiqui & Dincer performed a process-based life cycle assessment on the major types of electricity generation in Ontario: nuclear; hydroelectric; and wind [64]. The study produced similar results to Mallia & Lewis in terms of global warming potential, while providing other environmental impact characterizations such as acidification, human toxicity potential and eutrophication potentials. It is noted that these impacts for all three generation types occur mainly during the construction and decommissioning phases and development of methods which are environmentally benign which could decrease the environmental impact of these technologies. This study is an excellent example of how LCA can be used as an exploratory method to identify areas of improvement. Based on the recommendation of this study, future research should develop better construction methods for these technologies and, therefore, it is assumed that life cycle impacts of these technologies will be the same or better in the future.

There have also been public reports investigating life cycle emissions of electricity generation in Ontario [63], [66], [67]. Canadian Energy Research Institute (CERI) prepared a study [63] for the Canadian Nuclear Association (CNA), which compared life cycle emissions of Nuclear, Natural Gas and Coal electricity generation using data from 2005 and 2006. It found that Nuclear had a GHG intensity of 1.837 t CO_2e/GWh, Natural Gas and Coal had GHG intensities of 445.208 t CO_2e/GWh and 1051.215 t CO_2e/GWh, respectively. Bruce Power and the Asthma Society of Canada prepared the report *Clean Air Ontario* [66], which compared the life cycle emissions of electricity generation technologies in Ontario and explored the connections to climate change, allergies and asthma. The study found the following life cycle emission factors: Coal 1014 t CO_2e/GWh, Natural Gas 622 t CO_2e/GWh, Solar 39 t CO_2e/GWh, Hydroelectric 18 t CO_2e/GWh, Nuclear 17 t CO_2e/GWh and Wind 14 t CO_2e/GWh. This study supports minimizing the life cycle emissions as well as the criteria air contaminants (CAC) within the province including particulate matter, nitrogen oxides (NO_x) and sulphur oxides (SO_x), which can impact respiratory sicknesses such as asthma, bronchitis, and pneumonia. The report also acknowledges that climate change is increasing average temperatures, creating longer active pollen seasons, longer dry periods, and increased chance of forest fire, all of which will create more respiratory irritants.

Most recently, Intrinsik Corporation produced a study for OPG [67] to support the refurbishment of the Darlington Nuclear Generating Station. The report explored the operating stage emissions of Ontario's current electricity technologies and compared future operating emissions under two scenarios: Darlington is refurbished or Darlington closes. The study determined the operating emissions of electricity technologies to be: Hydroelectric 0 t CO_2e/GWh; Nuclear 0.15 t CO_2e/GWh; Wind 0.74 t CO_2e/GWh; Solar 6.15 t CO_2e/GWh; and Natural Gas 525 t CO_2e/GWh. Intrinsik determined that by refurbishing Darlington, the operating emissions of the province's electricity system would be reduced by 9.6 Mt CO_2e per year on average, resulting in 297 Mt CO_2e of avoided emissions over Darlington's extended lifetime.

These studies provided a good understanding of the life cycle impacts of the current state of electricity generation in Ontario and are comparatively synthesised in section 2.7 as a summary of literature review findings. However, applying LCA to Ontario's electricity future could provide insight and support decision-making for a more sustainable electricity supply. Although it is unlikely that Ontario-specific data will be available for all life cycle aspects of all generation types, other studies from other jurisdictions should be able to fill gaps in data.

2.6 Forecasting of Electricity Generation and Demand

The future of energy and, more specifically, the electricity industry is inherently uncertain across all temporal scales. From the IESO reacting to balance a change in demand every five minutes, to trying to plan for peak and total electricity demand twenty years from now, there is a measure of uncertainty that prohibits an exact determination. With the rate at which new technology is being developed, both consumers, through purchase of new devices or finding ways to conserve to lower cost, and generators, through the implementation of more efficient technology, can influence the balance of the electricity system.

There are several methods used when forecasting future energy scenarios [57]. The common exploratory method is to gather a collection of industry experts and professionals to discuss future outcome possibilities and narrow the uncertainty to a range of several reasonably plausible scenarios. This method has been utilized for the Ontario Long-term Energy Plans [68] and on a global scale [69]. Another method is to set specific outcomes, such as the percent of renewable generation to be implemented by the end of the outlook period. The scenario is then back cast to the starting point assuming reasonable technology uptake over each temporal period [55]. Back casting can provide an interesting perspective especially as jurisdictions become goal oriented to reduce or eliminate emissions by a specific year. This strategy is also further discussed in section 3.3 of the Method chapter. In some cases industry regulators have built proprietary economy-scale models that are utilized to create reoccurring reports and forecasts based on evolving policy, markets and technology trends [70]–[72]. These models often span multiple sectors and jurisdictions, providing high level data to support other studies. Although these other models track emissions related to various fuel types across several sectors and industries, and in some cases could forecast what emissions will be generated in the future, these models consider only operational emissions for reporting electricity generation emission intensities.

2.7 Long-Term Energy Planning in Ontario

The Ministry of Energy, Northern Developments and Mines has generated three Long Term Energy Plan (LTEP) reports for the province published in 2010, 2013 and 2017 [68]. Originally mandated to be released at a minimum of every four years, the provincial government has recently removed this timing requirement to review the government's responsibility in the energy sector and how to best coordinate this report with its agencies and stakeholders [73]. These reports were supported by power system planning, completed by the IESO and the OPA for sections specifically pertaining to the electricity sector. In comparison, the LTEP reports often provided high level goals and outcomes of Ontario's future electricity system whereas the supporting reports [15], [68], [70], [74] often provided a more in depth analysis and larger amounts of supporting data.

Others [62], [75] have explored future energy supply scenarios for Ontario through development of their own models. Norrie [62], explored three scenarios for 2006 to 2030. In the first, a "business as usual" scenario where existing coal plants would be maintained, hydroelectric capacity would be maintained and both nuclear and natural gas provincial capacity would be increased to match the increasing demand. The second scenario assumes that nuclear will be decommissioned as those plant reach their end of life while coal is extended slightly past its planned end of life through emission control technologies but ultimately being shut down before 2020. This reduction in generation capacity is resolved by an addition of 8000MW of natural gas, 6500MW of biomass and an additional 3600 MW of other renewable generation. Similarly, the third scenario plans to have both coal and nuclear expire as the existing plants reach their respective end of design life. The future demand is then met by an increase of 6900 MW of hydroelectric capacity due to aggressive development of run-of-river and pumped storage. As well as significant increases in solar, biomass and wind, 2900 MW, 4400MW and 14000MW, respectively by 2030, while waning off natural gas to only 3000MW by 2030 from a peak of more than 11000MW. These scenarios were evaluated across several life cycle impact categories with these values being weighted based on a criteria weighting questionnaire, which was completed by 18 industry professionals. Through this determination it was found that scenario three performed the best while the first scenario performed the worst. This is due to the larger capacities of lower impact generation, particularly renewables in scenario three and the continued operation of emission generation technologies, coal, and natural gas in scenario one.

More recently, Qudrat-Ullah [75] similarly developed a model and forecast three future electricity supply scenarios from 2000 to 2030; a Status Quo Scenario (SQS), a Renewable Focused Scenario (RFS) and a Low-Carbon Economy Scenario (LES). The main difference between the RFS and LES is that in the RFS non-hydroelectric renewables increase their market share to 22% rather than 10% in SQS and in the LES all-emitting technologies (coal and natural gas) have an associated emission cost of $48/ton, reducing their capacity share to zero and selecting other non-emitting generating technologies instead. Under these assumptions the results of the RFS scenario yielded the lowest emissions at 8725 tons, however this scenario had the highest consumer cost at over 20¢/kWh by 2030. Whereas the LES scenario resulted in a consumer electricity cost of 16¢/kWh, mainly due to the low cost and high availability of nuclear and hydroelectric. However, that study did not factor limits of technologies into its model and therefore some of the proposed capacity additions may not be practical.

2.8 Key Findings

Ontario is one of Canada’s largest electricity generators and consumers, and over the past two decades has made great improvements in reducing their GHG emissions from the electricity generation sector. This reduction has been driven by public policy from the Ontario provincial government through directives issued to its agencies, IESO, OPG, OEB and through technological improvements increase the efficiency of existing resources. However, it is also clear that when there is lack of information and communication to local communities where new generation is planned, society may resist legislative, ministry and agency decisions. Several LCA studies have focused on Ontario’s electricity system, the results of which are shown in Table 2.2. When comparing the results of these studies against each other, they show relatively similar results in terms of ranking of generation technology and values found. Some of the variation between studies is due to the scope of the LCA's performed. For example, the Intrinsik study had the lowest recorded values for nuclear, hydroelectric, wind and solar. These low life cycles emissions are because only the operational stage of the plant was considered in their study. Although several studies have been completed none have fulfilled an Ontario specific study on all generation sources in Ontario. This thesis aims to analyze all technologies and look at the future life cycle impacts of the Ontario electricity supply system.

Table 2.2: Summary of Life Cycle Emissions Studies of Electricity Generation in Ontario, Normalized to g CO_2e/kWh

Technology	CERI 2008 [63]	Zhang et al* 2010 [56]	Mallia & Lewis 2013 [14]	Bruce Power 2014 [66]	Intrinsik** 2016 [67]	Siddiqui & Dincer 2017 [64]
Nuclear	1.8		4.8	17	0.15	3.4
Natural Gas	445	386–414	154–707	622	525	
Hydroelectric			1.5–22.5	18	0	15.2
Biomass		123–127				
Wind			9.03–12.23	14	0.74	12.1
Solar				39	6.15	
Coal	1051	1001–1194	1040–1360	1041		

*Excludes infrastructure, construction, and equipment manufacturing
** Only operational emissions

This thesis aims to develop a forward focused model which will utilize forecast electricity demand and installed capacity, in conjunction with life cycle data to investigate future electricity scenarios in Ontario. This will provide insight into two sustainability factors, emissions, and cost, and how they could change in the future depending on technology selection and electricity demand. In addition, it will explore how life cycle factors can be prioritized to create a more sustainable electricity supply and how these futures compare to the reference scenario.

Chapter 3. Methodology

This chapter acknowledges work previously completed on which this thesis is built upon. Then the chapter briefly explains how the model developed in this thesis goes beyond previous work. Previously used methods for electricity and LCA forecasting are reviewed, followed by identifying LCA and LCC data that will be utilized by the model. Next, mathematical equations that were utilized by the Excel VBA model are described in the order they are used. The model then iterates these life cycle and capacity equations along with decision making on an annual time step across the modelling horizon for the years 2016 to 2035, when it reaches the upper temporal bound of the forecast model. Once this method was implemented it was validated against other Ontario-specific studies using historical electricity data to ensure temporal alignment. The logic of each of the alternate scenarios is then described.

3.1 Existing Research

Ryan Murphy-Snow and Jennifer McKellar had collected and organized life cycle data related to energy use in Ontario by sector (i.e. Residential, Commercial, Transportation, Industrial, Agricultural) in an Excel document [76]. Energy flows for sixteen energy carriers in Ontario were collected based on 2012 and 2014 publicly available data to support energy system analysis. The impacts related to each energy carrier, such as GHG emissions, criteria air contaminants, water use, etc. were quantified using literature data. The flows were then sorted into their respective sector of use and corresponding visuals were created to aid in the interpretation of results.

The final element added to their analysis was the implementation of a "User Input" scenario, which allows for a user to alter the market share of different electricity generation methods for a side-by-side comparison. An example of this User Input scenario explored a 50% reduction in nuclear generation that was compensated by a 10% increase in wind and 20% increase in natural gas generation. Although this analysis is useful for side-by-side comparisons, it lacks the ability to forecast; therefore, the comparisons imply an instantaneous switch in generation technology market shares. However, it is more realistic that a change of market share of generation, which could be implemented due to either economic, legislative, or environmental reasons, would occur over several years if not decades.

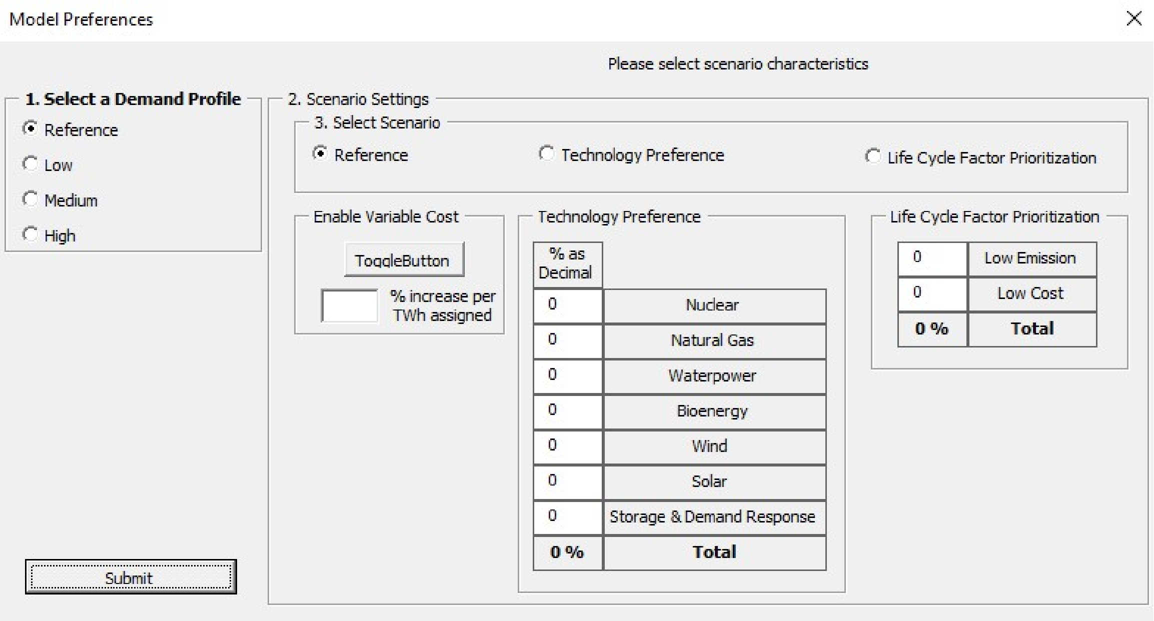
3.2 Model Development

This thesis aims to expand on previous work by creating a model to explore multiple future electricity generation scenarios through a dual life cycle perspective of both life cycle emissions and life cycle cost. This is done by using an annual electricity demand forecast as well as existing and forecast installed capacities from the IESO's Ontario Planning Outlook (OPO) [15]. To align with the available capacity data from the OPO a time horizon of 2016 to 2035 was selected. Forecasted installed capacities of each technology were converted to annual life cycle emission and life cycle cost data for each year, as described later in this chapter in section 3.4.

VBA, or Visual Basic for Applications and Microsoft Excel were the chosen applications for the development of the model due to their accessibility, as these programs are commonly used on most computers. Generally, in the engineering discipline, there are professionally developed programs that allow researchers to provide very detailed analysis. However, these programs are often expensive, as they require powerful hardware, software licencing and hours of training to learn the intricacies of the program. Others [77], [78], have also noted the accessibility of Excel and VBA in the academic environment, as Excel is available on most modern personal computers, which also allows the model to be readily shared to researchers and decision makers. As a coding language, VBA utilizes similar functions to the cell calculations that Excel uses. This allows users to easily interpret and alter code to vary a program for their own applications.

This model was initially done using Excel spreadsheet calculations which referenced relevant cells on previous pages for conversion factors, technology specific capacities, capacity factors and life cycle data. As alternate scenarios and demand profiles were explored the iteration of cell calculations became increasingly tedious. Therefore, a model was developed using VBA for Excel to convert the iterative calculations into nested loops. The sections of code, also referred to as macros or modules, that are utilized by the model are included in Appendix A.

For ease of running multiple alternate scenarios, a user interface was created. This allowed for four different electricity demand profiles, Reference, Low, Medium, and High to be selected as well as scenario-specific inputs such as life cycle factor prioritization or technology preference. A visualization of the user interface can be seen in Figure 3.1.



Please select scenario characteristics

1. Select a Demand Profile

● Reference
○ Low
○ Medium
○ High

2. Scenario Settings

3. Select Scenario

● Reference
○ Technology Preference
○ Life Cycle Factor Prioritization

Enable Variable Cost

☐ % increase per TWh assigned

Technology Preference

% as Decimal	
0	Nuclear
0	Natural Gas
0	Waterpower
0	Bioenergy
0	Wind
0	Solar
0	Storage & Demand Response
0 %	**Total**

Life Cycle Factor Prioritization

0	Low Emission
0	Low Cost
0 %	**Total**

Figure 3.1: VBA Model User Interface to Select and Input Scenario Preferences

3.3 Electricity Forecasting

Electricity generation forecasting often sets a specific target for a specific year and then back casts to current data to determine the steps necessary to eventually meet the stated goal. Previous studies [15], [55], [62] have set technology-specific installed capacity values for future years and then back cast, assuming a specific technology uptake per time period. However, back casting can resolve in the need for aggressive development of renewable energy sources due to the analysis setting high future renewable capacity targets, at level much greater than have previously been seen in the region. Two examples of backcasting analysis [79], [80], found that by setting a future sustainability goal and back casting the adaptation rate of renewables over the time horizon to meet that goal, that this would require a more aggressive uptake than has previously been done in the respective jurisdictions. This often results in additional incentives or support to the industry to stimulate enough growth to meet the aggressive targets which will enable the desired goal.

This study aims to look forward, assessing each annual time period to determine how much generation will be needed and based on user input criteria, which technology should be selected to achieve the desired goal. This method was chosen to ensure that technologies undertook reasonable growth from year to year, instead of setting a long-term goal that would require aggressive implementation of a technology throughout the time horizon. New generation that is selected will have a lead time, which can range from a couple of months in the case of some solar and bioenergy generation technologies, or longer than a decade in the case of new nuclear power development. This lead time of new assigned generation was not incorporated into the model as most technologies chosen within the timeline have an average lead time that is short enough to not create a hindrance on addition of more generation. Both nuclear and hydroelectric have longer lead times, and therefore these technologies have been limited to close to what currently exists. Similarly, each generation technology has a minimum lifetime of 20 years and therefore new generation end-of-life will occur outside the scope of this project. Facility lifetime is factored into both LCA and LCC of electricity generation as both emissions and cost are amortized over the lifetime by dividing the impact by the lifetime electricity produced by the facility. These amortized life cycle factors are then be applied to annual generation from each technology, which results in annual life cycle cost and life cycle emissions of each technology. Additionally, existing grid-connected generation capacity that expires is addressed as it is part of the forecast capacity data from the OPO report.

The model uses an iterative process to assign the generation required based on the difference between the scenario demand profile and the existing installed capacity. Then the model calculated the annual life cycle emissions and costs of each technology using the assigned generation and amortized life cycle factors. All the technology annual life cycle impacts can then be summed to create a system total for that year. Once this iteration is complete the model moves to the subsequent year and restarts its process. This means that, for example if 1 TWh of wind generation is assigned in year 1 it does not carry over to year 2. This means that for each year the model assess the generation deficit and meets the future electricity demand based on the scenario criteria.

This forecasting method provides a key perspective for decision-makers as it determines what the best option for the future would be from the current perspective. It also allows the model to expand further into the future as more electricity generation forecasts become available. The model can potentially evolve laterally to other sectors, such as transportation or residential heating and cooling, which would affect electricity demand in the province and change the amount of future generation required depending on sector electrification. Expansion of the model to other sectors could provide greater detail of the long-term sustainability of energy consumption in the province and identify sectors that have the greatest life cycle emissions or life cycle costs so that policy or programs could be implemented to mitigate them.

The analysis performed in this thesis considers several scenarios as it is unlikely that any single scenario will emulate Ontario's future electricity generation exactly. However, by comparing the results across multiple scenarios and demand profiles, recommendations regarding which technologies can improve the future sustainability of Ontario's electricity supply can be concluded. The model's annual analysis of future electricity supply and exclusion of carry over from year to year means that if future years see a large increase in a specific technology, future LCA research and an implementation plan could be directed at this technology to reduce its life cycle impacts and capital expenses required in a single year, increasing the sustainability of the future system.

3.4 Calculation of Relevant Factors

Previous work done by Murphy-Snow & McKellar [76] created a collection of Ontario-specific life cycle data for energy use and consumption across several sectors: transportation; electricity generation; industrial; agricultural; and residential. A large portion of the compiled data set was retrieved from Statistics Canada [81], Natural Resources Canada [82] and GHGenius [83] databases with any gaps being filled in by journal articles or other reports from outside Ontario, such as the National Renewable Energy Laboratory (NREL) [84] or the U.S. Energy Information Administration (EIA) [85]. Both NREL and EIA are US government agencies which focus on tracking and forecasting energy related data, similar to Canada's Nation Energy Board and Statistics Canada. As initial work of this thesis research, these values were verified against other values found in literature as described in chapter 2 and updated to align with the start of the temporal period, 2016. From this information, both life cycle emissions and the levelized cost of electricity for each technology (see Table 3.1), were determined using Equation (2) and Equation (3), respectively. Life cycle emissions for electricity generation technologies can be organized into three categories: Infrastructure: both the construction and decommissioning of a plant; Fuel: from extraction of the raw source for generation to the gate of the power plant; and Generation: operation and maintenance of the plant including emissions released from fuel consumption [54]. Therefore, the life cycle GHG equivalent emissions factor per unit energy for each technology ($_t$) is the sum of infrastructure ($Em_{t,Infrastructure}$), fuel ($Em_{t,Fuel}$) and generation ($Em_{t,Generation}$) emission intensity factors as shown in equation 2, with units of life cycle emissions amortized per unit of electricity generated (g CO_2e/kWh).

$$Life\ Cycle\ GHG\ Emissions\ (LCE) = Em_{t,Infrastructure} + Em_{t,Fuel} + Em_{t,Operations} \quad (2)$$

Table 3.1: Life Cycle Unit Emissions by Life Cycle Category

Technology	$Em_{t,Infrastructure}$ g CO_2e/kWh	$Em_{t,Fuel}$ g CO_2e/kWh	$Em_{t,Generation}$ g CO_2e/kWh	LCE g CO_2e/kWh
Nuclear	27.3 [83]	23.6 [83]	41.9 [83]	92.8
Natural Gas	1.9 [86]	105.5 [83]	443.7 [83]	551.1
Hydroelectric	10.0 [14]	0.0 [83]	44.3 [83]	54.3
Bioenergy	1.9 [56], [86]	70.8 [83]	36.6 [83]	109.3
Wind	33.4 [83]	0.0 [83]	4.4 [83]	37.8
Solar	48.9 [83]	0.0 [83]	4.3 [83]	53.2
Coal	3.3 [54]	80.1 [83]	1086.7 [83]	1170.1
S & DR**	29.8 [87], [88]	68.2*	0.0	98.0

*Weighted average of LCE of non-fossil fuel generation sources
** Storage & Demand Response

GHGenius is a free LCA tool that is mainly focused on transportation fuels in Canada and can also enable regional specific drill down of specific energy flows. GHGenius provided Ontario-specific emissions intensities for Fuel and Generation stages of all generation sources using the input year of 2016, the start of the temporal range of the model developed here. For hydroelectric, wind and solar, the assumption that their renewable fuel sources have negligible emissions, which was developed by GHGenius is carried into this model. There are, however, associated emissions with both construction and decommissioning creating an infrastructure impact as well as the manufacturing of generation technology creating an amortized generation impact. Bioenergy, though assumed to be carbon dioxide neutral, has fuel emissions associated with the upstream processing and transportation of the fuel stock. Although carbon dioxide emitted during bioenergy generation is considered to be net zero, other emissions such as carbon monoxide, nitrous oxide and methane are still emitted during fuel processing, i.e. farming, harvesting and transportation, creating an emission impact, which is why the bioenergy fuel process carries a value of 70.8 g CO_2e/kWh.

Similarly, life cycle cost is the sum of: Capital costs C_t, Fixed Operations and Maintenance costs $FO\&M_t,\ and$ Variable Operation and Maintenance $VO\&M_t$. The capital costs of a generation facility accounts for the infrastructure, land acquisition and establishing a grid connection. Fixed Operations and Maintenance costs $FO\&M_t$, accounts for fixed operation and maintenance of the plant, often amortized by capacity and year. Variable Operation and Maintenance $VO\&M_t$ costs are often related to the energy produced, for example the fuel of a natural gas generator. All these costs are summed and then divided by 1 plus the discount rate r to the power of the lifetime years. Then that total is all divided by the total electricity generated by a technology E_t, over its lifetime lt. The cost values used by the model were sourced from the U.S. Energy Information Administration as utilized in its Annual Energy Outlook [89] as it provides cost analysis and breakdown into capital, fixed operation and maintenance and variable operation and maintenance for all electricity generation technologies except storage. Energy storage is quickly growing market share through a variety of technologies such as pumped hydro, flywheel, compressed air, and several types of battery chemistries. For the life cycle cost factor of Storage and Demand Response an average of all technologies was taken from Schmidt et al. [90].

$$Life\ Cycle\ Cost\ (LCC) = \frac{\sum_{t=1}^{lt} \frac{C_t + FO\&M_t + VO\&M_t}{(1+r)^{lt}}}{\sum_{t=1}^{lt} E_t} \qquad (3)[89]$$

*Table 3.2: Amortized Life Cycle Unit Costs by Expense Type**

Technology	C_t (\$/MWh)	$FO\&M_t$ (\$/MWh)	$VO\&M_t$ (\$/MWh)	LCC (\$/MWh)
Nuclear	67.0	12.9	9.3	90.1
Natural Gas	15.5	1.3	30.3	48.1
Hydroelectric	56.7	14.0	1.3	73.9
Bioenergy	40.3	15.4	45.0	102.2
Wind	33.0	12.7	0.0	48.0
Solar	48.2	7.5	0.0	59.1
Coal**	84.0	9.5	35.6	130.1
S & DR***	-	-	-	150.0 [90]

*All values from [89] unless otherwise stated
** With 30% carbon capture and storage
*** Storage & Demand Response

Although Ontario specific cost studies have been completed in the past, they have not included all technologies or supplied the level of costing data that the EIA study provided. The EIA values were selected over the incomplete Ontario values to ensure that all technologies were evaluated equally using the same analysis procedures. These other

Ontario studies are utilized in section 3.6 Model Validation, to validate the model and costing values used. In the later section, EIA cost values and historical generation values are used to compare the model results to other studies.

There are several options for energy storage including batteries, flywheel, compressed air, and pumped reservoir, each with varying benefits and impacts. Currently, Ontario has 835 MW of storage and demand response, which span all the categories. Therefore an average cost of storage was taken from a recent journal article [90], which examined the cost of common electricity storage technologies which have been implemented at grid level. Table 3.3 provides the unit life cycle factors for each technology as taken from previously shown Tables 3.1 and 3.2, then converted to similar base units. The 30% carbon capture and storage is based on the source [89] assumptions for life cycle unit costs of coal and are matched for the life cycle unit emissions by applying a 30% reduction to the generation unit emissions. This 30% reduction also aligns with Canada's *Reduction of Carbon Dioxide Emissions from Coal-fired Generation of Electricity Regulations* for new and existing coal generation [91].

Table 3.3 Summary of Life Cycle Unit Emissions and Life Cycle Unit Cost of Electricity Supply Options

Technology	**Life Cycle Unit Emissions (kg CO_2e/MWh)**	**Life Cycle Unit Costs ($/MWh)**
Nuclear	92.8	90.1
Natural Gas	551.1	48.1
Hydroelectric	54.3	73.9
Biofuel	109.3	102.2
Wind	37.8	48.0
Photovoltaic Solar	53.2	59.1
Storage & Demand Response	98.0	150.0
Coal*	884.1	130.1

* With 30% carbon capture and storage

The capacity factor of an electricity generation technology (CF_t) is an important component when deciding how much capacity should be installed to be able to meet future electricity demand. Capacity factor is the ratio of the amount of electricity generated by a technology in a year ($E_{t,yr}$) compared to the installed capacity of the generation technology over that same time period ($P_{t,yr}$) multiplied by the length of the time period (one year = 8760 hours). For the model, the temporal lens of one year was chosen as it aligns with the historic and forecast capacities and provides an adequate resolution of results to support near and mid term analysis. A larger time step of 5 years would show larger increases in selected technology capacities and may miss key infrastructure events, such as the nuclear shutdowns and refurbishment in Ontario. Also, since a higher resolution of data than 5 years exists this should be leveraged by the model to more detailed outputs. Next the annual capacity factors were calculated for each technology based on historical data from the past 5 years. Then these annual technology specific capacity factors were averaged to be used for forecasting installed generation since annual generation can vary from year to year. For example, local wind speeds may not always be high enough to rotate the blades of a wind turbine, therefore if wind generation is observed at a higher temporal lens of a year and taken as a provincial average, an estimate of the capacity factor for similar new wind generation installation can be determined. This is only an estimate for the province, and it could be possible for the capacity factor to be above or below this value, depending on the resource availability at the chosen location. The Capacity Factors of all electricity generation technologies were calculated using historical installed capacity and annual electricity generation data from the IESO [92] and Equation (4). Following the equation, table 3.4, below, lists the determined capacity factors for each generation technology that were utilized by the model. The capacity factor of storage and demand response is an exception to this method, instead it was calculated to be able to cover the peak electricity periods for the year. For this model peak electricity demand is assumed to account for roughly 6 hours every workday, which works out to 17% for the year. Therefore, the storage and demand response generation resource was assumed to be available during this peak period.

$$CF_t = \frac{\sum_{yr=2014}^{2019} \left(\frac{E_{t,yr}}{P_{t,yr} \times 8760} \right)}{(2019 - 2014 + 1)} \tag{4}$$

Table 3.4: Determined Capacity Factors by Technology

Technology	Capacity Factor (%)
Nuclear	81
Natural Gas	13
Hydroelectric	49
Biofuel	12
Wind	28
Photovoltaic Solar	15
Storage & Demand Response	17
Coal	14

It is also important to note that natural gas, biofuel and coal have relatively low capacity factors when based off of historical generation. In reality, both of these technologies are capable of higher availability, upwards of 85% for natural gas and 80% for biofuels [89]. This will be further discussed in the results chapter when this issue is relevant.

3.5 Life Cycle Factor Validation

The historical annual life cycle impacts needed to be determined both to validate the model as well as to provide a benchmark to compare future alternate scenario against. Using historical electricity generation data from the IESO [92], which provides the total annual electricity (E_t) generated for Ontario broken down by generation technology. The technology electricity generation was then multiplied by the previously determined respective life cycle emission and cost factors, found in table 3.3, to determine the annual life cycle emissions and costs for each technology (Eq. 5). Next, all technology life cycle impacts were summed for an annual grid-wide total. These historical annual totals were then used to add context to future scenarios and to validate the model against values found in literature.

The previous calculated historical annual life cycle costs and life cycle emissions from 2003 to 2018 were plotted and are shown below in Figure 3.2 and Figure 3.3. The life cycle cost has decreased slightly from the early 2000s with a maximum value of 14.6 B$ CAD which occurred in both 2005 and 2007 and reached a minimum in 2017 at 12.3 B$ CAD. Over the same time period, the annual life cycle emissions have decreased by almost 80% from 49 Mt CO_2e in 2003 to 9.3 Mt CO_2e in 2017.

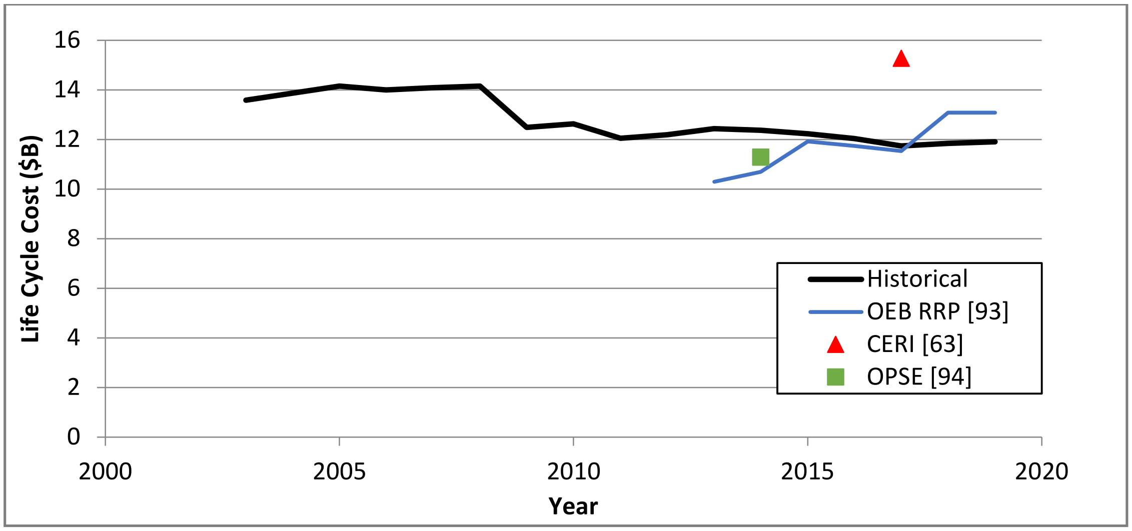


Figure 3.2: Ontario Annual Historical Life Cycle Costs from 2003 to 2018 in Comparison to Three Other Studies

Similarly, the historical annual life cycle costs generated by the model method were compared against other cost assessments of Ontario's electricity system, which has been visualized in Figure 3.2 in comparison to other sources [63], [93], [94]. The OEB has regularly generated a Regulated Price Plan (RPP) report since 2005 [93]. As of 2013 the report also included a section specifically dedicated to supply cost. However, these costs are not broken down into types of cost for each technology, simply a technology cost per electricity generated and therefore less suitable for this model as it would offer less transparency. The technology specific unit costs extracted from these reports have been multiplied against historical generation values to determine system costs and plotted with the historical model results in Figure 3.2, labeled OEB RPP. Although slightly divergent at first, the OEB RPP and historical lines draw closer and over the past couple years have crossed. Similarly, other electricity cost studies have been completed [63], [94] for Ontario and have also been plotted with the historical values generated by the model. These cost studies used to validate the model show a larger percent difference than the studies used to validate emissions; however, the scope of costs considered in these studies are loosely defined in comparison to the in-depth inventories of the life cycle emission cases. Costs vary far more than emissions due to market conditions, such as availability of technology and fuel. The fact that the model has produced results based on historical generation that fall within the range of other studies' results shows that it is a reasonable representation of system costs.

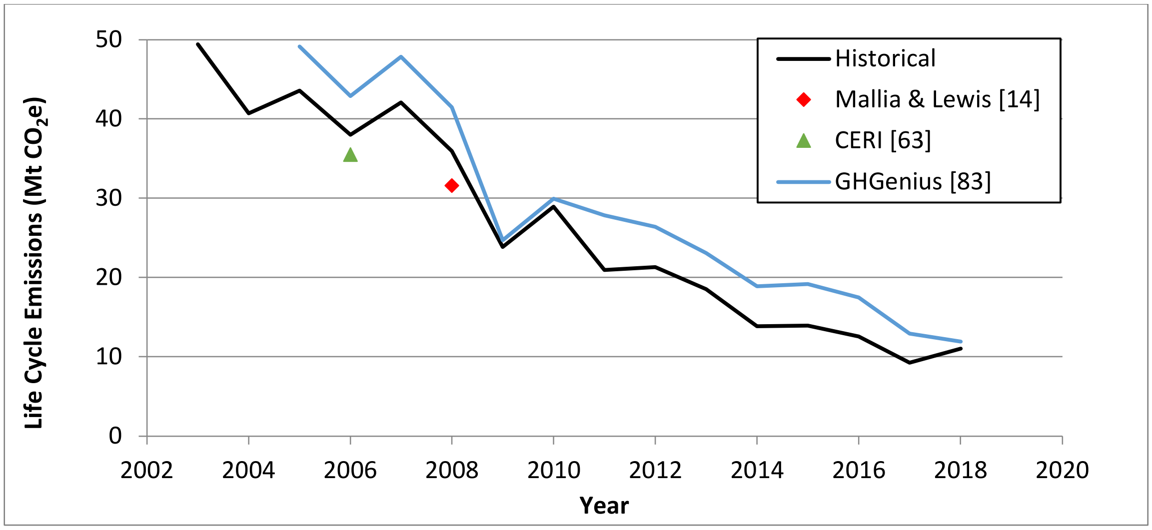


Figure 3.3: Ontario Annual Historical Life Cycle Emissions from 2003 to 2018 in Comparison to Two Other Studies

In comparison to Mallia & Lewis [14], who found that Ontario's life cycle electricity emission intensity was 201 t CO_2e/GWh for 2008, the model used here determined Ontario's life cycle electricity emission intensity to be 226 t CO_2e/GWh, in 2008. This value was converted to Mt CO_2e and plotted on Figure 3.3 for comparison. The difference can be explained by two main reasons. Firstly, the level of analysis that Mallia & Lewis observed electricity generation was at the individual generating station level. Their analysis segregated generation by both fuel type and cycle type, where corresponding data was available, whereas the model herein utilizes provincial level data and analyzes by technology type, which assume a single cost and emission factor for each technology. The life cycle factors used by the model, as seen in table 3.3, are higher than those found in Mallia & Lewis's study, which can be found in table 2.2. Secondly, the electricity generated by generation type, which was used to calculate the model capacity factors seen in table 3.4, and those factors determined by Mallia & Lewis differ slightly for 2008. For example, Mallia & Lewis estimated that coal produced 23.1 TWh, hydroelectricity generated 37.8 TWh and nuclear generated 83.3 TWh. In comparison, the IESO reported historical values that were used by the model of 23.2 TWh for coal, 38.3 TWh of hydroelectricity and 84.4 TWh of nuclear produced electricity. With these higher values being used by the model, it is expected that the model-calculated emission intensity would be higher than the article value but remains close enough to validate the model. Specifically, the percent difference in electricity produced is 2.6%. This difference combined with the factor of higher life cycle values used by the model result in a percent difference of 12% for 2008 emissions.

Similarly, the Canadian Energy Research Institute (CERI) prepared a report for the Canadian Nuclear Association in 2008 titled *Comparative Life Cycle Assessment (LCA) of Base Load Electricity Generation* [63]. In this report, CERI provides a comparative LCA on nuclear, natural gas and coal generation using data from 2005 and 2006. They found that the three explored electricity generation sources were responsible for 33.7 Mt CO_2e of annual life cycle emissions and contributed 116.3 TWh of Ontario's 156 TWh of electricity generation. Hydroelectric generation, which was not considered in the study, contributed 34.8 TWh in 2006 [28]. To provide a fair comparison the life cycle emission factor from table 3.3 was used to convert the historical value and therefore the annual life cycle emission contribution of hydroelectric in 2006 was determined to be 1.8 Mt CO_2e. In 2006, approximately 2 TWh of generation came from other renewable sources (i.e., solar, wind, and bioenergy); however, technology-specific historical data for these generation sources is not available as they were producing less than 1 TWh. Since the historical values of these technologies are so low, they were combined with natural gas in historical generation records as another source of generation. Therefore, the natural gas annual life cycle emissions are increased due to this added generation from other small sources. Combining the CERI annual life cycle emissions with the determined hydroelectric annual life cycle emissions results in a value of 35.5 Mt CO_2e for 2006. Comparing this to the 38.0 Mt CO_2e for 2006 as determined by the model results in a 6.6% difference in values.

The final comparison for emission validation was done using values from GHGenius. Some of the emission data used by the model is based on values from GHGenius [83] which is reflected in the similarity of both the GHGenius and model historical trendlines of Figure 3.3. However, GHGenius results remain slightly higher. This difference is because annual energy results vary between what the IESO reported [28], which was used by the model, and what GHGenius has factored. In this case, GHGenius carried higher energy generation values. A good example of this is to look at the years 2010 and 2011. In 2010, both GHGenius and the model have a total annual generation of 150.8 TWh, which results in system emission ouputs of 29.9 Mt CO_2e and 28.9 Mt CO_2e due to slight differences in life cycle emission factors. Although the life cycle emission factors of the model are based on some of the values retrieved from GHGenius, there are some differences for the infrastructure related emissions. Specifically, coal and natural gas are lower within the model than GHGenius because of the carbon capture assumed for coal and the higher efficiency assumed for natural gas generation based on the recent federal regulations [91]. In 2011, as a comparison, GHGenius used 153.2 TWh for total annual electricity generaion while the model used 149.8 TWh, creating a difference of 6.9 Mt CO_2e between the output from the model of 20.9 Mt CO_2e and GHGenius result of 27.8 Mt CO_2e.

Uncertainty analysis was also performed on the historical data to further validate the results achieved by the model in this thesis. The uncertainty analysis was performed on the life cycle emission and life cycle costs factors from table 3.3 that were used as inputs by the model. Life cycle values, seen in table 2.2, that were found during the literature review were collected and compiled by generation technology. Next the mean, standard deviation and standard error were determined for each generation technology. The technology specific standard error values were then applied to the respective technology life cycle factors as a plus-minus to create an upper and lower uncertainty bound. The model was then rerun twice across the historical generation using the lower bound values for all technologies, then again using the upper bound values. These results for historical system life cycle emissions and system life cycle costs were then plotted with the historical data, shown in Figure 3.4 and Figure 3.5 respectively. These figures show the historical reference line and the area of uncertainty in gray.

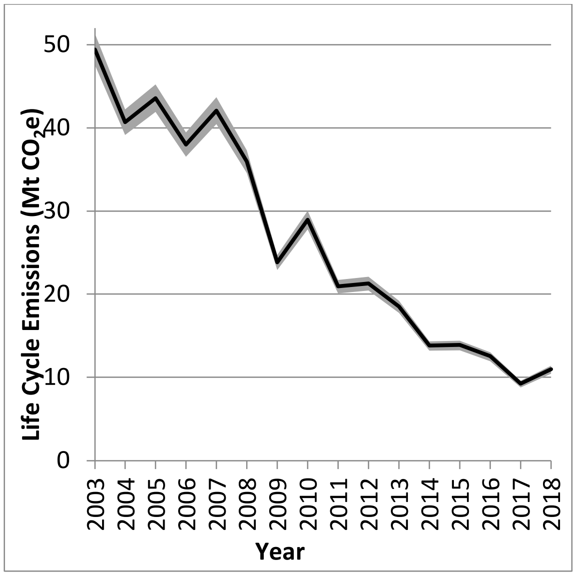


Figure 3.4: Uncertainty Analysis of Life Cycle Emissions

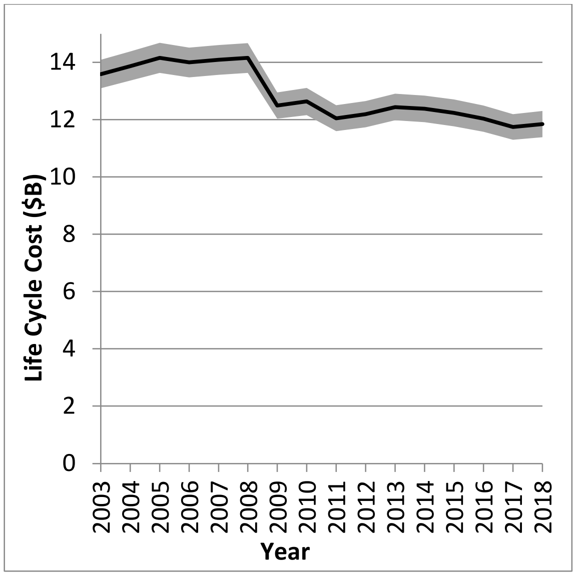


Figure 3.5: Uncertainty Analysis of Life Cycle Costs

With regards to uncertainty analysis of the model for the historical life cycle emissions of Ontario's electricity generation, shown in Figure 3.4, the area of uncertainty has a wider breadth at the beginning of the time horizon and narrows as it approaches more recent years. This taper is due to two main factors, the reduction in the amount of fossil fuel generation and the increased accuracy of annual electricity generation records. At the start of the historical time horizon almost a third of Ontario 152 TWh of generation came from coal and natural gas generation. With regards to life cycle emission factor these two sources have significantly higher emissions per unit of electricity generation. Due to these high factors and a larger spread of life cycle emission factors as depicted in table 2.2, the standard error of both coal and natural gas are larger than the mean values for nuclear, hydroelectric and wind. This relatively high standard error results in a larger area of uncertainty when larger amounts of these fossil fuel generation sources are implemented.

Also, newer renewable generation sources, such as wind, solar, and bioenergy were not independently tracked until 2008 and were lumped together with natural gas as other sources of generation prior to that year. The increase in detail of historical electricity generation assisted in further narrowing the area of uncertainty since renewable technologies have smaller life cycle emission factors and relatively smaller standard error.

The uncertainty analysis of the historical life cycle costs of the electricity generation in Ontario, shown in Figure 3.5, shows a relatively even area of uncertainty along the historical time horizon, 2003 to 2018. Though it may appear to have a larger area of uncertainty, in comparison to the previously discussed life cycle emissions chart, the area is relatively similar, but simply distorted by the shorter y-axis. The interesting point of note for Figure 3.5, is the change between 2008 and 2009. 2008 was Ontario's highest annual demand on record of over 159 TWh, followed by a drop of 10 TWh the following year. The additional insight that this uncertainty analysis provides is the fact that the lower bound of 2008 is still well above the upper bound of 2009. This means that despite the uncertainty, one of the most effective ways to reduce system life cycle costs is to reduce demand.

3.6 Reference Scenario (S.Ref)

The first future scenario is the reference scenario (S.Ref), which is based on the reference scenario in the IESO's Ontario Planning Outlook [15]. The forecasted annual installed capacity of this reference scenario was broken down into four categories: Existing Capacity, Committed Capacity, Directed Capacity and Expiring Contracts. Each was further divided in the IESO's report [15] into generation technologies: nuclear; natural gas; hydroelectric; bioenergy; wind; solar photovoltaic (PV); and storage and demand response. It is important to clarify here that storage and demand response as a resource does not generate electricity, rather it acts as a means of reducing generating capacity and transmission strains. This resource was carried with all the other generation technologies from the IESO as it provides benefits to the system, especially when paired with intermittent generation sources. Existing Capacity is the installed generation capacity that is currently producing electricity and receiving payments. Committed Capacity is a resource that has been given a contract or won a capacity auction to supply electricity, though not in service yet. Directed Capacity is the generation that is proposed to be installed in the future and is guided by competitive programs or government programs, for example the Large Renewable Procurements (LRP) or FIT. Finally, Expiring Contracts are capacity that has reached its commercial term with the IESO; however, if this capacity is not at its end of life it could continue to generate electricity for IESO either through capacity auction or participating in the electricity market. This capacity breakdown allows for the life cycle factors, both emission and cost per unit of electricity, to be applied to the respective technologies. As well, alternate scenarios (Section 3.8) are implemented by replacing the Directed and Existing Capacities of the reference scenario with generation capacities that meet the scenario's preferences.

Annual electricity generation ($E_{yr,t}$: TWh) was calculated for each technology (t) by first summing the Existing Capacity, Committed Capacity, Directed Capacity and Expiring Contracts, found in the Ontario Planning Outlook [15] to find the annual installed generation capacity ($P_{yr,t}$: MW). Second, the forecast capacities $P_{yr,t}$, which can be broken down by generation technology (t), are then multiplied by the respective technology capacity factor, determined in table 3.4, and hours per year to determine the annual electricity generation. Third, it is converted to terawatt-hours (TWh).

$$E_{yr,t} = \frac{P_{yr,t} \times 8760 \times CF_t}{10^6} \tag{5}$$

Technology-specific emission factors from previous model development [76] and cost factors from the EIA [89], as seen in Table 3.3, are used to convert annual electricity generated to annual life cycle emissions (LCE_{yr}) and annual life cycle costs (LCC_{yr}). This method utilizing equations 5 and 6 is depicted schematically in Figure 3.6, and shows the interconnects between model inputs, technology specific calculations and model outputs.

$$LCE_{yr,t} = E_{yr,t} \times LCE_t \qquad LCC_{yr,t} = E_{yr,t} \times LCC_t \tag{6}$$

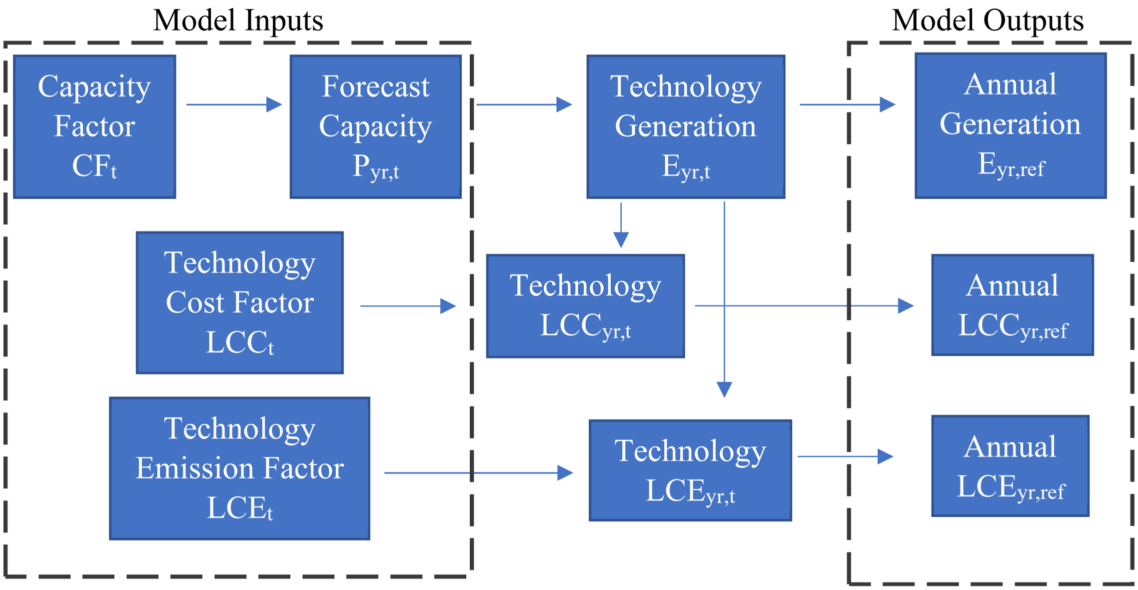


Figure 3.6: Model Reference Scenario Calculation Process Diagram

This reference scenario is a business-as-usual scenario assuming the IESO OPO [15] forecasted capacities for each technology. This reference scenario also assumes that life cycle impacts remain static throughout 2016 to 2035, although it is likely through technological advances that efficiencies could be improved, reducing life cycle impacts and therefore the results generated are likely conservative. Results for this baseline scenario are found in Section 4.1 and show expected results based on the assumed future capacities and life cycle impacts as defined previously.

3.7 Alternate Scenarios

In preparation for exploring alternative scenarios, the reference case annual electricity generation of all seven technologies was totalled and stored for future reference ($E_{yr,ref}$) as shown in Equation 7. This value will be used as the required demand that alternate scenarios will aim to achieve through a combination of electricity generation technologies.

$$E_{yr,ref} = \sum_{t=1}^{7} E_{yr,t} \tag{7}$$

Next, the annual electricity generation for each technology was recalculated, using only Existing and Committed Capacities found in the Ontario Planning Outlook because these capacities are currently in use or will arrive in service soon. Similar to the reference case, the sum of technology-specific capacity is then multiplied by the respective capacity factor to find the annual electricity generation, see Equation 5b.

$$E_{yr,new,t} = \frac{\left(P_{yr,Exis,t} + P_{yr,Comm,t}\right) \times 8760 \times CF_t}{10^6} \tag{5b}$$

All electricity generation was then summed, as described above, to find a new total annual generation ($E_{yr,new}$), based on only the Existing and Committed Capacities.

$$E_{yr,new} = \sum_{t=1}^{7} E_{yr,new,t} \tag{7b}$$

$$E_{yr,redis} = E_{yr,ref} - E_{yr,new} \tag{8}$$

The difference between the new annual electricity generation and the stored reference annual electricity generation ($E_{yr,redis}$) was determined, using equation 8, and redistributed, to technologies in a one terawatt-hour per iteration process following scenario-specific criteria, until the total annual electricity generation of the new scenario was equal to the stored reference value. One terawatt-hour was selected as it equates to between 140 MW and 990 MW depending on the technology. Starting in 2004, the IESO has on average contracted 1.8 GW of capacity, annually [95]. This shows that the one terawatt-hour iteration is an appropriate loop scale as it is well with the IESO's ability to procure. At the end of the time horizon a large amount of generation will be assigned as more existing generation sources reach their end of life, however it is expected to be addressed gradually throughout the time horizon. Even though the model does not carry over assigned capacity, the amount of assigned generation in the final year of the analysis will not be expected to all be installed that year, as previous years will have already assigned generation building up the capacity. As an example, if the scenario-specific criteria were to reduce the life cycle emissions of the system, then, in each iteration the model would determine the technology with the lowest life cycle emission and assign one terawatt-hour. The process would repeat following the logic depicted in Figure 3.7 until the scenario meets the required annual demand, $E_{yr,ref}$.

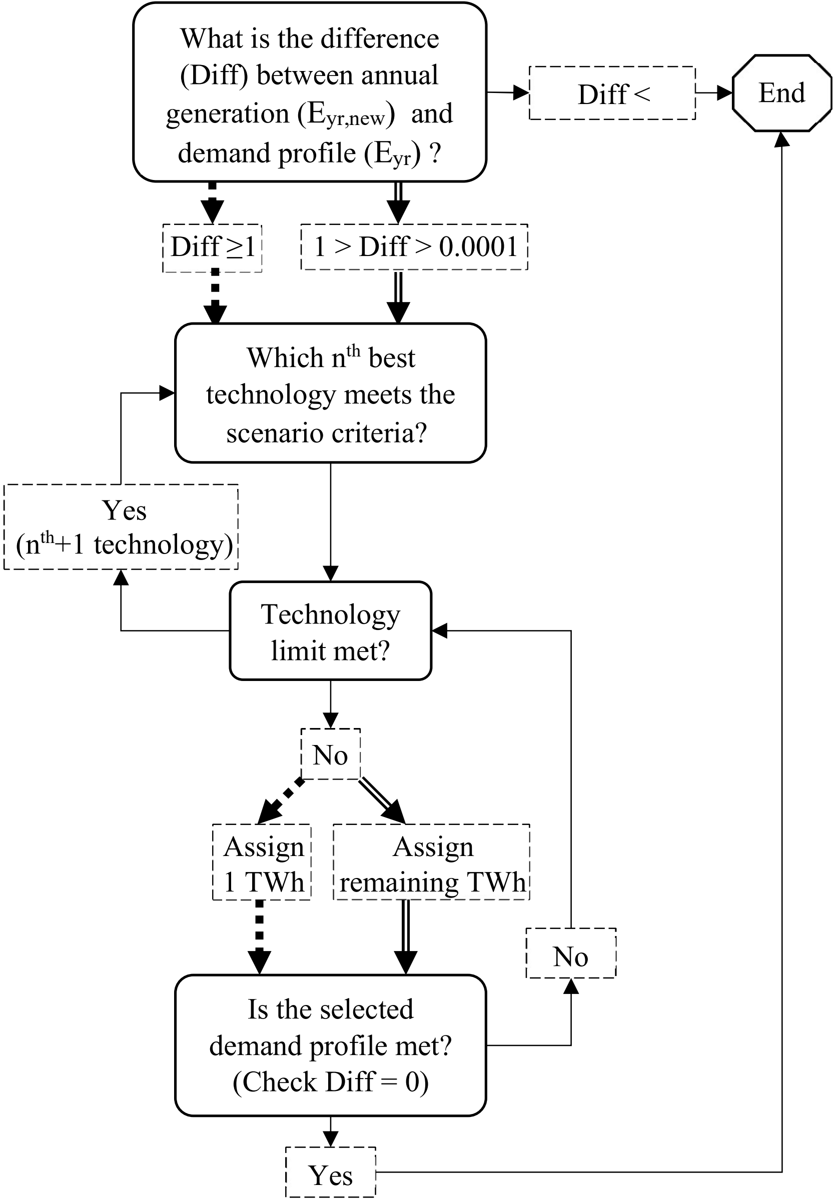


Figure 3.7: Logic Diagram for a Single Year of an Alternate Scenario for the nth Best Technology Selection, Starting with n=1. Dashed Line Path used when 1 TWh can be Assigned, Double Lines are used to Indicate when Assigning less than 1 TWh of Generation.

Further discussed in section 3.8.2 it is noted that in Ontario there are technology specific capacity limits to its electricity supply and therefore as part of the iteration process a logic gate is used. If the technology selected by the scenario criteria has reached its provincial limit, then the logic gate fails and the next technology is selected, else generation is assigned. For alternate demand profiles, as described in Section 3.8.7, an annual demand from the IESO's Ontario Planning Outlook [15] would replace the reference total annual generation. Once the required annual electricity generation is met, the technology specific annual generation is converted to life cycle impacts as shown in Figure 3.8.

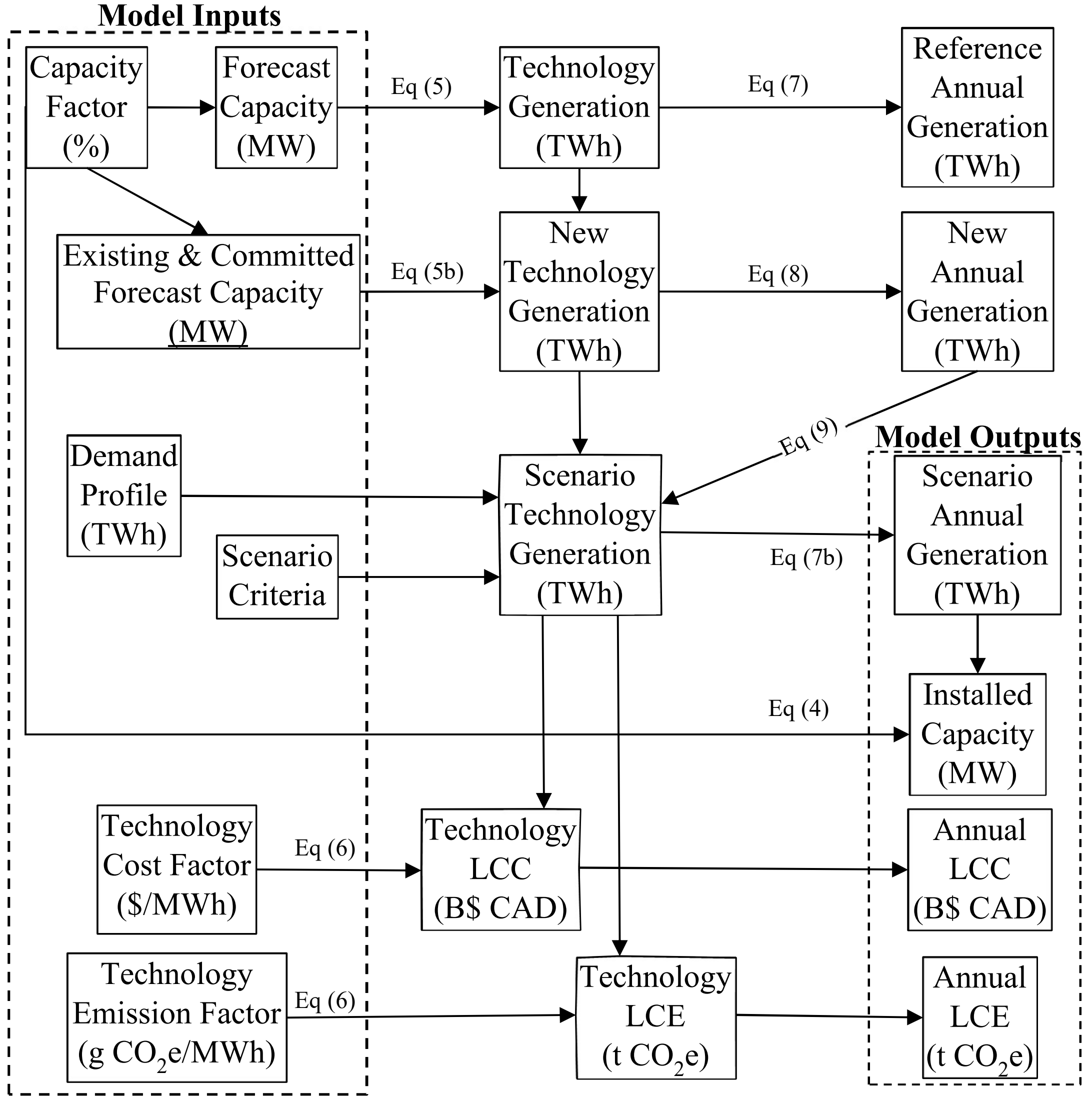


Figure 3.8: Process Flow of Alternate Scenario Model with Equation Notation

3.8 Scenario-Specific Criteria

The following subsections provide an overview and justification of the various scenarios explored in this thesis. Although the model can explore numerous different scenarios, the examined scenarios of this thesis are focused on investigating how to increase the sustainability of the Ontario electricity system by reducing life cycle emissions and life cycle costs. The goal of these scenarios is to provide information on the long-term sustainability of Ontario's electricity supply through a dual life cycle lens, observing both economic and environmental sustainability. These scenarios are not an attempt to generate a realistic forecast of future electricity supply in Ontario, as there are an infinite number of future possibilities. Instead, these scenarios will be used to collect useful information on the life cycle performance of individual technologies, combinations of technologies and options for the future. To accomplish this, first each technology is examined in the technology preference scenario to determine if any technology is an outlier relative to the rest of the technologies, either providing significant improvement or hinder the system by decreasing or increasing, respectively, the annual life cycle impact. Next the scenarios in which the model prioritizes minimizing life cycle impacts when assigning new generation are completed to create low life cycle emission and low life cycle cost scenarios. The goal of these life cycle prioritization scenarios is to observe the change that could be achieved if this factor was utilized when adding new generation. It also allows for observation of the effects on the secondary life cycle impacts when minimizing the primary life cycle impact.

Table 3.5 gives a brief overview of all the scenarios explored in this thesis, arranged by appearance. The table provides the objective function which outlines the logic utilized by the model to complete the scenario. The purpose provides an answer about why these scenarios were explored and the brief description adds additional detail that supports the objective function and purpose.

Table 3.5: Scenario Overview with Objective Function, Purpose, and Brief Description for each Scenario Explored

Scenario Name (Short Name)	**Objective Function**	**Purpose**	**Brief Description**
Reference (S.Ref)	Create a baseline, business as usual scenario	Define method and calculations of the model	Utilizing forecasted capacities found in the Ontario Planning Outlook [15], combined with historical capacity factors of electricity generation technologies, the annual electrical energy generated by the province can be determined, followed by the annual life cycle emissions and life cycle costs of the system. To create a baseline of life cycle results.
Technology Preference (S.Tech)	Assign all necessary generation to a single technology	To explore an extreme case to help bound other scenarios	Evaluate each technology’s ability to meet demand gap and its related impact on system life cycle emissions and costAssuming existing installed capacity remains in service, generation needed to meet forecast demand will be met by a single technology.

Scenario Name (Short Name)	Objective Function	Purpose	Brief Description
Technology Preference w/ Limits (S.Tech.Lim)	Assign all generation to a single technology until demand or technology limit is met	To explore an extreme case to help further bound the other scenarios, by also considering provincial resource limits	Evaluate each technology's ability to meet demand gap and its related impact on system life cycle emissions and costAssuming existing installed capacity remains in service, generation needed to meet forecast demand will be met by a single technology while considering provincial resource limits.
Life Cycle Cost Prioritization* (S.LC.Cost)	Minimize annual life cycle costs of the system	Reduce life cycle cost of the system and observe the resulting impact on the life cycle emissions	Required generation to meet forecast demand above the existing installed capacity will be selected by the model to minimize life cycle costs of the system while considering provincial resource limits.
Life Cycle Emission Prioritization* (S.LC.Emsn)	Minimize annual life cycle emissions of the system	Reduce life cycle emissions of the system and observe the resulting impact on the life cycle costs	Required generation to meet forecast demand above the existing installed capacity will be selected by the model to minimize life cycle emissions of the system while considering provincial resource limits.
Intermittent Generation and Storage (S.WinSol)	Maximize solar and wind market share	Identify maximum storage/demand response necessary to support intermittent generation sources	Assign the available demand to wind and solar. Then under the assumption that wind and solar will not be available and storage will be available during the peak annual demand, assign enough storage capacity to meet the annual peak demand.
Variable Cost* (S.VarCost)	Minimize Life Cycle Cost while considering variability of generation sites	Minimize life cycle costs while technology cost increases each time it is assigned generation	Under the assumption that the most economical option is selected first, and the cost will gradually increase with more installations as generation sites get further away or have less favourable energy resources

*Scenario utilized for alternate demand analysis

3.8.1 Technology Preference (S.Tech)

As an initial alternate scenario, the model was set up to assign the necessary electricity generation ($E_{yr,redis}$) to a single technology at a time, thus creating seven technology preference scenarios. Although it is likely unrealistic to heavily favour a single technology for all new generation, this scenario is meant to explore these extreme cases to help bound other potential scenarios. This initial scenario also ensured that the VBA model was able to prioritize and assign each technology and demonstrated an instance in which heavy technology preference is given. This drive to a specific technology could be achieved through methods such as government direction and industry support or from significant technology advancement, making a single generation type preferred over others. These scenarios also helped to develop the model further through identifying the need for limits to be placed on generation sources and for storage and demand response to be implemented in conjunction with intermittent sources. This realization led to the development of alternate scenarios as described in sections 3.9.2 and 3.9.5, respectively.

3.8.2 Technology Preference with Limits (S.Tech.Lim)

The initial model simulations using the technology preference scenarios (S.Tech) raised concerns of Ontario's electricity generation capacity for some of the energy sources, more specifically with Ontario's capacity for renewable generation sources. With regards to the limits of the installed capacity of each of the electricity generation technologies available in the province of Ontario, various studies [15], [57], [68], [96]–[98] have previously theorized practical limits of energy resources in the province. The data used by the model to limit the total annual generation of each technology is listed in Table 3.6 below. When a range is given for the capacity factor by the data source, the historical capacity factor for that technology in Ontario is used to calculate to annual generation limit in table 3.6 below. These factors were determined earlier in section 3.4, as shown in Table 3.4 and were used to calculate the technology annual generation using equation 5.

Table 3.6: Capacity Limit, Capacity Factor, Annual Generation Limit of Generation Technologies with Sources

Technology	**Capacity Limit (GW)**	**Capacity Factor (%)**	**Annual Generation Limit (TWh)**	**Source**
Nuclear	12.1	0.7 to 0.95	86	[15]
Natural Gas	N/A	0.14	N/A	[96]
Hydroelectric	9.3	0.3 to 0.7	40	[15], [68]
Bioenergy	3.6	0.56	18	[97]
Wind	26.5	0.531	123	[98]
Solar	10	0.1	9	[57]
Storage & Demand Response	5.0	0.25	44	[57]

For this thesis, nuclear technology has been limited to the current capacity of Ontario, as determined in the Ontario Planning Outlook [15], as any new nuclear power project would have longer lead times than the scope of this study. It is important to note that Ontario [99] and Canada [100] are leaders in the nuclear industry and continue to explore nuclear generation as an option for future electricity supply. Through the upcoming period of refurbishment at both the Bruce and the Darlington nuclear plants and with the eventual decommissioning of Pickering in 2025 [101], Ontario's nuclear capacity varies over the scope of the study as reactors are shut down and brought back online. This long-term planning demonstrates the level of forecasting and planning required when incorporating large scale nuclear generation into the provincial electricity supply. Conversely, with respect to natural gas, no limit is set as generation can be increased relatively quickly, either by ramping up existing generation or through the addition of new natural gas plants to add generation to growing demand areas. Although this flexibility is a strong benefit to natural gas generation, both life cycle cost and emissions are dependent on the amount of fuel consumed and, therefore, the electricity produced. Since the price of natural gas fluctuates daily, it creates uncertainty in a long-term system analysis as the price could increase due to lack of supply or decrease if new sources are found.

The renewable electricity generation harnesses energy from renewable energy sources throughout the province such as biofuels, wind, solar and water. There is a limit to these energy sources from which electricity generation at a grid scale can be produced. Ontario plans to access all feasible hydroelectricity sources by 2025, bringing the provincial total to over 9300 MW [68]. Some of these generation facilities, such as the DeCew Falls Generating Station in St. Catharines originally brought into service in 1898 or the Kakabeka Generating Station located west of Thunder Bay and originally brought into service in 1914 [70], have been in service for over a century. By implementing new technology the capacity and efficiency of these older plants can be improved [102]. Other potential generation sites are in remote northern Ontario where it was previously unfeasible. It was not until recent expansion of the electricity grid to reach remote northern communities that the electricity infrastructure was brought closer to these generation sites [103]. This yet to be harnessed hydroelectric capacity also must go through lengthy environmental impact assessments, meaning that any new hydroelectric sites that are not currently in development will likely not be operational within the time horizon of this study. For the capacity factor of hydroelectricity generation, the historical provincial average of 48.5% was used to set the limit of annual electricity generation of 40 TWh.

Bioenergy capacity has begun to grow in Ontario in recent years; however, the currently installed 295 MW is less than 10% of the 3614.6 MW maximum capacity of bioenergy in the province as estimated by Griffin and Nyboer of the Canadian Industrial Energy End-use Data and Analysis Centre [97]. This estimate of maximum Ontario bioenergy capacity is broken out into biomass and biogas, providing a maximum of 3530.2 MW and 84.4 MW, respectively. These capacities are limited by the feedstocks available, such as solid combustible by-products of the forestry industry found in northern Ontario or municipal solid waste, more common in populous areas of southern Ontario, that can create biogas through anaerobic digestion. The capacity factor of the bioenergy determined by Griffin and Nyboer using reported annual generation and capacity from a national sample of facilities was found to be 56%.

Both Solar and Wind generation have seen large growth in the province of Ontario over the past decade. Harvey's study on the potential of wind to replace both fossil and nuclear electricity generation [98] found that utilizing wind resources close to demand centres could reduce the need for traditional electricity generation methods and lower the cost of electricity. This study assumed that existing hydroelectric resources could be utilized to address supply-demand mismatches and that the province-wide moratorium on off-shore wind energy would be resolved in such a way to permit off-shore wind. Therefore, Harvey determined that 25.5 GW of wind capacity could be added to Ontario's electricity supply at a capacity factor of 53.1% based on Canadian Wind Energy Atlas data and ideal turbine selection and array spacing. This scenario could add up to 123 TWh of annual generation, enough to meet 83% of Ontario's 2019 electricity demand. Similarly, optimal large-scale integration of solar PV generation was explored by Richardson [57]. His study found that solar PV generation has a higher capacity factor and a greater ability to ramp up and down with demand when paired with battery storage, compared to solar PV alone. The study theorized that up to 10000 MW of solar PV generation and 5000 MW of storage could be added to the electricity generation infrastructure of the province.

These limits were applied to the model, and the technology preference scenarios were rerun for comparison, see Section 4.2 of the Results chapter. For the technology specific scenarios, since all new generation was focused on a single technology, some technologies will be unable to meet the reference demand on their own. These limits were also implemented for future scenarios.

3.8.3 Life Cycle Emission Prioritization (S.LC.Emsn)

The life cycle prioritization scenarios aim to explore Ontario's future electricity supply when life cycle emissions or life cycle costs are prioritized. For example, when life cycle emissions are prioritized, the model assigns a terawatt-hour of electricity generation to the technology with the lowest emission factor. The model iterates until the required electricity supply is met or the selected low life cycle emission technology reaches its provincial generation capacity limit. If the technology electricity generation eventually equals the technology's respective limit, the model finds the next lowest life cycle emission technology and continues to iterate, as previously seen in Figure 3.7. This scenario aims to emulate a future in which both public policy and energy stakeholders prioritize decarbonization.

3.8.4 Life Cycle Cost Prioritization (S.LC.Cost)

Similarly, if low life cycle cost is prioritized, the model assigns a terawatt-hour of electricity generation to the technology with the lowest life cycle cost factor. Economic sustainability is prioritized in this scenario with the goal of making electricity more affordable. Although it is the electricity plant operators who will bear the life cycle costs of generation, the competitive market Ontario has created is a system that favours lower cost generation. If the market becomes saturated with available generation the cost will be driven down through competition. If a long-term pattern of low-cost electricity generation occurs the savings of low purchasing costs can be passed to the consumers through provincial price reduction. Again, this savings adjustment would require both public policy and energy stakeholders to prioritize reducing life cycle costs of the Ontario electricity supply.

The model was further developed to allow user input to allocate the percentage of generation to each life cycle factor. This modification allows for experimentation through blending prioritization of both life cycle factors. It is likely that future grid mixes will require a balance between emissions and cost as jurisdictions continue to limit their emissions and continue to strive to provide affordable electricity to meet the growing demand.

3.8.5 Intermittent Generation and Storage (S.WinSol)

When introducing renewable technology into an electricity system, there are often concerns of intermittency, specifically from wind and solar. This thesis does not address the effects of weather variance on the amount of electricity generation from these sources, as it observes the energy converted by these technologies on an average annual basis. The motivation of this scenario is to explore the need for storage and demand response when heavily selecting intermittent renewables. This scenario evenly distributes required electricity generation ($E_{yr,redis}$) between wind and solar, unless a technology reaches its limit, in which case the remaining generation is assigned to the other technology. The model then allocates enough storage to meet forecasted peak energy demands, assuming a worst-case scenario of no solar or wind generation during peak demand. This leaves Ontario's existing baseline generation of nuclear and hydroelectric as well as any existing bioenergy and natural gas capacity to be called upon to meet the peak demand, with the difference being made up by storage and demand response capacity. The scenario primarily aims to explore the limitations of variable generation sources and secondarily, aims to understand the need for storage and demand response to support intermittent sources in meeting future peak demands.

To determine the amount of storage and demand response required, the forecasted technology capacities, excluding solar and wind, are summed and compared to the peak demand forecast from the IESO's Ontario Planning Outlook [15]. If the model does not have sufficient capacity to meet peak demand, then the deficit amount is added to the storage and demand response to enable the scenario to meet the respective peak demand. The storage and demand response costs and emissions are then calculated, using Equation (6), and annual totals for that scenario are recalculated. For this scenario this consideration is likely to be utilized by decision-makers when the model selects large amounts of wind and solar, both heavily intermittent generators, that cannot be relied upon to be generating when Ontario is peaking, hence the need for additional storage and demand response..

3.8.6 Variable Cost (S.VarCost)

Life cycle costs of each electricity generation facility will not be the same, when comparing between facilities of the same generation type. The previous scenarios of this thesis assumed life cycle costs to be static for all generation added in the forecast calculations. Costs of electricity generation can be highly variable; in some cases, economies of scale or continual improvements by learning from experience may be able to drive the cost of additional generation down. Conversely, as more generation is allocated, less desirable sites will have to be utilized, which would increase transmission length and line loss as well as possibly decreasing the amount of electricity generated. For example, the development of a hydroelectric generating station in northern Ontario will be significantly more resource and cost intensive than building the same facility in southern Ontario, due to shipping of material, site development, and restricted by a shortened construction season. All these factors would decrease the total electricity delivered, increasing the life cycle cost of the assigned technology. Therefore, it is assumed that the most economical choice for the assigned technology generation will be implemented first. Then the life cycle cost of the technology selected will exponentially increase after each terawatt-hour is assigned until the demand profile is met, while considering provincial technology limits.

Sensitivity analysis on the percent change per TWh assigned for the variable cost life cycle cost prioritization scenario was also completed for a range of values from negative five percent to fifteen percent. Whereby the values [-0.05, -0.02, 0.02, 0.05, 0.1, 0.15] were used as inputs and the scenario was run for all 6 cases, recording all output values each time. These results are depicted in section 4.7 to show the spread of the values against the reference scenario for comparison.

3.8.7 Alternate Demand Profiles

All of the alternate scenarios were additionally run across three different demand profiles: low, medium and high from the Ontario Planning Outlook [15], with the reference demand falling in between the low and medium demand profiles. The OPO [15] outlines the assumptions utilized to create the 2035 demand for each profile, which are compared to the reference demand hereafter. The low demand profile estimates annual electricity use of 133 TWh in 2035, which will require large conservation efforts, in comparison to the

143 TWh consumed in 2015. Consumption reductions in the residential, commercial, and industrial sectors would be required to lower the annual consumption of these sectors from 138 in 2015 to 126 TWh in 2035. The medium demand scenario will reach 177 TWh in 2035 through growth in electricity demand across all sectors. The demand profile assumes: 25% of the gas market share for both residential and commercial heating will be replaced by electric alternatives; 5% of industrial fossil energy processes will change to electric equivalent; 2.4 million electric vehicles will be in use by 2035, consuming 8 TWh compared to less than 1 TWh in 2015; and 1 TWh of planned projects in the transit sector. The high demand profile holds similar assumptions to the medium demand profile with twice as much electrical conversion in the residential, commercial, and industrial sectors, i.e., 50%, 50%, 10%, respectively, generating an electricity demand of 197 TWh by 2035.

These alternative demand profiles are used in place of the reference scenario previously utilized. Therefore, in Equation (9), instead of $E_{yr,ref}$ being used to find the amount of electricity generation to be redistributed, the corresponding annual electricity demand from the selected demand profile will be used instead. Then, the model follows the scenario specific criteria to assign generation to meet the relevant demand profile and iterates until all annual demands are met up to 2035.

3.9 Summary of Methodology

In summary, first historical installed generation capacity data from the IESO [28], along with technology capacity factors calculated from historical electricity data and life cycle factors of electricity generation technologies, were used to determine Ontario's historical life cycle impacts. This historical analysis was used to validate the model method against other recent studies and publications [14], [93], [94], [104]. Then the reference scenario (S.Ref), using the same method, was determined using forecast capacity data from the OPO [15] to create a future baseline of system life cycle impacts. Next alternate scenarios were explored by removing Directed and Expiring technology capacities from the OPO forecasts, which then allows for scenario criteria to be used to select technology to meet the required electricity demand. The first alternate scenario explores technology preference (S.Tech), which aims to investigate if a single technology can meet Ontario's future electricity needs. This initial scenario raised concerns about provincial energy resources and so provincial limits were determined and implemented in the model. This technology preference scenario was then rerun with the new limits as a comparison (S.Tech.Lim). Next, prioritizing life cycle factors when selecting new generation technologies to be implemented was considered, while considering the previously discovered provincial technology limits. For the two main cases of the life cycle prioritization scenarios the life cycle emissions (S.LC.Emsm) and life cycle costs (S.LC.Cost) are each used to select new generation in respective scenarios. Next, the intermittent generation of wind and solar was explored as well as the required storage and demand response in order to meet forecasted annual peak demand (S.WinSol). This was followed by, variably increasing the life cycle cost of new generation when prioritizing life cycle costs, under the assumption that the most economically effective generation will be selected first and further assigned generation will degrade economically as energy resources within the province are consumed (S.VarCost). Finally, alternate demand profiles are considered across several previous scenarios.

Chapter 4. Results and Discussion

In this chapter the results produced from the model are presented and discussed. The chapter first shows the reference scenario life cycle emissions and cost in comparison to historical values. It also compares the reference scenario energy output to the OPO reference scenario. The subsequent sections explore the alternate scenarios previously described in chapter 3 and mirror section 3.9 appearing in the same order. Next, a case study was included to provide a perspective on how an Ontario decision maker could use the model to investigate eliminating nuclear from the grid mix. After all scenarios have been discussed they are compared against one another utilizing the cost of GHG reduction by 2035 in comparison to the reference scenario. Finally, limitations of this study and future development of the model are discussed.

4.1 Reference (S.Ref)

Ontario, through conservation programs, efficiency upgrades [105], and a decline in manufacturing due to high electricity prices, have all contributed to a decline in its annual electricity demand since halfway through the first decade of the 2000s [106]. Total annual electricity demand peaked in 2005 at 157 TWh and reached its lowest in IESO's recorded history in 2017 at 132.1 TWh. Similarly, the IESO also tracks summer and winter peak demand, which have records of 27,005 MW on August 1, 2006 and 24,979 MW on December 20, 2004, respectively [28]. Ontario's historical electricity consumption as well as the four demand profiles from the IESO OPO report [15] are depicted in Figure 4.1.

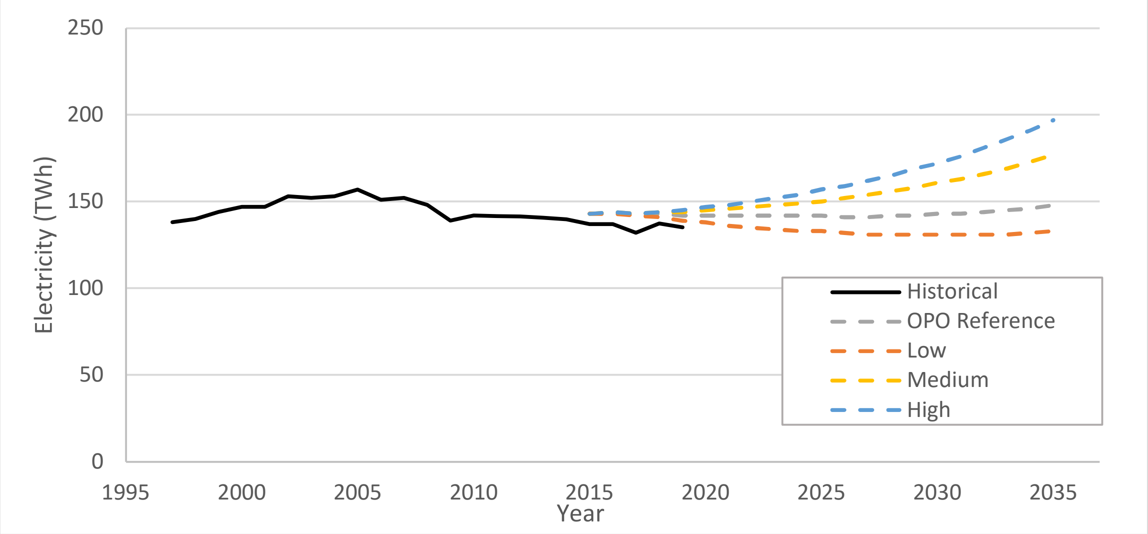
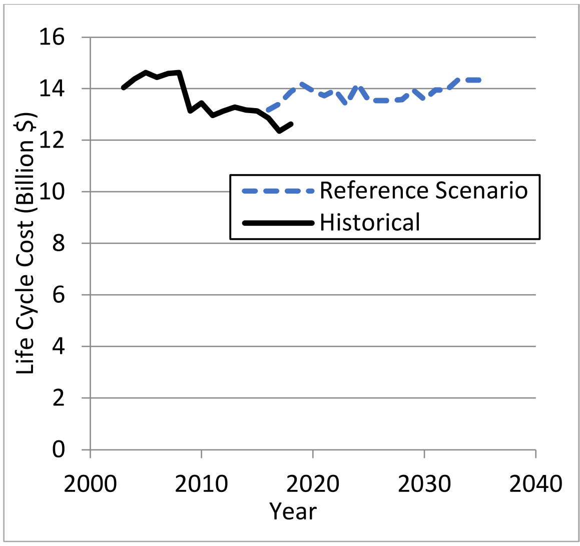


Figure 4.1: Historical and IESO Ontario Planning Outlook [15] Forecast Annual Electricity Demand Scenarios

These outlook demand profiles vary, as previously discussed in the literature review, from a relatively level business as usual reference case to a slight decrease due to conservation efforts and increases in efficiency in the low case, to increased demand due to electrification of other sectors to reduce emissions to varying extents for the medium and high demand profiles.

Through applying life cycle factors, from Table 3.3, to the historical electricity generation data, historical life cycle costs and emissions can be seen in both Figure 4.2 and Figure 4.3, as previously seen in section 3.5. In addition, the annual life cycle emissions, and annual life cycle costs of the reference scenario (S.Ref) have been plotted using a dashed line, as a comparison to historical values. These charts show the annualized total system life cycle cost and life cycle emissions of Ontario's electricity generation. These values were determined by converting the forecast installed technology capacities, from the IESO OPO [15], for each year to annual electricity generation using the respective capacity factor and Equation 5. Then, the corresponding life cycle emission and life cycle cost factors were used to convert annual generation to annual emissions and costs (Eq. 6) for each technology. These values were summed to an annual life cycle total for the system which was plotted to create the dashed series of the following charts, Figure 4.2 and Figure 4.3. Over the historical period, annual life cycle costs from 2003 – 2018 have remained relatively steady, with a slight drop due to the economic downturn that occurred in 2008 which lead to major industrial consumption reduction in Ontario [106] Over this historical period the province and its agencies also implemented conservation initiatives [107], to lower overall electricity consumption and as a result system life cycle costs as well. Over the past decade and a half, annual life cycle emissions have decreased by almost 75%, largely due to the elimination of coal generated electricity by 2014 and the introduction of renewables.



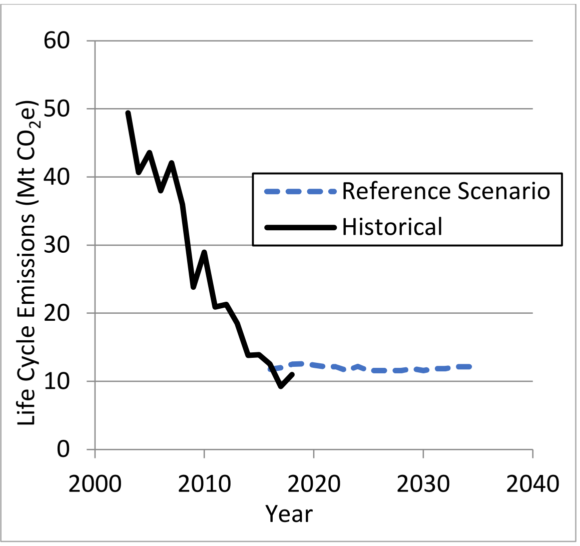


Figure 4.2: Historical & Reference Life Cycle Costs

Figure 4.3: Historical & Reference Life Cycle GHG Emissions

The model indicates that for the reference scenario (S.Ref) both life cycle costs and life cycle emissions will remain relatively flat for this business-as-usual scenario. However, bear in mind that the high-level system analysis of this thesis utilizes the assumption that all technologies, both existing sources and new generation, as assigned by the model have the same life cycle impacts, both cost and emissions. In reality, each site will vary from one another which was made clear by Mallia & Lewis' work [14]. These site differences would cause the life cycle impacts to differ slightly across generation facilities, due to increased cost efficiencies due to previous experience or economies of scale resulting in a lower life cycle cost as well as differences in environmental impacts because of construction and transportation resources required for a specific site.

In comparing the model's ability to meet the forecast electricity demand of the OPO [15], both were plotted in Figure 4.4 in comparison to historical values. To reiterate the Reference Demand line is that which is based off of the forecast capacities from the IESO OPO and the historically calculated capacity factors, which were determined in section 3.4. Whereas the Ontario Planning Outlook line is the IESO's forecast annual electricity demand over the time horizon. The reference model (S.Ref) results initially start at the same value as the historic consumption of 150 TWh of electricity generation in 2016, whereas the OPO was lower, forecasting 143 TWh for 2016. The reference scenario results, based on OPO projected installed capacities and historical capacity factors as seen in table 3.4, continue above the OPO electricity forecasts until 2023; then after a single jump above in 2024 the reference continues below the OPO values gradually increasing to eventually match the OPO in the final years of the scope.

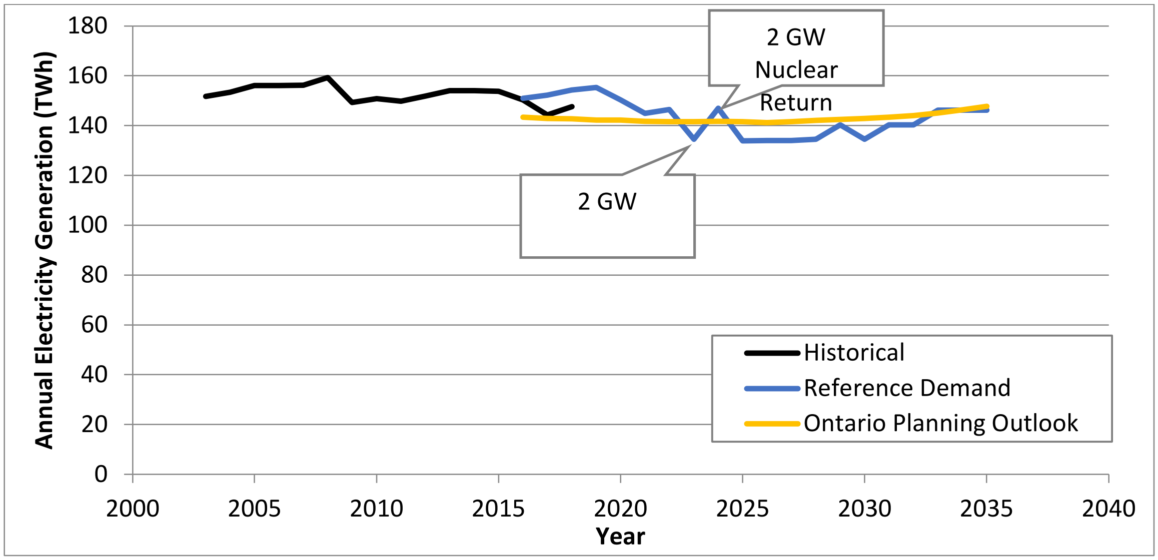


Figure 4.4: Model Annual Reference Electricity Generation in Comparison to OPO and Historical Values

The difference and jumps between the reference results and the OPO forecasts can be attributed to capacity factor and nuclear generation refurbishment and decommissioning. The capacity factors are based on recent historical generation and installed capacity. As previously discussed in section 3.4, the way that these capacity factors are determined, based off historical generation, underrepresents the capabilities of both natural gas and biofuel technologies. Over recent years, the high availability of nuclear and renewable energy have resulted in lower utilization of natural gas, creating a lower capacity factor value of natural gas for the model. Similarly, the high utilization of nuclear generation creates a high capacity factor input into the model. However, during the refurbishment period the nuclear capacity factor will go down as nuclear reactors are shut down and existing natural gas generation will be called upon, therefore increasing its capacity factor based on annual generation and installed capacity.

The schedule of nuclear refurbishment and decommissioning also impacts these results. As nuclear capacity is taken offline, the total electricity generated reduces significantly due to its high capacity factor, eventually falling below the forecasted electricity demand in 2023, when the nuclear capacity falls to 8,619 MW [101]. The following year enough refurbished capacity is planned to come back online to bring the capacity to 10,322 MW. These changes can be seen in the stacked area capacity graph in

Figure 4.5. The reference scenario electricity generation does not align perfectly with the OPO business as usual generation forecast. For the periods were the reference scenario runs over the forecast demand, on demand generation such as natural gas or large hydroelectric will be scaled back to better meet the demand need, again altering the capacity factors of these technologies. Similarly, when the reference scenario falls under the OPO forecast the on-demand generation will be called upon if electricity is needed. Over the observed time horizon, the average percent difference between the model reference electricity output and the OPO forecast electricity is 0.3% which equates to approximately 6.0 TWh.

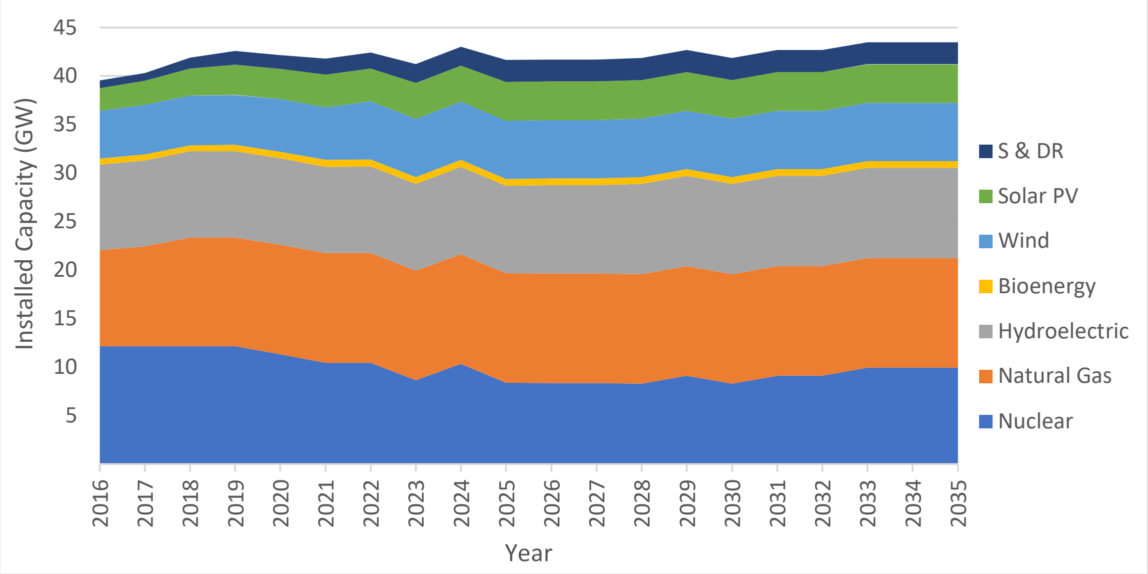


Figure 4.5: Stacked Installed Capacity of Reference Scenario (S.Ref) Forecast

In summation, using the same method that was previously used and validated against historical studies, future life cycle costs and life cycle emissions of Ontario's electricity supply were generated. This reference scenario (S.Ref) produced relatively flat business as usual projections in comparison to recent historical data. When comparing the model electricity production to historical system generation and IESO forecast, it was found that the model follows the forecast generation with minor variation due to the static capacity factors of the model. These capacity factors have been noted as a weakness of the model, as for the purpose of this model they have been held static, when in realitythey fluctuate annually. These results will act as a good comparison for future alternate scenarios.

4.2 Technology Preference (S.Tech)

The first scenario explored was technology preference (S.Tech), in which all future capacity installations needed to meet the reference demand are fulfilled by a single generation technology. Figures 4.6 and 4.7, show the annual life cycle costs and annual life cycle emissions of scenarios in which 100% of the required electricity generation is assigned to a single generation technology. For reference, both the historical values and reference scenario results are plotted.

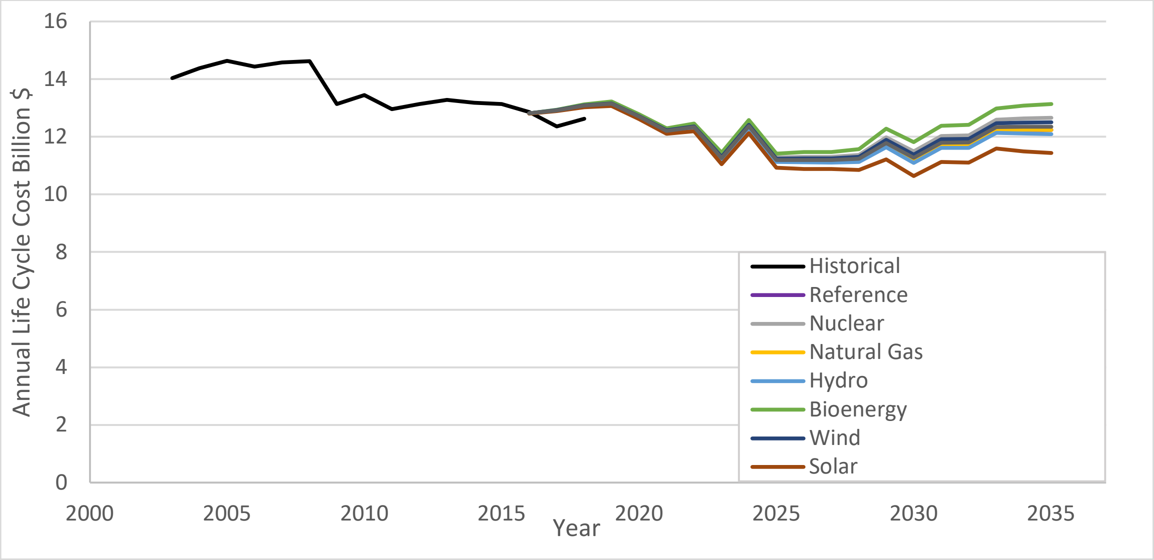


Figure 4.6: Ontario Annual Life Cycle Cost of Electricity Generation for Technology Preference Scenarios

The results of the 100% technology preference annual life cycle costs shown in Figure 4.6 compare closely to the reference scenario. The bioenergy technology preference scenario (S.Tech.Bio) generated the highest system life cycle cost and exceeds the cost of the reference scenario by $0.9 billion.This overage is due to the higher life cycle cost associated with bioenergy fuelstock processing, noted by Zhang et. al [56]. Other scenarios, cluster closely to the reference line with the total range of the scenarios being $1.6 billion. Solar, which is lower than the cluster of other technologies, is the exception of the clustered scenarios due to its lower cost factor. Although it is initially less costly, as more generation is required, the total life cycle cost of bioenergy increases past the reference scenario. Alternatively, solar offers the largest life cycle cost decrease; however, as the capacity is installed, cost could increase because of lack of available land and lower electricity generation due to lower solar irradiance in less desirable locations, due to latitude or local climate.

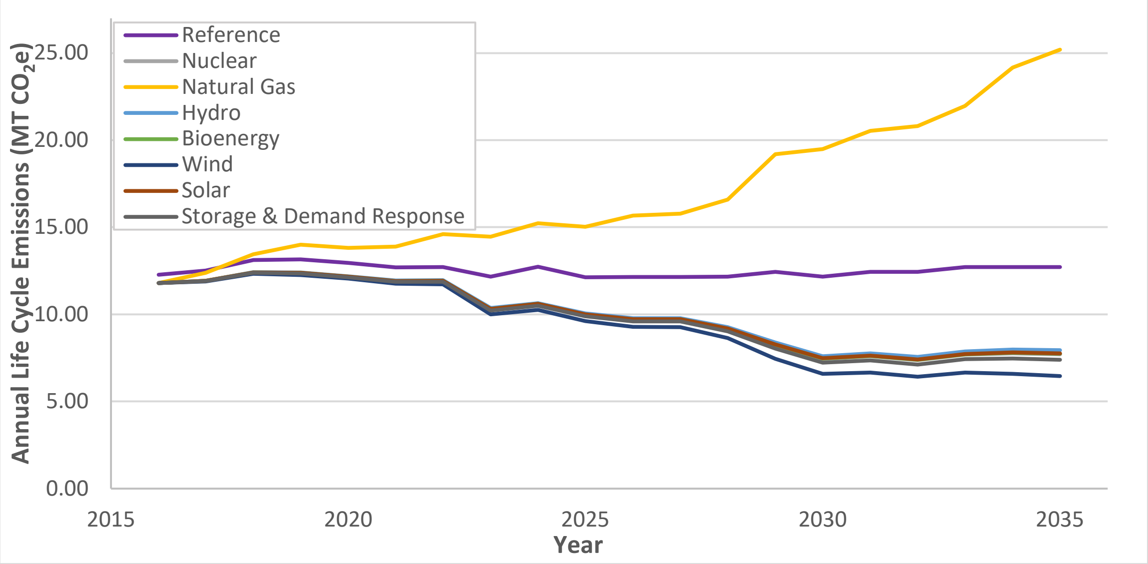


Figure 4.7: Ontario Annual Life Cycle Emissions of Electricity Generation for Technology Preference Scenarios

The annual life cycle emissions of the technology preference scenarios, illustrated in Figure 4.7, have a larger divergence from the reference values compared to the life cycle costs. The differences occur in a predictable way with renewable generation technologies falling below the reference scenario, and the natural gas technology preference scenario increasing the system life cycle emissions greatly above the reference scenario due to emissions produced during generation.

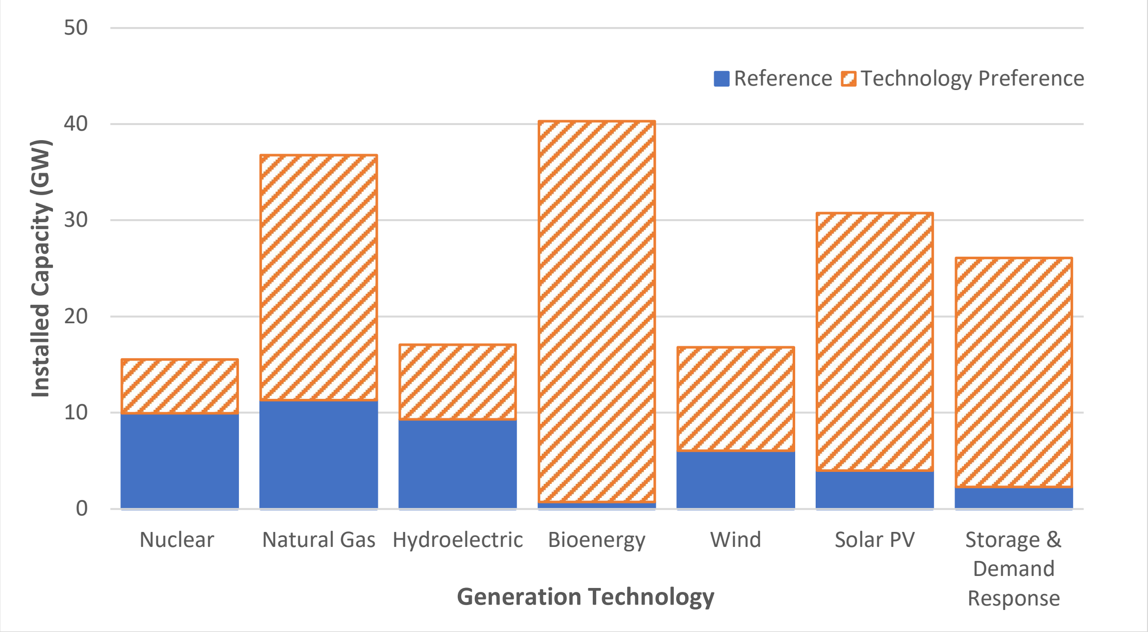


Figure 4.8: Additional Required Capacity Above the Reference Scenario to Meet the Reference Demand, given Sole Technology Preference

The additional capacity required in 2035 for each of the 100% technology preference scenarios above the installed and committed capacities is depicted above in Figure 4.8. The additional capacity needed to meet the reference electricity demand from each technology varies due to the capacity factor of each. Nuclear and hydroelectric both have relatively high availability, while bioenergy, natural gas and solar require more than double the additional capacity to meet the required electricity generation. This low availability is due to the low assumed capacity factors of these technologies, which were based on historical generation. As previously mentioned, both bioenergy and natural gas have higher theoretical capacity factors of upwards of 80% compared to the values determined from historical generation of bioenergy and natural gas, 12% and 13% respectively. Therefore, the model has an inherent bias against these technologies built into its decision making. The large capacities of bioenergy and solar energy required raised concern regarding the availability of the resources in the province: therefore, limits were determined as discussed in the methodology (Table 3.4) and applied to all future scenarios. It was found that nuclear, hydroelectric, bioenergy and solar all exceeded the provincial limits of grid connected generation facilities as described in sub-section 3.9.2. These resources limits are explored further in Section 4.3, as the technology preference scenario was run again with these limits in place.

4.3 Technology Preference with Limits (S.Tech.Lim)

Once province-specific generation technology limits were implemented into the model all 100% technology preference scenarios (S.Tech.) were run again, now with consideration for provincial limits (S.Tech.Lim). Figures 4.9 and 4.10 show the annual life cycle costs and life cycle emissions of all technology preference scenarios, respectively, while adhering to technology limits. Hydroelectric generation was the first to hit its limit in the year 2018, followed by solar in 2022, each unable to supply the reference electricity demand by 22% and 21% respectively. Both nuclear and Bioenergy will reach their respective limits in each scenario in 2029, resulting in these scenarios being unable to meet the required electricity supply by 16% and 15%, respectively. Natural gas, Wind and

Storage & Demand response were able to meet the required reference electricity generation while remaining under their provincial limits.

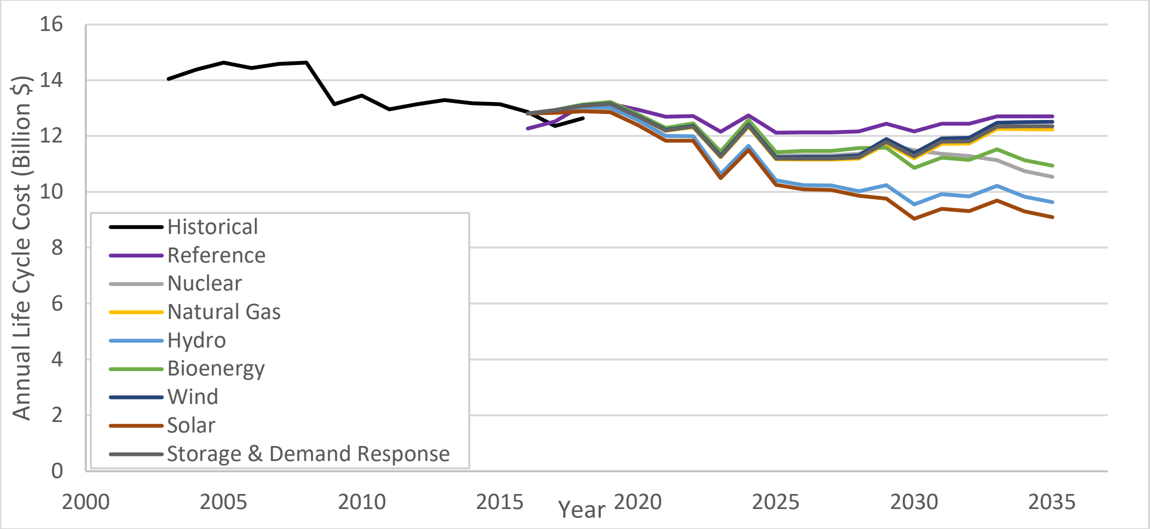


Figure 4.9: Ontario Annual Life Cycle Costs of Electricity Generation for Limited Technology Preference Scenarios

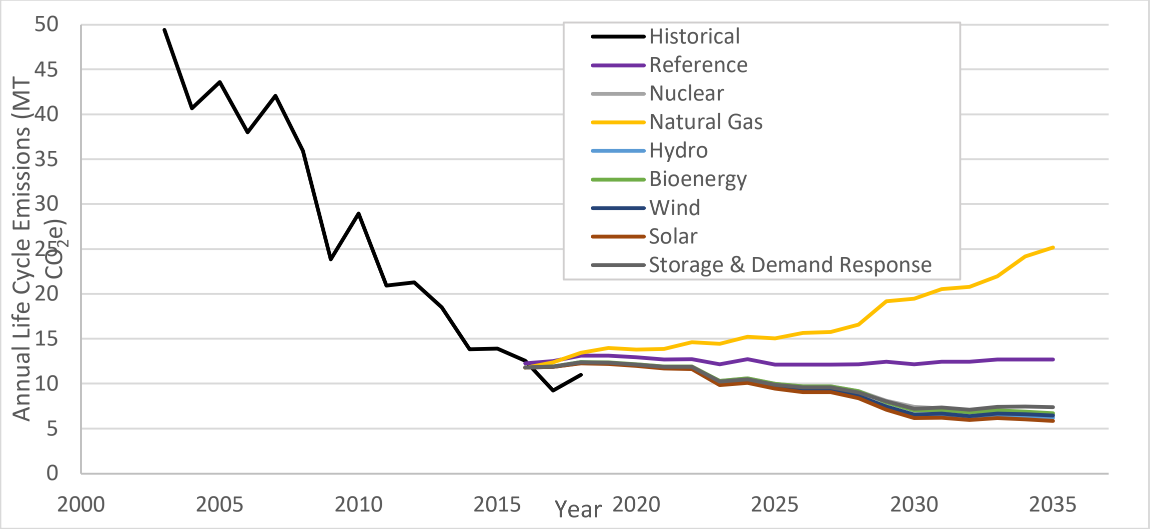


Figure 4.10: Ontario Annual Life Cycle Emissions of Electricity Generation for Limited Technology Preference Scenarios

The annual life cycle emissions graph, Figure 4.10 above, shows little change compared to the results from the model prior to implementing limits. Natural Gas will still generate more emissions than the reference case, while all other technologies show reduction in emissions. The technologies that reach their limit under this scenario appear lower in the life cycle emission chart compared to the results of section 4.2 but remain clustered within the group. The annual life cycle cost shows relatively larger reductions in system life cycle costs for the technologies that reach their respective limits. However, these reductions are met by under-sizing the system which would reduce electricity reliability.

Figure 4.11 depicts the assigned capacities for the 100% technology preference scenarios (diagonal orange stripes) stacked on top of the reference scenario (solid blue) technology capacity with the insufficient capacity (checkered green), the required additional capacity to meet the reference demand, staked on top of both. Both bioenergy and solar would require over 20 GW of capacity above the provincial limits. Hydroelectric generation had reached its capacity limit in 2018; and therefore, it was found that the hydroelectric scenario wass insufficient by 7.6 GW of capacity when remaining within the provincial limit. Nuclear would require an additional 3.3GW of generating facilities, which would require another plant similar to the size of the Darlington Nuclear Generating Station to be built as well as the refurbishment of the Pickering Nuclear Generating Station, which is scheduled to go offline in 2025. Although nuclear does play a critical role in Ontario's energy supply, its previous track record of over budget and extended timelines does not bode well for future large capacity nuclear projects. However, technology development in small modular reactors (SMR) could lead to a new generation of nuclear in Ontario, though these projects provide much less capacity, less than 300 MW per reactor [99]. This capacity is also arguably an excess amount of nuclear generation considering that nuclear facilities, at least in Ontario, operate almost continuously for long periods of time. This continuous operation would supply an excess amount of electricity in off peak hours, requiring the reactors to reduce reactor generation or for the system operators to transfer electricity to other jurisdictions to be paired with electricity storage. Ontario's average hourly electricity demand by year ranges from 13 GW to 20 GW [108]; therefore, the 15.5 GW of installed nuclear capacity required by a nuclear preference scenario would create excess generation for 11 approximately hours a day, and that is without considering other existing baseload generation.

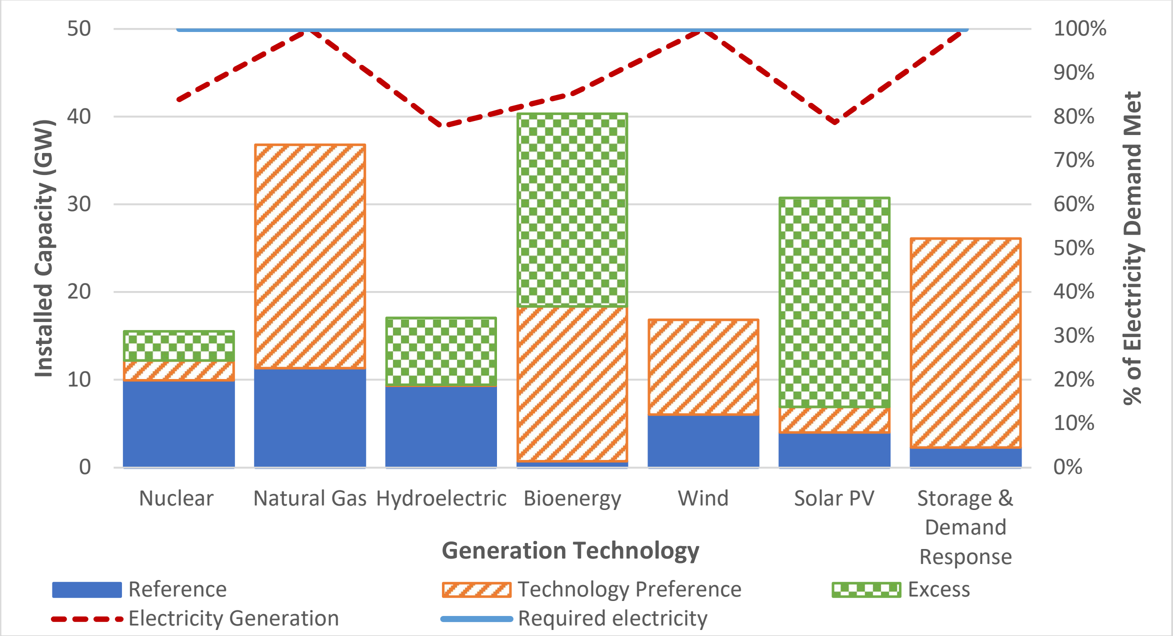


Figure 4.11: Technology Preference Additional Capacity Required (Orange Stripes) to Meet Reference Demand for 2035, Including Excess (Green Checkers) above Provincial Limit as well as the Required Electricity (Solid Line) Compared to the Scenario Generation (Dashed Line) when Technology Limits are Considered

The other technologies, these being natural gas, wind, and storage & demand response, were able to meet the required generation without reaching the provincial energy limits. However, there are still concerns of over installation of technology capacity. If a given technology is selected and underutilized, i.e., it does not produce enough electricity to be economical or produces when electricity is not needed, it would be a negative cost that could increase the cost of the system. In the technology preference scenario in which only wind is selected, concerns of intermittent generation are raised, especially in consideration of peak demand, as this option may not be able to meet future peak demands if all wind is not generating. If natural gas is solely selected for all future procured generation, emissions would increase greatly, resulting in Ontario not being able to meet its 2030 emission goal. Finally, although in theory storage & demand response may be able to meet future demand, other generation would still be required to supply electricity storage as well as significant improvements in electricity conservation methods. Since storage & demand response simply redistributes generation or curtails electricity demand, without associated generation technology, its ability to meet demand is questionable. Considering that the technology preference storage & demand response scenario allotted 40 TWh to the technology for 2035, it is very unlikely that this level of storage or demand curtailment would be possible without investment in other generation capacity. In the IESO's 2020 year in review, variable renewables being mainly wind and solar, with some nuclear manoeuvres, accounted for 2.6 TWh of supply curtailment and storage contributed 14 GWh. Similarly, preliminary estimates of energy efficiency saving account for 800 GWh of demand reduction [109]. Larger amounts of demand response would also be required to facilitate this scenario. All these aspects of storage and demand response are still less than 10% of what would be required, meaning that an additional 36 TWh of generation would still need to be procured. These concerns are all based solely on the reference scenario demand and therefore, it is even more unlikely for a single technology to be able to meet higher future electricity demands.

The technology preference scenario (S.Tech.Lim) shows that when taking into consideration the provincial resources limit and solely selecting a technology for future capacity installation, nuclear, hydroelectric, biofuel and solar cannot meet Ontario's future electricity demands. It is possible that through research and development the provincial capacity for these technologies could improve, however it is unlikely to happen within the time horizon of this study. The technologies that were capable of meeting demand, natural gas, wind, and storage & demand response all have inherent concerns, emissions, intermittent generation and supply electricity, respectively. Therefore, it is unlikely that one single technology will be used to meet Ontario's future electricity demand, however multiple technologies could meet the future demand if utilized together. Although these scenarios are unrealistic, they have helped to improve the model through the development of technology limits as well as providing bounds for other scenarios. The S.Tech.Lim and the S.Tech scenarios have presented a dozen alternate futures for Ontario's electricity supply, which will help to ground the other future scenarios presented in the remainder of this chapter.

4.4 Life Cycle Emission Factor Prioritization (S.LC.Emsn)

Next the life cycle factor prioritization scenarios were explored, the first being the prioritizing the reduction of the Ontario generation sources life cycle emissions. For these scenarios the model selects the technology with the lowest respective unit life cycle emission per unit generation and assigns 1 TWh of generation to that technology, this is repeated, while checking that the selected technology had not reached its limit, until the selected demand profile is met. This was done for multiple demand profiles thus completing all alternate scenarios described in section 3.8.7.

When observing the annual life cycle emissions of future electricity scenarios in Figure 4.12.B) in comparison to the historical annual life cycle emissions, the reference scenario remains relatively stable, as previously discovered in section 4.1 As predicted the annual system life cycle emissions fall lower than the reference scenario (S.Ref) for all three demand profiles where life cycle emission factors are used to assign new generation. The life cycle preference low emission scenario (S.LC.Emsn) annual system life cycle GHG emissions in 2035 fell below the reference scenario (S.Ref) emissions of 12 Mt CO_2e, to values of 6.2 Mt CO_2e, 6.9 Mt CO_2e and 7.2 Mt CO_2e for the reference, medium and high demand profiles. All three demand profiles can be seen to cluster together in the annual life cycle emission chart (Figure 4.12.B) and run horizontally as they approach the end of the time horizon, which suggests that there is limit to the amount that the system's life cycle emission can be reduced without additional efforts to drive technology life cycle emissions down. However, the static values of life cycle unit factors assumed for each technology across the time horizon does not account for performance improvements and reduction in life cycle emission impacts of the technologies that may occur in the future. Conversely, the cost of heavy investment in low emission generation technologies increases the system life cycle cost above the reference scenario, which can be seen in Figure 4.12.A. This increase in system costs is especially significant under the medium and high demand scenarios with annual life cycle costs reaching \$55 billion dollars and \$69 billion dollars, respectively by 2035 in comparison to the reference scenario \$13 billion dollars by 2035. Generally, it is understood that there will be an increased cost in order to reduce emissions

[110], [111], but scenarios that increase cost too aggressively are likely to upset the public and raise concerns about energy poverty as cost of electricity increases [112]–[114].

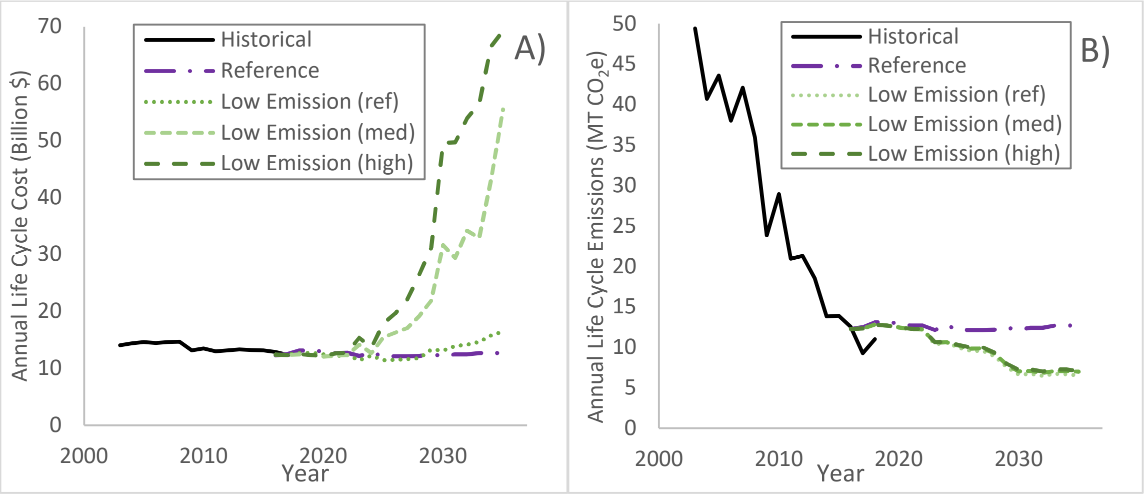


Figure 4.12: Annual Life Cycle Costs and Emissions of Life Cycle Factor Preference Scenarios: A) Low Emission Preference Life Cycle Costs, B) Low Emission Preference Life Cycle Emissions,

4.5 Life Cycle Cost Factor Prioritization (S.LC.Cost)

Similarly, the life cycle factor prioritization scenario was run again this time assigning generation based on lowest life cycle cost per unit. As expected, the opposite results of the S.LC.Emsn scenarios were observed for the S.LC.Cost, with annual life cycle costs remaining close to the reference scenario and annual life cycle emissions increasing greatly above the reference scenario results, as seen in Figure 4.13. The only demand profile that was able to achieve a cost reduction in comparison to the reference scenario ($13 billion in 2035) was low life cycle cost scenario following the reference demand, which resulted in a system annual life cycle cost of $12 billion in 2035. When the scenario was run following the medium and high demand profiles, the annual life cycle costs of the system in 2035 were found to be $15 billion for the former and $16 billion for the latter. Due to the relatively low cost and high provincial capacity limit of natural gas generation, it is heavily assigned in this scenario with 2035 natural gas installed capacity for this scenario totaling 22 GW, 50 GW, and 68 GW for the reference, medium and high demand profiles, respectively. Comparing these installed natural gas capacities to the reference scenario 9.3GW, the model has allocated significant capacity additions. However, as previously stated the historically calculated fixed capacity factor assumed by the model, has exaggerated the required capacity. Therefore, instead of increasing installed natural gas capacity within the province, the existing natural gas can be called upon more frequently, decreasing the total capacity needed to meet the energy demand and increasing the capacity factor. However, most life cycle impacts, both cost and emissions come from the generation life cycle phase due to the consumption of fuel. Therefore, although the capacities of the system are higher than required the system life cycle costs and emissions are still relatively accurate, if natural gas is used this intensely. Furthermore, with heavy natural gas usage it could result in higher cost as the demand for the commodity increases.

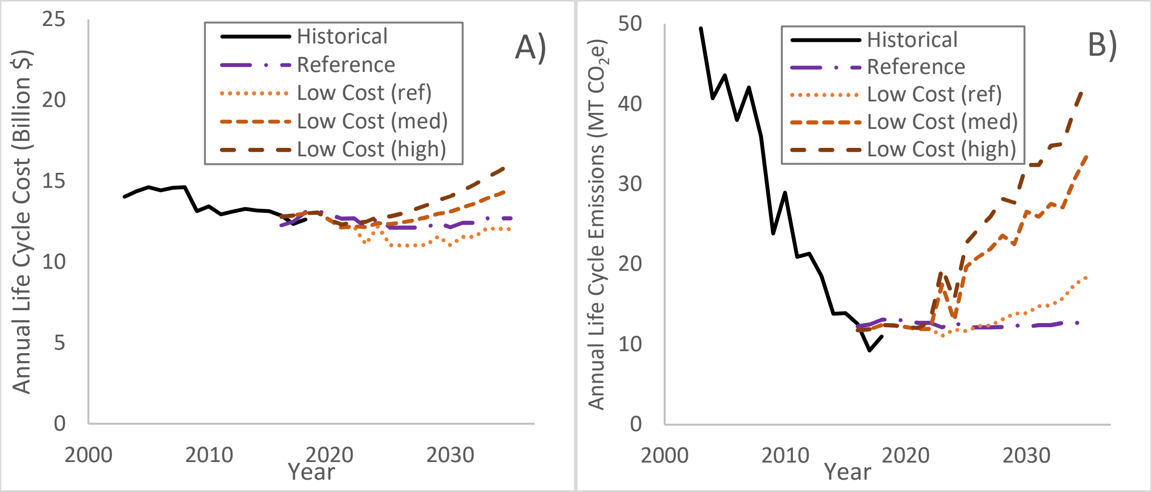


Figure 4.13: Annual Life Cycle Costs and Emissions of Life Cycle Factor Preference Scenarios: A) Low Cost Preference Life Cycle Costs, B) Low Cost Preference Life Cycle Emissions

4.6 Intermittent Generation and Storage (S.WinSol)

Examining the solar and wind technology preference scenarios (S.WinSol), specifically a 50/50 split between solar and wind technology preference, was chosen to better understand variable generation as well as storage which may be required to meet peak demands. Under the reference demand outlook, the IESO predicts that the 2035 summer and winter peak demands could be 24,792 MW and 22,422 MW, respectively [15]. The model assigned 9960 MW of solar and 14000 MW of wind for 2035 to help meet the reference demand for a 50/50 wind/solar scenario. Comparing these results to the projected future capacities found in the OPO [15], solar was forecast to have a total capacity of 4000 MW and wind was forecast to have 6000 MW. This means that for the S.WinSol scenario to be realized, this would require an aggressive implementation to more than double the forecast capacity installed by the end of the time horizon (2035). With both wind and solar being highly intermittent, they cannot be reliably depended upon and therefore 3400 MW of storage and demand response was implemented to support the summer peak demand. This is the difference between the peak demand and baseload generation capacity of all other generation sources. As of 2019, Ontario had 835 MW of grid connected storage and demand response capacity [70]. An additional 3400 MW of storage and demand response capacity would require significant procurement to quadruple the existing capacity by 2035. However this is not unreasonable considering that numerous companies are implementing storage and demand response across the province [70] and the reference scenario from the OPO forecasts 1416 MW by 2035 [15]. Similar results were also found for medium and high demand outlooks, having large solar capacity and insufficient wind to meet seasonal forecast peak capacity demands. Although it is generally understood that high levels of solar and wind implementation must be associated with efforts to increase storage and demand response capacity to ensure that future peak demand can be effectively met. In comparison to the reference scenario, the S.WinSol results showed a slightly higher system life cycle cost by 2035 by \$0.29 billion. Compared to the reference scenario the cost contribution from solar doubled from \$0.31 billion to \$0.77 billion and the total storage cost increased by nearly a billion dollars. Both technologies are going through significant development which are increasing lifetime energy output and reducing emissions and waste [115], [116]. Due to the heavy renewable generation investment in this scenario the system life cycle emissions were reduced by 4.1 Mt CO_2e below the reference scenario (S.Ref) results. There are also significant gains that can be achieved through directly pairing wind or solar with storage, to compensate for intermittent generation that would add additional value to the system. The results of this scenario show that Ontario's storage and demand response will need to quadruple if solar and wind are used to support Ontario's existing generation capacity to meet future demand profiles.

4.7 Variable Cost (S.VarCost)

To further explore life cycle costs of the system and acknowledging that life cycle unit costs are not fixed, the model was adapted to a take a user determined percentage price increase per TWh assigned. Therefore, the model selects a generation technology and assigns 1 TWh of generation calculates the associated life cycle emission and life cycle costs of the generation and adds that to the technology totals. Next the model increases the life cycle unit cost of the technology by the user specified amount. An initial percent change of life cycle cost increase was set at 2% per TWh assigned. Figure 4.14 shows the results of the variable life cycle cost applied to the life cycle cost factor prioritization scenario in comparison to historical, reference and S.LC.Cost results. The results show little variation from the S.LC.Cost scenario in the first half of the time horizon, however in the second half of the time horizon as more generation is required the new scenario diverges upwards from the original as the life cycle unit costs are increased. The S.VarCost scenario has an annual life cycle cost of $12.4 billion in 2035, $0.4 billion more than the previous S.LC.Cost scenario, however it remains lower than the S.Ref by $0.6 billion. With regards to emission comparison the S.VarCost scenario had an annual life cycle emission total value of 12.8 Mt CO_2e at the end of the time horizon, which is just above the S.Ref value of 12.7 Mt CO_2e and much lower than the S.LC.Cost end value of 18.4 Mt CO_2e. This is because more renewables are able to be selected as the price of natural gas is increased, whereas in the S.LC.Cost scenario natural gas was repeatedly selected as it has the second lowest life cycle cost and a large capacity limit.

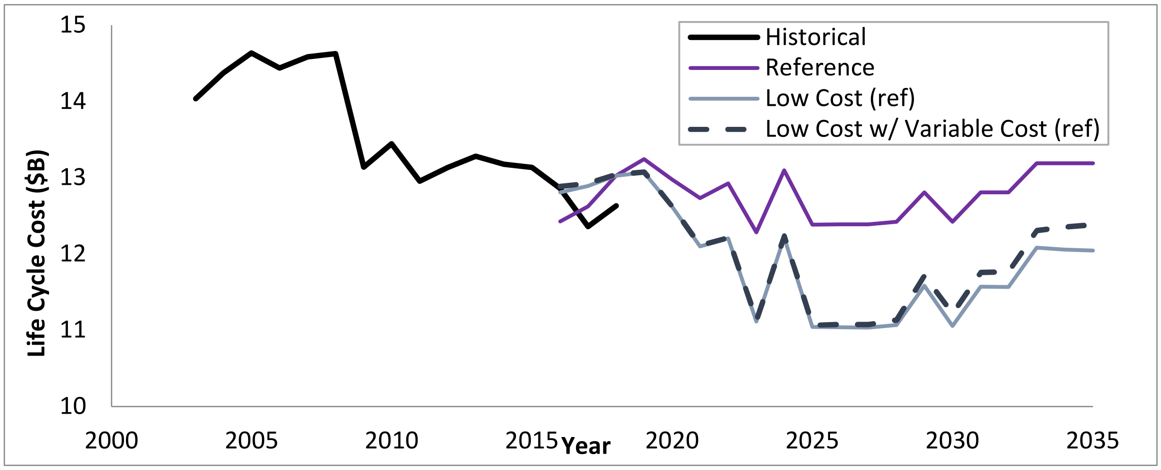


Figure 4.14: Life Cycle Costs of the Variable Cost Life Cycle Cost Preference Scenario in Comparison to Previous Scenarios

Next, similar to the S.LC scenarios the S.VarCost scenario was used to meet alternate demands. Figure 4.15 shows the life cycle emissions and life cycle costs of the variable cost scenario across multiple demand profiles in comparison to the reference and historical values.

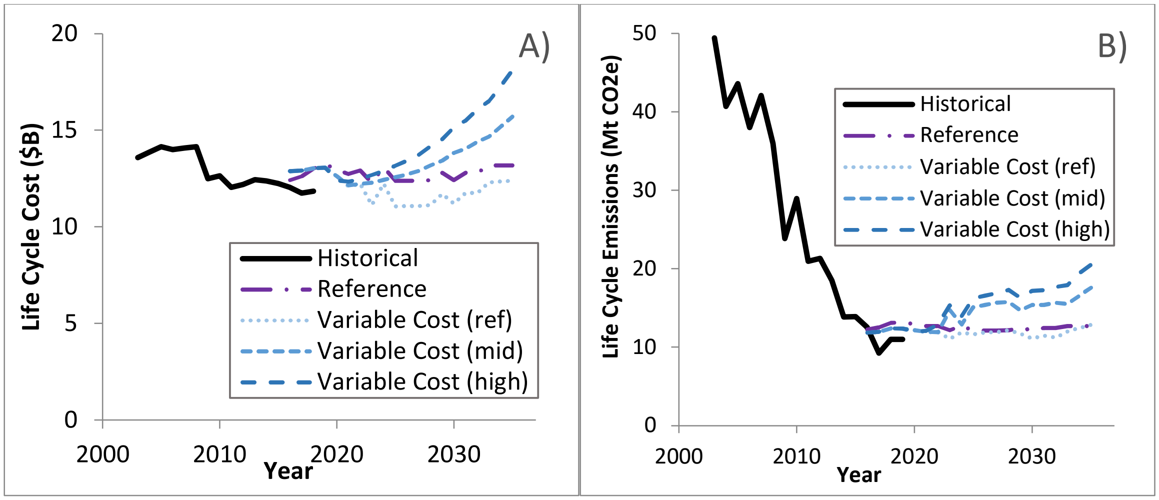


Figure 4.15: Variable Cost Scenario Annual Total Life Cycle Impacts across Multiple Demand Profiles A) Life Cycle Costs B) Life Cycle Emissions

An interesting result of this scenario is the range of the plotted results, specifically in comparison to the previous life cycle cost factor prioritization scenarios, see Figures 4.12 and 4.13. In the previous scenario the life cycle costs profiles were all clustered relatively closely together with the reference profile. However, due to the increase in cost as generation is assigned the life cycle cost profiles have diverged. Conversely the life cycle emissions were spread greatly in the S.LC.Cost scenario, while in this scenario the life cycle emissions group closer. This result is due to less natural gas being assigned. In the previous scenario natural gas, which has the second lowest life cycle unit cost, was assigned over 25 TWh for the reference demand and triple that (over 75 TWh) to meet the high demand profile. Whereas in the S.VarCost scenario as the price of natural gas increases it increases high enough to allow renewables and nuclear to claim larger market shares. As a comparison, natural gas is only assigned 14 TWh and 27 TWh in the S.VarCost scenarios to meet the reference and high demand.

. Sensitivity analysis was completed on the life cycle cost factor prioritization scenario, which was done by implementing the variable cost option and using values between the range of -5% and 15% for the value of percent change. Next, all life cycle costs profiles were plotted with the reference scenario life cycle cost in Figure 4.16. It can be observed that initially all low cost scenarios diverge downwards away from the reference scenario cost line, however as the range of sensitivity widens as more generation is assigned to meet the reference demand some of the higher percent change sets begin to climb above the reference scenario cost. This widening is due to the compounding growth of the percent change in life cycle unit cost factor as a larger number of iterations are required to ensure that the demand is met to assign enough generation 1 TWh at a time.

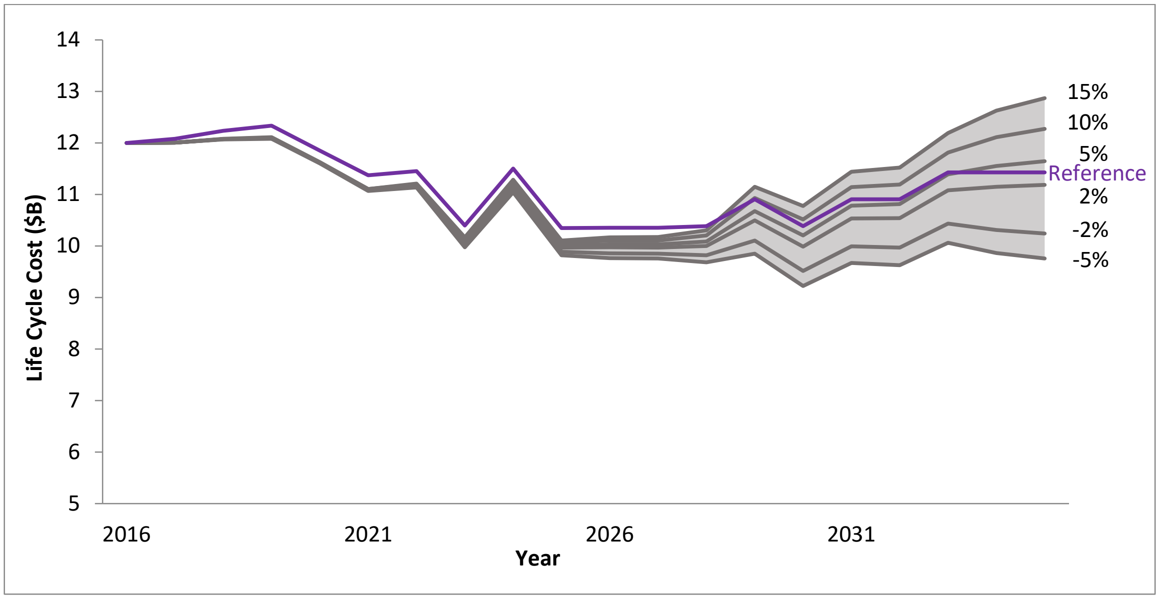


Figure 4.16: Sensitivity Analysis of Percentage Increase per TWh of Generation Assigned

It is important to note that when a negative percentage is used the model selects the technology with the lowest life cycle unit cost, assigns a TWh of generation to that technology and then lowers the life cycle unit cost of the respective generation type. This effectively means that the model will continue to select the same technology until the demand or the provincial capacity limit for the selected technology is met. In both the negative percentage cases over 28 TWh of generation were assigned to wind. These negative percentage scenarios could show how technology development and economies of scale could reduce the life cycle cost of a technology, thereby making it highly preferable over others. On the opposite side of the spectrum the scenario shows that as resources become restricted the opportunities for procurement for new generation capacity become more competitive as several sources will fight for the market share.

4.8 Summary and Comparison of Scenarios

The goal of this thesis was to create a model to investigate the future sustainability of Ontario’s electricity supply through a dual life cycle lens of life cycle emissions and life cycle costs. In chapter 3, the development and validation of the model was completed. In this chapter the results of future scenarios were presented in the order they were described in section 3.8 of chapter 3. This thesis examined the life cycle emissions and life cycle costs of Ontario's future electricity supply across several scenarios. First a reference scenario (S.Ref) was examined and compared againstthe OPO with regards to annual energy outlook across the time horizon, to further validated the model. The S.Ref scenario also set a baseline of life cycle emisions and life cycle costs for alternate scenarios to be compared against. Next each individual technology was evaluated for its ability to meet future demand when selected as the sole technology for new generation in the S.Tech scenario. Then the S.Tech.Lim scenario considered the provincial limit of generation capacity of each technology, resulting in nuclear, hydroelectric, bioenergy and solar being unable to meet the provincial reference demand if solely selected for all new generation. Next the S.LC scenarios were investigated, in which life cycle unit factors were used to reduce the system life cycle costs and life cycle emissions by selecting the technology with the lowest factor in the S.LC.Cost and S.LC.Emsn scenarios, respectively. The S.WinSol scenario provided valuable insight into how a fixation on intermittent renewable generation for all new generation would also require investment into storage and demand response to ensure enough capacity would be available to meet the forecasted peak demands. Finally, the variability of cost was explored in the S.VarCost scenario. This section will compare all scenarios against each other through observing installed capacities and calculating the cost of GHG reduction for each scenario.

Figure 4.17 compares the installed capacity of each scenario across the reference demand profile. The Solar/Wind scenario showed large increases in both wind and solar capacity by 2035 compared to the reference scenario. Alternatively, when emissions are prioritized, the overall capacity could decrease through the addition of storage and demand response and some added renewable generation. If low cost is prioritized the system capacity will greatly increase due to natural gas selection, however as previously discussed, due to the low capacity factor assumed for natural gas this additional natural gas capacity could be reduced by increasing the usage of existing infracsturcture. Throughout all scenarios, both nuclear and hydroelectric generation remain relatively consistent. Although there is potential to expand technology capacity limits through innovation, for example, small modular reactors or low head power generation. These technologies are relatively low capacity (less than 300MWe [99]) and will not make a significant difference within the temporal range of this work as they are still being developed.

Again, it is important to note the lack of bioenergy generation across all scenarios due to capacity factor bias and higher relative life cycle costs and GHG emissions. Even though bioenergy is considered a source of renewable generation, it has a larger emission factor than wind or solar. In the model, bioenergy combustion is assumed to be CO_2 neutral, which means thatall CO_2 generated during combustion will be captured by the next plant cycle. However, upstream emissions from machinery used to farm, process and transport bioenergy materials, as well as other gases produced from combustion have a greater impact than other renewables. Similarly, because of the intensive processing required, bioenergy is more cost intensive and therefore was selected less by the model.

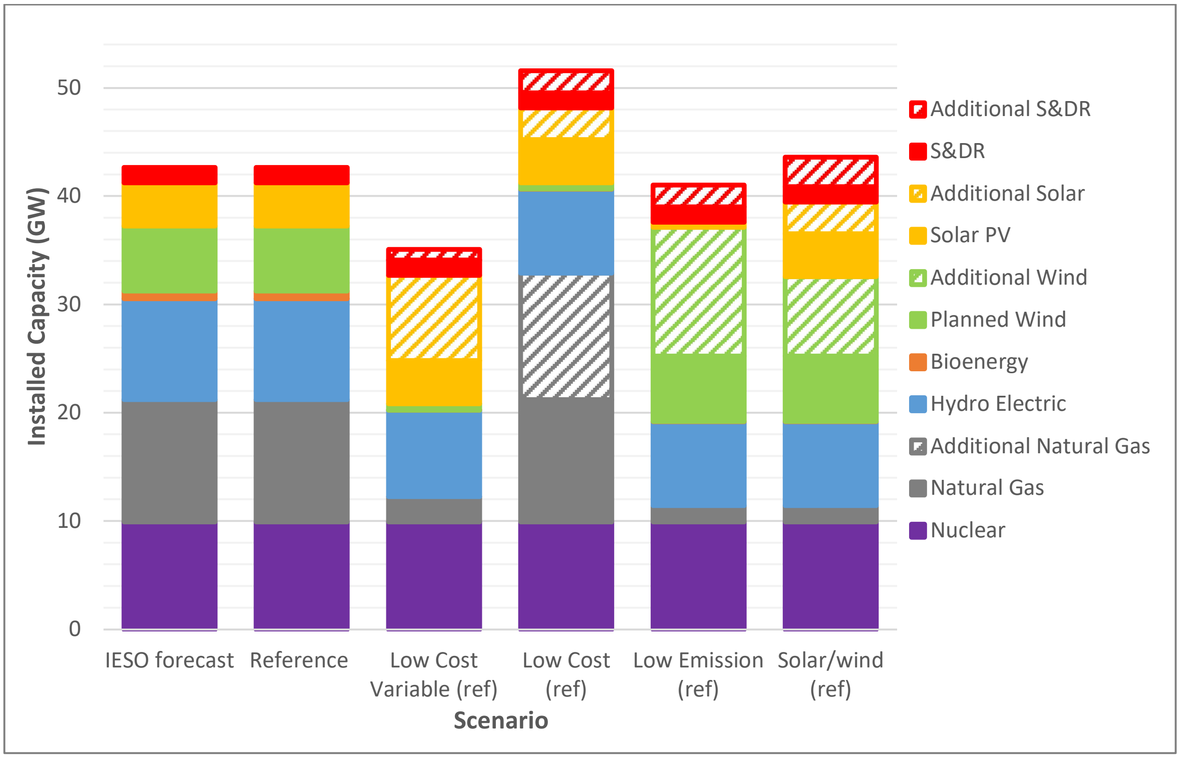


Figure 4.17: Installed Capacity Comparison of Multiple Scenarios for 2035 with Diagonal Stripes Showing Extra Capacity Required of a Technology which is Above the Planned Reference Capacity for that Technology

All scenarios were compared against the reference scenario by calculating the cost effectiveness of GHG reduction using equation 1. This equation is the difference of the life cycle unit costs of the system between the alternate scenario and the reference scenario divided by the difference of life cycle unit emissions between the alternate scenario and the reference scenario. This allows for a comparison not only of cost reduction but also emission reduction combined into a single metric. The determined values are displayed in Table 4.1 along with the 2035 life cycle values normalized to MWh. The values of the cost effectiveness of GHG reduction range from -4.9 to 0.044 \$/t CO_2e. These are significantly lower than values found by Zhang et al [56]. This difference is due to the emission intense technologies that Zhang et al. were investigating, coal, natural gas and bioenergy. Coal generation was used as the reference case, which is very emission intense and both natural gas and bioenergy were able to offer significant reductions in emissions. The analysis of Zhang et al. considered only alternative fuel types for existing coal generation stations in Ontario, while the model developed in this thesis has generated multiple alternate technology mixes for Ontario's future electricity supply. With this consideration, Ontario's electricity supply already has relatively low emission intensity and cost. Therefore, it is difficult to find significant reduction in cost or emissions.

Table 4.1: Cost Effectiveness of GHG Reductions for All Scenarios at 2035 in Comparison to the Reference Scenario

Scenario	2035 Life Cycle Costs (\$/MWh)	2035 Life Cycle Emissions (t CO_2e/MWh)	Cost Effectiveness of GHG Reduction (\$/t CO_2e)
S.VarCost (med)	89	99	-4.9
S.Tech.Lim.Wind	44	86	-3.1
S.Tech.Lim.Bioenergy	54	88	-2.8
S.Tech.Lim.Nuclear	54	86	-2.4
S.Tech.Lim.S&DR	51	84	-2.4
S.Tech.Lim.Hydro	55	85	-2.1
S.Tech.Lim.Solar	51	79	-1.7
S.VarCost (high)	92	104	-1.4
S.WinSol (ref)	79	49	-0.092
S.Tech.Lim.NaturalGas	84	172	-0.0072
S.LC.Cost (high)	82	219	0.013
S.LC.Cost (med)	82	189	0.014
S.LC.Cost (ref)	82	126	0.029
S.LC.Emsn (med)	86	39	0.042
S.LC.Emsn (high)	86	37	0.042
S.LC.Emsn (ref)	86	44	0.044
S.VarCost (ref)	85	88	0.15
S.Ref	83	98	NA

When comparing all scenarios that were analysed by the model, several clear conclusions can be drawn. Across all scenarios, both nuclear and hydroelectric energy continue to supply baseload energy for Ontario into the future. This continuation is due to their long operating life, low life cycle cost and low life cycle emissions. Both will continue to play a key role supplying electricity to Ontario into the future. In scenarios that reduce Natural Gas generation Storage & Demand Response is required to offset the intermittency of Wind and Solar generation. Traditionally, Natural Gas has been utilized with Wind and Solar to offset that intermittency. Here the model calls for an increase in storage and demand response instead when supplying enough electricity to meet the reference demand. The selection of storage and demand response to assist in meeting demand is a built-in bias of the model for the wind-solar scenario S.WinSol, since the model assigns storage and demand response capacity if the existing capacity of reliable sources is unable to meet the forecast annual peak demands.

With new renewable technologies, such as wind, solar and bioenergy, still being developed and finding their market share in Ontario's electricity generation supply, more technology uptake likely to continue. As these technologies gain momentum, economies of scale will drive improvements in the upstream life cycles stages, which will reduce the life cycle impacts by reducing the resources required as well as increasing the life time electricity generated. Furthermore, as some of the early adopter installations, which were implemented at the turn of the century, reach their end of life, valuable insight will be gained with regards to the end-of-life life cycle impacts. Specifically, the amount of waste and the amount of recyclable material that can be reused to support the next generation of capacity.

4.9 No New Nuclear Case Study

The following is a case study which explores a hypothetical use of the model to support decision makers in assessing a future scenario. Similar to the influence of public opinion on wind implementation, explored in section 2.2, nuclear energy has also had to endure similar debate. Due to nuclear accidents over the years, some of the public perceptions view nuclear energy as a high risk technology, while other still see great value in the technology in supporting clean energy transitions [117]. If a policy or decision maker was to compare Ontario to other jurisdictions with nuclear fleets, they might be curious if Ontario could handle a nuclear withdrawl similar to Spain or Switzerland [118], [119]. This case study explores the idea of letting the existing installed nuclear capacity reach its end of life, rather than the currently planned refurbishment of some of Ontario's nuclear fleet, and then the model will allocate necessary generation to other technologies.

Other jurisdictions have drawn back nuclear generation in reaction to nuclear accidents around the globe. The three major accidents that have influenced nuclear generation are the Three Mile Island partial nuclear meltdown in the United States in 1979, the Chernobyl disaster in the USSR (now Ukraine) in 1986, and the Fukushima Daiichi nuclear disaster in Japan in 2011. These incidents have prompted increased safety measures globally, with some jurisdictions sticking to their path of increasing and maintaining their nuclear fleet while other jurisdictions drastically changed their nuclear power strategy [120]. Most recently, after Fukushima in 2011, Germany shut down eight of its 17 reactors with plans to close all nuclear generation by 2022 [121]. Similarly, Switzerland [119] and Spain [118] initially took the stance in 2011 that their countries would not add any new nuclear stations. Since then, both countries have begun shutting down and decommissioning their nuclear fleets as they reach end of life.

Over the time horizon of this study, 2016-2035, Ontario's nuclear fleet will experience significant change as all plants (Pickering, Darlington, and Bruce) reach their end of life [15]. The province's current plan [122] is to refurbish units at both Bruce and Darlington and extend Pickering's life to cover significant capacity reduction at the start of this process. Then as refurbished reactors are brought back on-line, Pickering will be shut down in 2025 and begin to be decommissioned.

This case study uses the model developed in this thesis to explore a similar Swiss/Spanish nuclear strategy for Ontario and to compare the resulting life cycle impacts to the reference scenario. In this case study no new nuclear generation, including refurbishment of existing units, will be counted as future nuclear capacity. Instead, the existing nuclear reactors will be systematically turned off as they reach their end of useful life. This large reduction in base load electricity supply will be compensated by the model, through allocating other generation sources to meet the forecast demand. For this No New Nuclear case study the forecast installed nuclear capacity was recalculated to only include the existing nuclear capacity and to account for nuclear reduction as each nuclear reactor is brought offline. The model was then rerun using both the low emission and low cost selection logic. Both LCE and LCC results of both model iterations are plotted in comparison to the reference scenario below.

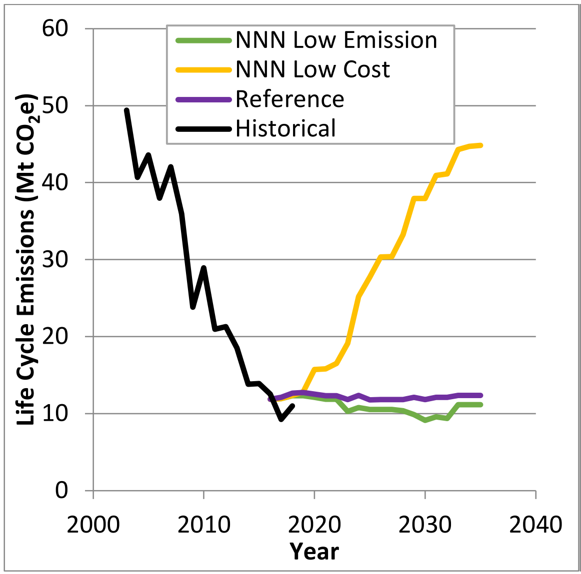


Figure 4.18: No New Nuclear Life Cycle Emissions

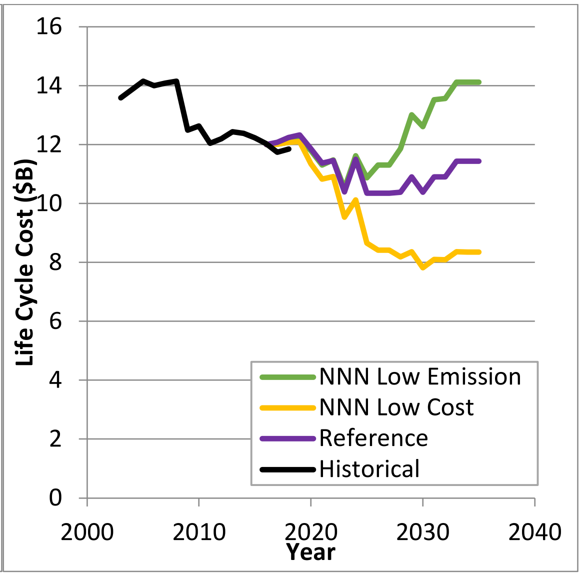


Figure 4.19: No New Nuclear Life Cycle Costs

The life cycle emissions chart, Figure 4.18 shows that the No New Nuclear Low Emission results shows a slight reduction of 1.2 Mt CO_2e of annual life cycle emissions by 2035 compared to the Reference scenario. This comes with an increase in cost to the system with the No New Nuclear Low Emission results rising to $14.1 Billion, $2.7 Billion above the Reference value for 2035. Conversely, the No New Nuclear Low Cost showed a reduction in the system annual life cycle cost of $3.1 Billion below the Reference scenario for 2035, as seen in Figure 4.19. However, the reduction in cost is completed through heavy implementation of natural gas generation, increasing the system life cycle emissions by 32.5 Mt CO_2e above the Reference scenario by 2035. The most interesting insight that this case study provides is the fact that nuclear capacity with refurbishment in the Reference scenario was 9920 MW in 2035, in the No New Nuclear case study this is reduced to 1550 MW in 2035. This reduction in nuclear capacity requires the model to allocate additional generation capacity to meet the reference demand. For the No New Nuclear Low Emission and Low Cost results the model assigned 36100 MW and 49700 MW, respectively, of additional generation above the reference capacity of 43.5 GW. This massive infrastructure addition is due to the fact that nuclear has such a high capacity factor (81%, Table 3.4), while the other technologies average 23.4%. For the No New Nuclear Low Emission case, the large amount of capacity required means that hydroelectric, bioenergy, solar and wind all reach their maximum provincial generation limits in 2033, requiring additional natural gas capacity to meet the reference demand in the final years of this outlook.

This case study shows the value of Ontario's nuclear fleet. From a life cycle perspective nuclear provides a large amount of energy with relatively low life cycle cost and life cycle emission impacts, on top of providing a large amount of annual energy per nameplate capacity installed. If the decision was made to stop new nuclear development in Ontario, including the current planned refurbishments, Ontario's installed capacity would need to double to meet the reference demand. This expansion in capacity would also require significant transmission and distribution upgrades to accommodate all the new generation interconnections. The life cycle emissions and life cycle costs of this infrastructure upgrade were not included in the scope of this study; therefore, the annual life cycle emissions and life cycle costs of the Ontario generation system would be higher than the results shown in this case study. Further system capital expense and operational expense analysis between no new nuclear and the model proposed alternative of doubling Ontario's total generation capacity would need to be completed to evaluate the total cost impact of the alternative in comparison to the current path.

This case study shows that with relatively little effort a decision maker could utilise this model to quickly assess proposed alternative futures for Ontario's electricity supply and with additional effort could be applied to other jurisdictions. From a policy or decision maker perspective, this would show both the high value of Ontario's nuclear fleet, both in terms of emissions and costs reductions. This analysis also shows that a significant amount of resources and a strong strategy would need to be generated to justify a nuclear shutdown in Ontario, thus making it unlikely to be a feasible option at this juncture.

4.10 Limitations of this Study

Due to the high-level lens of this research, some of the limits and assumptions made to create the model restrict the results that are found. Where some values were unavailable for Ontario-specific electricity generation, values from nearby jurisdictions were used. Similarly, as technologies continue to advance, new installations are likely to have higher efficiency, lowering cost and environmental impacts per unit electricity generated. As more LCA research is completed in this area, the model could be updated to provide higher accuracy results. Although all data used is not Ontario specific, validation of the model was completed through comparing model results of historical generation to other recent studies of specific annual periods for both cost and emissions. Over time, the life cycle data used in this model will become obsolete, due to improvements in upstream stages, which will be shown as more research and data becomes available. This model can then be updated and rerun to determine how the updated life cycle factors will influence future electricity generation selection.

The way the model is based on future electricity demand and the installed capacity of electricity generation technologies means that without extrapolation, the model is limited to the temporal period of the source data. This method could limit the model further as other sectors, such as transportation or heating, are worked into the model if other sector data only provide a single forecast value at a single year in the future. To create broader scenarios other sector data, which has forecasts that align with the time horizon of the model, would be required. For example, although electric vehicle adoption is low in Ontario, peaking at about 3% of annual sales before provincial incentives were cut [123], it is expected that adoption will grow quickly through to the mid-century [124], [125]. The model can be expanded to run scenarios of variable adoption of electrification within its temporal range. This would alter the demand profile, thus changing the amount of generation the model would have to assign to meet the new demand profile. However, long term estimates of electrification of transportation, for example 2050 estimates, would be difficult to work into the model due to the difference in time horizon. Though this could still be adapted through interpolation to create a target within the time horizon.

Due to the high-level lens of this research, some of the limits and assumptions made to create the model restrict the results that are found. Although nuclear is relatively clean and low cost, current nuclear power plans for refurbishments and shut downs in the province extend past the scope (2016-2035) of this model. Since it is unlikely that new nuclear will be implemented within the timeframe of these scenarios nuclear is therefore restricted to its maximum capacity of currently installed nuclear power. Similarly, the province has limits on the amount of renewable energy resources within its borders. Most of Ontario's hydroelectric resources have been harnessed [103]. Wind and solar generation have the largest potential for growth, although wind is limited by current legislation to onshore sources which limits the provincial capacity. The moratorium on off-shore wind in Ontario was created in 2011 [126] after concerns of environmental impacts were voiced to the government from communities close to planned off-shore projects. The ban of off-shore wind greatly limits the province's potential as some of the most favourable sites with the highest wind potential are off-shore [127]. Both wind and solar are also inherently intermittent, which raises concerns regarding reliability of electricity supply and in some cases requires electricity storage to meet peak demands. Finally, natural gas is an inexpensive, efficient, and reliable alternative to coal, although it often is not utilized in low carbon scenarios of the model as adoption could limit the province's ability to reduce emissions. This result aligns closely to the findings of Qudrat-Ullah [75] who created a dynamic model based on the analysis of green power in Ontario. The three scenarios explored found that nuclear and hydroelectric generation will continue to supply the majority of electricity generation. However, how the remaining future capacity needed to meet demand is assigned will determine the cost to consumers. Their model determined that a new renewable-focused scenario would increase the cost of electricity significantly; however, a low carbon economy scenario, which focused more on productivity and efficiency within the system could reduce consumer costs in the future below the business-as-usual case.

The future is inherently uncertain. With the rate of technology development, new applications on the supply and demand side, as well as in storage of the electricity, will impact the balance of the electricity system. Consumers continue to become more connected through electric products, manufacturers create more efficient products and electricity generators improve efficiency. Although it is uncertain how these factors may impact the system in the future, this work aims to give insight on how to increase the long-term sustainability of a system's electricity supply.

This analysis includes broad assumptions such as static life cycle factors, lack of geographic specificity of generation sites and implementation of some sources by two or three orders of magnitude larger than what has previously been done in the province. However, this model can act as a tool to support initial investigation of future electricity generation sustainability, which will drive further research that will be able to feed back into the model to enhance future versions with greater detail. The model still provides valuable insight into how to move towards a more sustainable electricity generation future, both through life cycle emissions and costs, for the province of Ontario. The scenarios explored by the model showed that no one generation source is best suited for Ontario. It is likely that future electricity generation in the province will continue to be a blended mix to balance both emissions and cost. If demand increases quickly over the coming decades, storage and demand response will be crucial to meet future peak demands, especially as more intermittent generation (solar/wind) is implemented.

This model could be used by other jurisdictions to assess the sustainability of current and future electricity generation within their system or at a larger national scale. Although there is variation in life cycle assessment data for electricity generation, sources such as NREL's Life Cycle Assessment Harmonization [128] could provide average inputs for technologies used within the jurisdiction. To be applied to other jurisdictions adequate future electricity projections would be required as well as existing installed capacities, as these are the initial inputs required by the model.

Chapter 5. Conclusions and Recommendations

Ontario's electricity supply is one of the cleanest in Canada; however, electricity generation capacity in Ontario is expiring. By 2035 only 24%, or 7.1 GW of Ontario's 2016 existing supply will remain [15]. This lack of capacity will be compensated by an additional 8.3 GW of refurbished nuclear, which will be in service by 2035. The remaining 7.9 GW will need to be fulfilled by other directed procurements or renewal of expiring contracts, and it is within this area in which there is a great amount of flexibility in the system. Ontario also has a unique existing electricity supply that is heavily dependent on hydroelectric and advanced nuclear generation which have contributed base load generation to Ontario's supply for decades. In addition to the variability of capacity in the province, demand has potential to grow as sectors such as transportation or residential and commercial heating are converted to electric power equivalents in order to reduce GHG emissions. Although economic downturns and conservation programs have reduced annual demand significantly in the past decade, further conservation while other sectors electrify to reduce emissions is unlikely [70].

LCA and LCC are tools that can be used to evaluate options of current electricity systems around the world. Recent states of Ontario's electricity system have been evaluated using LCA [14], [56], [57], [63], [64]. Previous studies had also used LCA to look at the impacts of future possible electricity systems in other jurisdictions [55], [58]–[60]. This thesis explored Ontario's future electricity supply through a dual LCA and LCC lens to gain a better understanding of how to enable long-term sustainability both environmentally and financially. Through these criteria, future scenarios were observed in comparison to a reference scenario developed by the IESO.

The major conclusions of this study:

- A model was developed to investigate Ontario's electricity generation supply through a dual lens of life cycle costs and life cycle emissions. This model was verified by using historical installed generation as a model input and compared the life cycle outputs against other recent studies. The historical lifecycle results determined by the model fell within their bounds of the other life cycle studies. It is now a tool that can be used to support long term sustainability planning of electricity generation systems not only in Ontario, but in any other jurisdiction.

- Ontario's future electricity capacity cannot be met using a single generation technology while also supporting emission goals and minimizing system costs.
- From a system perspective, prioritization of one life cycle factor leads to the increase in the other, especially while natural gas remains cost competitive. This reinforces the need to drill down to site specific impacts when considering the addition of new generation in order to reduce both life cycle impacts. In the most competive scenarios system LCC and LCE could be reduced by 4 \$/MWh and 50 t CO_2e/MWh, respectively. However, these factor prioritizations cause a converse increase in the other factor and thus the actual future system will need to comprimize between these two extremes.
- Storage and demand response will need to be implemented to shift energy and reduce peaks. This is especially important as more renewable generation is implemented in the future as Pickering Nuclear closes and carbon taxes make fossil fuel generation less attractive. To support heavy renewable investment storage and demand response capacity would need increase by an additional 2 GW by 2035.
- A case study was performed to show how a policy or decision maker would use the model to generate a nuclear withdrawl scenario. This scenario showed that by halting the planned nuclear refurbishment, the installed generation capacity in Ontario would have to double to meet Ontario's future demand without the support of nuclear. This case study shows the value of the model to decision makers to quickly asses alternate futures, to direct more in depth investigations.

From observing the results of the technology preference scenarios, for the reference demand, only natural gas, wind, and storage & demand response were able to meet the demand for 2035 individually. Under further investigation, although in theory both wind and storage and demand response were determined to be able to supply enough annual electricity, both are questionable due to energy availability. Conversely, the estimated capacity for natural gas generation in the technology preference scenario is likely higher than required, as existing generation facilities could increase production, which would also increase capacity factor, life cycle emissions and life cycle costs. These scenarios show that it is unlikely for a single technology to supply Ontario with its future electricity needs, as the resources are not available within the province's borders, or the technology would increase the annual life cycle costs and life cycle emissions of the system above the reference scenario. These scenarios also helped to bound the the model through the development of provincial technology specific capacity limits, as well as providing preliminary future life cycle costs and life cycle emissions of alternate scenarios.

The life cycle preference scenarios showed that a blend of technologies is required when either low cost or low emission is prioritized. Both scenarios see renewables selected for new generation, supported by existing nuclear and hydroelectric generation. However, excessive commitment to renewable generation will raise annual life cycle costs to the system. In the life cycle emission prioritization scenario (S.LC.Emsn), the life cycle costs of the system increased by \$4 billion by the end of the time horizon. Similarly, the life cycle cost prioritization scenario (S.LC.Cost), saw the system life cycle emissions increase by 6 Mt CO_2 above the reference case by 2035. Also, if demand grows quickly, a higher commitment to renewables will require an increase in storage and demand response to ensure peak demand can be met without relying on intermittent generation sources. These scenarios showed that fixation on a single life cycle factor will negatively impact the other life cycle factor and therefore both need to hold equal priority when deciding

When all scenarios are compared against one another through the metric of cost effectiveness of GHG reduction there was little change in comparison to the reference scenario, in terms of cost effectiveness. Though some scenarios showed a reduction in one life cycle factor the other life cycle factor would conversely increase resulting in no significant improvement in the system, creating a relatively small cost effectiveness of GHG reduction. This result confirms that Ontario's existing electricity system is relatively clean and cost-effective meaning that changes in technology will have low overall impact. However, these small increases in sustainability will need to be chased to continue to reduce both life cycle emissions and life cycle costs in a system that already has relatively low impacts. It is important to note that although the scenarios were comparable in terms of life cycle factors the additional capacity required for some of the scenario, specifically the high future demand scenarios would require significant procurement of additional generation. Across all scenarios both nuclear and hydroelectric generation capacity remained the same, confirming that Ontario will not shift away from its traditional base load generation. These generation sources are effectively at their maximum capacity for the province for the foreseeable future and therefore other generation will be required to meet the demand. Further investigation would be required to determine if larger improvements are available however this would require a study to drill down to site specific information to determine the best technology(s) to meet demand, economic and emission goals.

There are some limitations to this study. This high-level analysis of Ontario's electricity supply utilized some broad assumptions to complete its analysis such as the assumption of static life cycle factors, the non-specific geographic placement of generation sites, and the reliance on capacity and demand forecasts. In relying on capacity and demand data from the IESO, the model also inherits the assumptions used to forecast that data. The model relies heavily on the reported and forecast values provided by public corporations and government bodies such as Natural Resources Canada and Statistics Canada.

This work examined Ontario's future electricity supply through a dual life cycle lens of both life cycle cost and life cycle emissions. Through investigating several scenarios, across multiple demand profiles, it was found that single technology supply for the province is unlikely without tremendous developments in electricity generation technologies. Therefore, Ontario's future electricity supply will require a blend of technologies to meet demand and balance cost and emissions. Through the S.LC scenarios it was shown that fixation on a single life cycle factor causes the results of the other life cycle factor to increase. Therefore, both emissions and costs need to be considered when selecting and implementing new generation. Since the turn of the century Ontario has created a relatively low life cycle emission electricity supply, further emission reduction is possible with increased costs however a limit would be reached by the end of the time horizon. To obtain further emission reduction supply chain and end of life processes would need to be improved. The model developed for this thesis can be updated as more data becomes available or be adapted to analyze other jurisdictions allowing for continuous insights into life cycle impacts of future electricity supply. As shown by the case study in section 4.9, the value of the model developed in this thesis is that it can be used to quickly assess alternate futures in terms of life cycle costs, emissions, and change in generation capacity. This will support decision makers and researchers to quickly assess their hypotheses, enabling them to identify where to focus more detailed investigations.

5.1 Recommendations

The model developed in this thesis can be used by policy makers, decision makers and researchers to quickly preform high level life cycle analysis of Ontario's future electricity generation. Through further generation of alternate scenarios, the breadth of possible futures for Ontario's electricity life cycle emission and life cycle costs can be explored. With capacity and annual generation changing year to year the model should be regularly updated with the most recent Ontario data, which will build the historical profile and expand the time horizon of the model further into the future.

The recommendations for the future development of this model are to; continue to update the model inputs, expand the model to other sectors and to apply the model to other jurisdictions. To update the model both installed and forecast generation capacity need to be updated as well as the life cycle factors of all generation technology should be reassessed against relevant literature. Ontario's electricity system has a complex relationship between supply and demand. By pulling in another sector that is linked to the electricity sector, for example transportation, the impact of electrification of that sector could show the overall life cycle impacts of Ontario's energy system. Additionally, other sustainability factors can be added to the model such as land use, water use and access to reliable energy to further examine the sustainability of Ontario's electricity supply.

This model should be tested against other jurisdictions, to both provide a comparison to this analysis of Ontario as well as provide this new jurisdiction with high level insights on how to drive long term sustainability. A realistic next step would be to setup the model for other Canadian provinces, particularly those with larger contributions from high GHG emission sources, i.e., coal, diesel, and natural gas, such as the provinces Alberta, Saskatchewan, or Nova Scotia. The model developed in this thesis would be able to provide value in determining how to reduce both life cycle emission and life cycle costs of the system, enabling decision makers to guide future electricity generation in the respective jurisdiction.

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Appendix A: VBA Excel Modules

A.1 Reference Scenario

```
Sub Ref()
Worksheets("M2").Activate
Set ActSh = ThisWorkbook.ActiveSheet
Set Data = ThisWorkbook.Worksheets("Gen.Data")
YearHours = 8760
'---TWh Yearly Generation Reference---
For i = 1 To 20
    'Nuclear
    Cells(40, 2 + i).Value = Data.Cells(31, 1 + i).Value *
(Data.Range("D43").Value) * YearHours / (10) ^ 6
    'Natural Gas
    Cells(41, 2 + i).Value = (Data.Cells(4, 1 + i).Value + Data.Cells(12,
1 + i).Value + Data.Cells(20, 1 + i).Value _
                            + Data.Cells(33, 1 + i).Value) *
(Data.Range("D44").Value) * YearHours / (10) ^ 6
    'Waterpower
    Cells(42, 2 + i).Value = (Data.Cells(5, 1 + i).Value + Data.Cells(13,
1 + i).Value + _
                       Data.Cells(21, 1 + i).Value + Data.Cells(34, 1 +
i).Value) _
                       * (Data.Range("D45").Value) * YearHours / (10) ^
6
    'Bioenergy
    Cells(43, 2 + i).Value = (Data.Cells(6, 1 + i).Value + Data.Cells(14,
1 + i).Value + _
                       Data.Cells(22, 1 + i).Value + Data.Cells(35, 1 +
i).Value) _
                       * (Data.Range("D46").Value) * YearHours / (10) ^
6
    'Wind
    Cells(44, 2 + i).Value = (Data.Cells(7, 1 + i).Value + Data.Cells(15,
1 + i).Value + _
                       Data.Cells(23, 1 + i).Value + Data.Cells(36, 1 +
i).Value) _
                       * (Data.Range("D47").Value) * YearHours / (10) ^
6
    'Solar PV
    Cells(45, 2 + i).Value = (Data.Cells(8, 1 + i).Value + Data.Cells(16,
1 + i).Value + _
                       Data.Cells(24, 1 + i).Value + Data.Cells(37, 1 +
i).Value) _
                       * (Data.Range("D48").Value) * YearHours / (10) ^
6
    'Storage & Demand Response
    Cells(46, 2 + i).Value = (Data.Cells(9, 1 + i).Value + Data.Cells(17,
1 + i).Value + _
                       Data.Cells(24, 1 + i).Value + Data.Cells(38, 1 +
i).Value) _
                       * (Data.Range("D49").Value) * YearHours / (10) ^
6
    'Total
    Cells(47, 2 + i).Value = Application.Sum(Range(Cells(40, 2 + i),
Cells(46, 2 + i)))
Next i

'Store Reference Total Generation for Future Reference
```

```
Dim Ref As Variant
Set Ref = Range("C47:V47")
'Selection = Range("C48:V48").Select
'Selection.Value = Ref.Value

'---Emissions---
For i = 1 To 20
    'TWh*g/GJ*3600000GJ/TWh*MegaTonne/1000000000000gram
    'i.e. (3.6[GJ*MtCO2e]/[TWh*g])
    For j = 1 To 7
    Cells(49 + j, 2 + i).Value = ActSh.Cells(39 + j, 2 + i).Value *
Sheets("Gen.Data").Cells(42 + j, 2).Value * 0.0000036
    Next j
    'Total
    Cells(57, 2 + i).Value = Application.Sum(Range(Cells(50, 2 + i),
Cells(56, 2 + i)))
Next i

'---COSTS---
For i = 1 To 20
    'TWh*LOCE$/MWh*[10^6MWh]/TWh*B$/10^9$
    For j = 1 To 7
    Cells(59 + j, 2 + i).Value = Cells(39 + j, 2 + i).Value * Data.Cells(42
+ j, 5).Value / ((10) ^ 3)
    Next j
    'Total
    Cells(67, 2 + i).Value = Application.Sum(Range(Cells(60, 2 + i),
Cells(66, 2 + i)))
Next i

'---MW from total TWh assigned---
For i = 1 To 20
    For j = 1 To 7
    Cells(69 + j, 2 + i).Value = Cells(39 + j, 2 + i).Value * ((10) ^ 6)
/ (Data.Cells(42 + j, 4).Value * 8760)
    Next j
    Cells(77, 2 + i).Value = WorksheetFunction.Sum(Range(Cells(70, 2 +
i), Cells(76, 2 + i)))
Next i

End Sub
```

A.2 Graph Scenario Life Cycle Results

```
Sub Graphs()
'Emission Graph
Dim Egraph As ChartObject
Dim LCE As Chart
Dim Emissions As SeriesCollection
Dim Ref_Ems As Series
Dim Hist_Ems As Series
Dim years As Range
Set years = Range("C39:V39")
Dim Hist_years As Variant
Hist_years = Sheets("Gen.Data").Range("B70:Q70").Value
If Sheets("M2").ChartObjects.Count > 0 Then
    Sheets("M2").ChartObjects.Delete
End If
Selection = Cells(2, 3).Select

'Create a chart
```

```
Set Egraph = Sheets("M2").ChartObjects.Add(Left:=ActiveCell.Left + 1,
Width:=665, Top:=ActiveCell.Top, Height:=405)
    'Name Chart
    Egraph.Name = "Yearly Life Cycle Emissions"
    '
    Set LCE = Egraph.Chart
    With LCE
        .HasTitle = True
        .ChartTitle.Text = "Yearly Life Cycle Emissions"
        .ChartType = xlXYScatterLinesNoMarkers
        .Axes(xlValue).MinimumScale = 0
        .Axes(xlValue).HasTitle = True
        .Axes(xlValue).AxisTitle.Caption = "Life Cycle Emissions (Mt
CO2e)"
        .Axes(xlValue).AxisTitle.Characters(Start:=28,
Length:=1).Font.Subscript = True
        .Axes(xlCategory).HasTitle = True
        .Axes(xlCategory).AxisTitle.Caption = "Year"
        Set Emissions = .SeriesCollection
        Set Ref_Ems = Emissions.NewSeries
            With Ref_Ems
                .Name = ScenarioName
                .XValues = years
                .Values = Range("C57:V57")
                .Format.Line.Weight = 2
            End With
        Set Hist_Ems = Emissions.NewSeries
            With Hist_Ems
                .Name = "Historical"
                .XValues = Hist_years
                .Values = Sheets("Gen.Data").Range("B78:Q78")
                .Format.Line.ForeColor.RGB = RGB(0, 0, 0)
                .Format.Line.Weight = 2
            End With
    End With

Selection.Offset(0, 10).Select
'Cost Graph
Dim Cgraph As ChartObject
Dim LCC As Chart
Dim Costs As SeriesCollection
Dim Ref_cost As Series
Dim Hist_Cost As Series

'Create a chart
Set Cgraph = ActiveSheet.ChartObjects.Add(Left:=ActiveCell.Left + 1,
Width:=665, Top:=ActiveCell.Top, Height:=405)
    'Name Chart
    Cgraph.Name = "Yearly Life Cycle Costs"
    '
    Set LCC = Cgraph.Chart
    With LCC
        .HasTitle = True
        .ChartTitle.Text = "Yearly Life Cycle Costs"
        .ChartType = xlXYScatterLinesNoMarkers
        .Axes(xlValue).MinimumScale = 0
        .Axes(xlValue).HasTitle = True
        .Axes(xlValue).AxisTitle.Caption = "Life Cycle Cost ($B)"
        .Axes(xlCategory).HasTitle = True
        .Axes(xlCategory).AxisTitle.Caption = "Year"
```

```
        Set Costs = .SeriesCollection
        Set Ref_cost = Costs.NewSeries
            With Ref_cost
                .Name = ScenarioName
                .XValues = years
                .Values = Range("C67:V67")
                .Format.Line.Weight = 2
            End With
            Set Hist_Cost = Costs.NewSeries
            With Hist_Cost
                .Name = "Historical"
                .XValues = Hist_years
                .Values = Sheets("Gen.Data").Range("B88:Q88")
                .Format.Line.ForeColor.RGB = RGB(0, 0, 0)
                .Format.Line.Weight = 2
            End With
    End With

End Sub
```

A.3 Technology Preference

```
Sub TechPref()
'---TWh Yearly Generation Reference---
Set Data = ThisWorkbook.Worksheets("Gen.Data")
YearHours = 8760
For i = 1 To 20
    'Nuclear
    Cells(40,   2   +   i).Value   =   Data.Cells(31,   1   +   i).Value   *
(Data.Range("D43").Value) * YearHours / (10) ^ 6
    'Natural Gas
    Cells(41, 2 + i).Value = (Data.Cells(4, 1 + i).Value + Data.Cells(12,
1 + i).Value + Data.Cells(20, 1 + i).Value _
                            +   Data.Cells(33,   1   +   i).Value)   *
(Data.Range("D44").Value) * YearHours / (10) ^ 6
    'Waterpower
    Cells(42, 2 + i).Value = (Data.Cells(5, 1 + i).Value + Data.Cells(13,
1 + i).Value + Data.Cells(21, 1 + i).Value _
                            +   Data.Cells(34,   1   +   i).Value)   *
(Data.Range("D45").Value) * YearHours / (10) ^ 6
    'Bioenergy
    Cells(43, 2 + i).Value = (Data.Cells(6, 1 + i).Value + Data.Cells(14,
1 + i).Value + Data.Cells(22, 1 + i).Value _
                            +   Data.Cells(35,   1   +   i).Value)   *
(Data.Range("D46").Value) * YearHours / (10) ^ 6
    'Wind
    Cells(44, 2 + i).Value = (Data.Cells(7, 1 + i).Value + Data.Cells(15,
1 + i).Value + Data.Cells(23, 1 + i).Value _
                            +   Data.Cells(36,   1   +   i).Value)   *
(Data.Range("D47").Value) * YearHours / (10) ^ 6
    'Solar PV
    Cells(45, 2 + i).Value = (Data.Cells(8, 1 + i).Value + Data.Cells(16,
1 + i).Value + Data.Cells(24, 1 + i).Value _
                            +   Data.Cells(37,   1   +   i).Value)   *
(Data.Range("D48").Value) * YearHours / (10) ^ 6
    'Storage & Demand Response
    Cells(46, 2 + i).Value = (Data.Cells(9, 1 + i).Value + Data.Cells(17,
1 + i).Value + Data.Cells(24, 1 + i).Value _
                            +   Data.Cells(38,   1   +   i).Value)   *
(Data.Range("D49").Value) * YearHours / (10) ^ 6
    'Total
```

```
    Cells(47, 2 + i).Value = Application.Sum(Range(Cells(40, 2 + i),
Cells(46, 2 + i)))
    'Demand profile
    'Cells(48, 2 + i).Value = DemandProfile(i)
Next i

'Store Reference Total Generation for Future Reference
Dim Ref As Variant, Diff As Double, XS As Double
Set Ref = Range("C47:V47")
Selection = Range("C48:V48").Select
Selection.Value = Ref.Value

If ScenarioName <> "Reference Demand " Then
    For i = 1 To 20
        If Cells(48, 2 + i).Value < DemandProfile(i) Then Cells(48, 2 +
i).Value = DemandProfile(i)
    Next i
End If

'Removing Directed and Expiring Capacity
For i = 1 To 20
    'Nuclear
    Cells(40, 2 + i).Value = Data.Cells(31, 1 + i).Value *
(Data.Range("D43").Value) * YearHours / (10) ^ 6
    'Natural Gas
    Cells(41, 2 + i).Value = (Data.Cells(4, 1 + i).Value + Data.Cells(12,
1 + i).Value) * (Data.Range("D44").Value) * YearHours / (10) ^ 6
    'Waterpower
    Cells(42, 2 + i).Value = (Data.Cells(5, 1 + i).Value + Data.Cells(13,
1 + i).Value) * (Data.Range("D45").Value) * YearHours / (10) ^ 6
    'Bioenergy
    Cells(43, 2 + i).Value = (Data.Cells(6, 1 + i).Value + Data.Cells(14,
1 + i).Value) * (Data.Range("D46").Value) * YearHours / (10) ^ 6
    'Wind
    Cells(44, 2 + i).Value = (Data.Cells(7, 1 + i).Value + Data.Cells(15,
1 + i).Value) * (Data.Range("D47").Value) * YearHours / (10) ^ 6
    'Solar PV
    Cells(45, 2 + i).Value = (Data.Cells(8, 1 + i).Value + Data.Cells(16,
1 + i).Value) * (Data.Range("D48").Value) * YearHours / (10) ^ 6
    'Storage & Demand Response
    Cells(46, 2 + i).Value = (Data.Cells(9, 1 + i).Value + Data.Cells(17,
1 + i).Value) * (Data.Range("D49").Value) * YearHours / (10) ^ 6
    'Total
    Cells(47, 2 + i).Value = Application.Sum(Range(Cells(40, 2 + i),
Cells(46, 2 + i)))
Next i
'Set base Emissions and Cost before difference is alloted
For i = 1 To 20
'---Emissions---
    'TWh*g/GJ*3600000GJ/TWh*MetricTonne/1000000gram
    'i.e. (3.6[GJ*MtCO2e]/[TWh*g])
    'Nuclear
    Cells(50, 2 + i).Value = Cells(40, 2 + i).Value * Factors(0, 1) *
0.0000036
    'Natural Gas
    Cells(51, 2 + i).Value = Cells(41, 2 + i).Value * Factors(1, 1) *
0.0000036
    'Waterpower
    Cells(52, 2 + i).Value = Cells(42, 2 + i).Value * Factors(2, 1) *
0.0000036
```

```
    'Bioenergy
    Cells(53, 2 + i).Value = Cells(43, 2 + i).Value * Factors(3, 1) *
0.0000036
    'Wind
    Cells(54, 2 + i).Value = Cells(44, 2 + i).Value * Factors(4, 1) *
0.0000036
    'Solar PV
    Cells(55, 2 + i).Value = Cells(45, 2 + i).Value * Factors(5, 1) *
0.0000036
    'Storage & Demand
    Cells(56, 2 + i).Value = Cells(46, 2 + i).Value * Factors(6, 1) *
0.0000036
    'Total
    Cells(57, 2 + i).Value = Application.Sum(Range(Cells(50, 2 + i),
Cells(56, 2 + i)))
'---COSTS---
    'TWh*LOCE$/MWh*[10^6MWh]/TWh*B$/10^9$
    'Nuclear
    Cells(60, 2 + i).Value = Cells(40, 2 + i).Value * Factors(0, 2) /
((10) ^ 3)
    'Natural Gas
    Cells(61, 2 + i).Value = Cells(41, 2 + i).Value * Factors(1, 2) /
((10) ^ 3)
    'Waterpower
    Cells(62, 2 + i).Value = Cells(42, 2 + i).Value * Factors(2, 2) /
((10) ^ 3)
    'Bioenery
    Cells(63, 2 + i).Value = Cells(43, 2 + i).Value * Factors(3, 2) /
((10) ^ 3)
    'Wind
    Cells(64, 2 + i).Value = Cells(44, 2 + i).Value * Factors(4, 2) /
((10) ^ 3)
    'Solar PV
    Cells(65, 2 + i).Value = Cells(45, 2 + i).Value * Factors(5, 2) /
((10) ^ 3)
    'Storage & Demand
    Cells(66, 2 + i).Value = Cells(46, 2 + i).Value * Factors(6, 2) /
((10) ^ 3)
    'Total
    Cells(67, 2 + i).Value = Application.Sum(Range(Cells(60, 2 + i),
Cells(66, 2 + i)))
Next i

'Distribution of difference to meet demand
'Add respective emissions and costs
For i = 1 To 20
    'Reset boolean limit checks
    LimitNuc = False
    LimitNG = False
    LimitWat = False
    LimitBio = False
    LimitWin = False
    LimitSol = False
    LimitSDR = False
    'define active limits
    If Nuc = 0 Then LimitNuc = True
    If NG = 0 Then LimitNG = True
    If Wat = 0 Then LimitWat = True
    If Bio = 0 Then LimitBio = True
    If Win = 0 Then LimitWin = True
```

```
    If Sol = 0 Then LimitSol = True
    If SDR = 0 Then LimitSDR = True
    'Find difference
    Diff = Cells(48, 2 + i).Value - Cells(47, 2 + i).Value
    Do While Diff > 0.001
    'Apply Difference
        'Nuclear
        If Nuc > 0 Then
            XS = Factors(0, 0) - Cells(40, 2 + i)
            Cells(50, 2 + i).Value = Cells(50, 2 + i).Value + XS *
Factors(0, 1) * 0.0000036
            Cells(60, 2 + i).Value = Cells(60, 2 + i).Value + XS *
Factors(0, 2) / ((10) ^ 3)
            Cells(40, 2 + i).Value = Factors(0, 0)
            LimitNuc = True
        End If
        'Natural Gas
        If NG > 0 Then
            XS = Factors(1, 0) - Cells(41, 2 + i)
            Cells(51, 2 + i).Value = Cells(51, 2 + i).Value + XS *
Factors(1, 1) * 0.0000036
            Cells(61, 2 + i).Value = Cells(61, 2 + i).Value + XS *
Factors(1, 2) / ((10) ^ 3)
            Cells(41, 2 + i).Value = Factors(1, 0)
            LimitNG = True
        End If
        'Waterpower
        If Wat > 0 Then
            XS = Factors(2, 0) - Cells(42, 2 + i)
            Cells(52, 2 + i).Value = Cells(52, 2 + i).Value + XS *
Factors(2, 1) * 0.0000036
            Cells(62, 2 + i).Value = Cells(62, 2 + i).Value + XS *
Factors(2, 2) / ((10) ^ 3)
            Cells(42, 2 + i).Value = Factors(2, 0)
            LimitWat = True
        End If
        'Bioenergy
        If Bio > 0 Then
            XS = Factors(3, 0) - Cells(43, 2 + i)
            Cells(53, 2 + i).Value = Cells(53, 2 + i).Value + XS *
Factors(3, 1) * 0.0000036
            Cells(63, 2 + i).Value = Cells(63, 2 + i).Value + XS *
Factors(3, 2) / ((10) ^ 3)
            Cells(43, 2 + i).Value = Factors(3, 0)
            LimitBio = True
        End If
        'Wind
        If Win > 0 Then
            XS = Factors(4, 0) - Cells(44, 2 + i)
            Cells(54, 2 + i).Value = Cells(54, 2 + i).Value + XS *
Factors(4, 1) * 0.0000036
            Cells(64, 2 + i).Value = Cells(64, 2 + i).Value + XS *
Factors(4, 2) / ((10) ^ 3)
            Cells(44, 2 + i).Value = Factors(4, 0)
            LimitWin = True
        End If
        'Solar
        If Sol > 0 Then
            XS = Factors(5, 0) - Cells(45, 2 + i)
```

```
            Cells(55, 2 + i).Value = Cells(55, 2 + i).Value + XS *
Factors(5, 1) * 0.0000036
            Cells(65, 2 + i).Value = Cells(65, 2 + i).Value + XS *
Factors(5, 2) / ((10) ^ 3)
            Cells(45, 2 + i).Value = Factors(5, 0)
            LimitSol = True
        End If
        'Storage
        If SDR > 0 Then
            XS = Factors(6, 0) - Cells(46, 2 + i)
            Cells(56, 2 + i).Value = Cells(56, 2 + i).Value + XS *
Factors(6, 1) * 0.0000036
            Cells(66, 2 + i).Value = Cells(66, 2 + i).Value + XS *
Factors(6, 2) / ((10) ^ 3)
            Cells(46, 2 + i).Value = Factors(6, 0)
            LimitSDR = True
        End If
        'Re-Total
        Cells(47, 2 + i).Value = WorksheetFunction.Sum(Range(Cells(40, 2
+ i), Cells(46, 2 + i)))
        'Recalculate Difference
        Diff = Cells(48, 2 + i).Value - Cells(47, 2 + i).Value
        If LimitNuc = True And LimitNG = True And LimitWat = True And
LimitBio = True And LimitWin = True And LimitSol = True And LimitSDR =
True Then
            MsgBox ("All limits reached")
            Exit Do
        End If
    Loop
Next i

'---MW from total TWh assigned---
For i = 1 To 20
    For j = 0 To 6
    Cells(70 + j, 2 + i).Value = Cells(40 + j, 2 + i).Value * ((10) ^ 6)
/ (Data.Cells(43 + j, 4).Value * YearHours)
    Next j
    Cells(77, 2 + i).Value = WorksheetFunction.Sum(Range(Cells(70, 2 +
i), Cells(76, 2 + i)))
Next i

End Sub
```

A.4 Technology Preference with Limits

```
Sub TechPref()
'---TWh Yearly Generation Reference---
Set Data = ThisWorkbook.Worksheets("Gen.Data")
YearHours = 8760
For i = 1 To 20
    'Nuclear
    Cells(40, 2 + i).Value = Data.Cells(31, 1 + i).Value *
(Data.Range("D43").Value) * YearHours / (10) ^ 6
    'Natural Gas
    Cells(41, 2 + i).Value = (Data.Cells(4, 1 + i).Value + Data.Cells(12,
1 + i).Value + Data.Cells(20, 1 + i).Value _
                            + Data.Cells(33, 1 + i).Value) *
(Data.Range("D44").Value) * YearHours / (10) ^ 6
    'Waterpower
    Cells(42, 2 + i).Value = (Data.Cells(5, 1 + i).Value + Data.Cells(13,
1 + i).Value + Data.Cells(21, 1 + i).Value _
```

```
                            +   Data.Cells(34,   1   +   i).Value)   *
(Data.Range("D45").Value) * YearHours / (10) ^ 6
    'Bioenergy
    Cells(43, 2 + i).Value = (Data.Cells(6, 1 + i).Value + Data.Cells(14,
1 + i).Value + Data.Cells(22, 1 + i).Value _
                            +   Data.Cells(35,   1   +   i).Value)   *
(Data.Range("D46").Value) * YearHours / (10) ^ 6
    'Wind
    Cells(44, 2 + i).Value = (Data.Cells(7, 1 + i).Value + Data.Cells(15,
1 + i).Value + Data.Cells(23, 1 + i).Value _
                            +   Data.Cells(36,   1   +   i).Value)   *
(Data.Range("D47").Value) * YearHours / (10) ^ 6
    'Solar PV
    Cells(45, 2 + i).Value = (Data.Cells(8, 1 + i).Value + Data.Cells(16,
1 + i).Value + Data.Cells(24, 1 + i).Value _
                            +   Data.Cells(37,   1   +   i).Value)   *
(Data.Range("D48").Value) * YearHours / (10) ^ 6
    'Storage & Demand Response
    Cells(46, 2 + i).Value = (Data.Cells(9, 1 + i).Value + Data.Cells(17,
1 + i).Value + Data.Cells(24, 1 + i).Value _
                            +   Data.Cells(38,   1   +   i).Value)   *
(Data.Range("D49").Value) * YearHours / (10) ^ 6
    'Total
    Cells(47,  2  +  i).Value  =  Application.Sum(Range(Cells(40,  2  +  i),
Cells(46, 2 + i)))
    'Demand profile
    'Cells(48, 2 + i).Value = DemandProfile(i)
Next i

'Store Reference Total Generation for Future Reference
Dim Ref As Variant, Diff As Double, XS As Double
Set Ref = Range("C47:V47")
Selection = Range("C48:V48").Select
Selection.Value = Ref.Value

If ScenarioName <> "Reference Demand " Then
    For i = 1 To 20
        If Cells(48, 2 + i).Value < DemandProfile(i) Then Cells(48, 2 +
i).Value = DemandProfile(i)
    Next i
End If

'Removing Directed and Expiring Capacity
For i = 1 To 20
    'Nuclear
    Cells(40,   2   +   i).Value   =   Data.Cells(31,   1   +   i).Value   *
(Data.Range("D43").Value) * YearHours / (10) ^ 6
    'Natural Gas
    Cells(41, 2 + i).Value = (Data.Cells(4, 1 + i).Value + Data.Cells(12,
1 + i).Value) * (Data.Range("D44").Value) * YearHours / (10) ^ 6
    'Waterpower
    Cells(42, 2 + i).Value = (Data.Cells(5, 1 + i).Value + Data.Cells(13,
1 + i).Value) * (Data.Range("D45").Value) * YearHours / (10) ^ 6
    'Bioenergy
    Cells(43, 2 + i).Value = (Data.Cells(6, 1 + i).Value + Data.Cells(14,
1 + i).Value) * (Data.Range("D46").Value) * YearHours / (10) ^ 6
    'Wind
    Cells(44, 2 + i).Value = (Data.Cells(7, 1 + i).Value + Data.Cells(15,
1 + i).Value) * (Data.Range("D47").Value) * YearHours / (10) ^ 6
    'Solar PV
```

```
    Cells(45, 2 + i).Value = (Data.Cells(8, 1 + i).Value + Data.Cells(16,
1 + i).Value) * (Data.Range("D48").Value) * YearHours / (10) ^ 6
    'Storage & Demand Response
    Cells(46, 2 + i).Value = (Data.Cells(9, 1 + i).Value + Data.Cells(17,
1 + i).Value) * (Data.Range("D49").Value) * YearHours / (10) ^ 6
    'Total
    Cells(47, 2 + i).Value = Application.Sum(Range(Cells(40, 2 + i),
Cells(46, 2 + i)))
Next i
'Set base Emissions and Cost before difference is alloted
For i = 1 To 20
'---Emissions---
    'TWh*g/GJ*3600000GJ/TWh*MetricTonne/1000000gram
    'i.e. (3.6[GJ*MtCO2e]/[TWh*g])
    'Nuclear
    Cells(50, 2 + i).Value = Cells(40, 2 + i).Value * Factors(0, 1) *
0.0000036
    'Natural Gas
    Cells(51, 2 + i).Value = Cells(41, 2 + i).Value * Factors(1, 1) *
0.0000036
    'Waterpower
    Cells(52, 2 + i).Value = Cells(42, 2 + i).Value * Factors(2, 1) *
0.0000036
    'Bioenergy
    Cells(53, 2 + i).Value = Cells(43, 2 + i).Value * Factors(3, 1) *
0.0000036
    'Wind
    Cells(54, 2 + i).Value = Cells(44, 2 + i).Value * Factors(4, 1) *
0.0000036
    'Solar PV
    Cells(55, 2 + i).Value = Cells(45, 2 + i).Value * Factors(5, 1) *
0.0000036
    'Storage & Demand
    Cells(56, 2 + i).Value = Cells(46, 2 + i).Value * Factors(6, 1) *
0.0000036
    'Total
    Cells(57, 2 + i).Value = Application.Sum(Range(Cells(50, 2 + i),
Cells(56, 2 + i)))
'---COSTS---
    'TWh*LOCE$/MWh*[10^6MWh]/TWh*B$/10^9$
    'Nuclear
    Cells(60, 2 + i).Value = Cells(40, 2 + i).Value * Factors(0, 2) /
((10) ^ 3)
    'Natural Gas
    Cells(61, 2 + i).Value = Cells(41, 2 + i).Value * Factors(1, 2) /
((10) ^ 3)
    'Waterpower
    Cells(62, 2 + i).Value = Cells(42, 2 + i).Value * Factors(2, 2) /
((10) ^ 3)
    'Bioenery
    Cells(63, 2 + i).Value = Cells(43, 2 + i).Value * Factors(3, 2) /
((10) ^ 3)
    'Wind
    Cells(64, 2 + i).Value = Cells(44, 2 + i).Value * Factors(4, 2) /
((10) ^ 3)
    'Solar PV
    Cells(65, 2 + i).Value = Cells(45, 2 + i).Value * Factors(5, 2) /
((10) ^ 3)
    'Storage & Demand
```

```
    Cells(66, 2 + i).Value = Cells(46, 2 + i).Value * Factors(6, 2) /
((10) ^ 3)
    'Total
    Cells(67, 2 + i).Value = Application.Sum(Range(Cells(60, 2 + i),
Cells(66, 2 + i)))
Next i

'Distribution of difference to meet demand
'Add respective emissions and costs
For i = 1 To 20
    'Reset boolean limit checks
    LimitNuc = False
    LimitNG = False
    LimitWat = False
    LimitBio = False
    LimitWin = False
    LimitSol = False
    LimitSDR = False
    'define active limits
    If Nuc = 0 Then LimitNuc = True
    If NG = 0 Then LimitNG = True
    If Wat = 0 Then LimitWat = True
    If Bio = 0 Then LimitBio = True
    If Win = 0 Then LimitWin = True
    If Sol = 0 Then LimitSol = True
    If SDR = 0 Then LimitSDR = True
    'Find difference
    Diff = Cells(48, 2 + i).Value - Cells(47, 2 + i).Value
    Do While Diff > 0.001
    'Apply Difference
        'Nuclear
        If LimitNuc = False And Nuc > 0 And (Cells(40, 2 + i) + Diff *
Nuc) <= Factors(0, 0) Then
            Cells(40, 2 + i).Value = Cells(40, 2 + i) + Diff * Nuc
            Cells(50, 2 + i).Value = Cells(50, 2 + i).Value + Diff * Nuc
* Factors(0, 1) * 0.0000036
            Cells(60, 2 + i).Value = Cells(60, 2 + i).Value + Diff * Nuc
* Factors(0, 2) / ((10) ^ 3)
        ElseIf LimitNuc = False And Nuc > 0 Then
            XS = Factors(0, 0) - Cells(40, 2 + i)
            Cells(50, 2 + i).Value = Cells(50, 2 + i).Value + XS *
Factors(0, 1) * 0.0000036
            Cells(60, 2 + i).Value = Cells(60, 2 + i).Value + XS *
Factors(0, 2) / ((10) ^ 3)
            Cells(40, 2 + i).Value = Factors(0, 0)
            LimitNuc = True
        End If
        'Natural Gas
        If LimitNG = False And NG > 0 And (Cells(41, 2 + i) + Diff * NG)
<= Factors(1, 0) Then
            Cells(41, 2 + i).Value = Cells(41, 2 + i) + Diff * NG
            Cells(51, 2 + i).Value = Cells(51, 2 + i).Value + Diff * NG
* Factors(1, 1) * 0.0000036
            Cells(61, 2 + i).Value = Cells(61, 2 + i).Value + Diff * NG
* Factors(1, 2) / ((10) ^ 3)
        ElseIf LimitNG = False And NG > 0 Then
            XS = Factors(1, 0) - Cells(41, 2 + i)
            Cells(51, 2 + i).Value = Cells(51, 2 + i).Value + XS *
Factors(1, 1) * 0.0000036
```

```
            Cells(61, 2 + i).Value = Cells(61, 2 + i).Value + XS *
Factors(1, 2) / ((10) ^ 3)
            Cells(41, 2 + i).Value = Factors(1, 0)
            LimitNG = True
        End If
        'Waterpower
        If LimitWat = False And Wat > 0 And (Cells(42, 2 + i) + Diff *
Wat) <= Factors(2, 0) Then
            Cells(42, 2 + i).Value = Cells(42, 2 + i) + Diff * Wat
            Cells(52, 2 + i).Value = Cells(52, 2 + i).Value + Diff * Wat
* Factors(2, 1) * 0.0000036
            Cells(62, 2 + i).Value = Cells(62, 2 + i).Value + Diff * Wat
* Factors(2, 2) / ((10) ^ 3)
        ElseIf LimitWat = False And Wat > 0 Then
            XS = Factors(2, 0) - Cells(42, 2 + i)
            Cells(52, 2 + i).Value = Cells(52, 2 + i).Value + XS *
Factors(2, 1) * 0.0000036
            Cells(62, 2 + i).Value = Cells(62, 2 + i).Value + XS *
Factors(2, 2) / ((10) ^ 3)
            Cells(42, 2 + i).Value = Factors(2, 0)
            LimitWat = True
        End If
        'Bioenergy
        If LimitBio = False And Bio > 0 And (Cells(43, 2 + i) + Diff *
Bio) <= Factors(3, 0) Then
            Cells(43, 2 + i).Value = Cells(43, 2 + i) + Diff * Bio
            Cells(53, 2 + i).Value = Cells(53, 2 + i).Value + Diff * Bio
* Factors(3, 1) * 0.0000036
            Cells(63, 2 + i).Value = Cells(63, 2 + i).Value + Diff * Bio
* Factors(3, 2) / ((10) ^ 3)
        ElseIf LimitBio = False And Bio > 0 Then
            XS = Factors(3, 0) - Cells(43, 2 + i)
            Cells(53, 2 + i).Value = Cells(53, 2 + i).Value + XS *
Factors(3, 1) * 0.0000036
            Cells(63, 2 + i).Value = Cells(63, 2 + i).Value + XS *
Factors(3, 2) / ((10) ^ 3)
            Cells(43, 2 + i).Value = Factors(3, 0)
            LimitBio = True
        End If
        'Wind
        If LimitWin = False And Win > 0 And (Cells(44, 2 + i) + Diff *
Win) <= Factors(4, 0) Then
            Cells(44, 2 + i).Value = Cells(44, 2 + i) + Diff * Win
            Cells(54, 2 + i).Value = Cells(54, 2 + i).Value + Diff * Win
* Factors(4, 1) * 0.0000036
            Cells(64, 2 + i).Value = Cells(64, 2 + i).Value + Diff * Win
* Factors(4, 2) / ((10) ^ 3)
        ElseIf LimitWin = False And Win > 0 Then
            XS = Factors(4, 0) - Cells(44, 2 + i)
            Cells(54, 2 + i).Value = Cells(54, 2 + i).Value + XS *
Factors(4, 1) * 0.0000036
            Cells(64, 2 + i).Value = Cells(64, 2 + i).Value + XS *
Factors(4, 2) / ((10) ^ 3)
            Cells(44, 2 + i).Value = Factors(4, 0)
            LimitWin = True
        End If
        'Solar
        If LimitSol = False And Sol > 0 And (Cells(45, 2 + i) + Diff *
Sol) <= Factors(5, 0) Then
            Cells(45, 2 + i).Value = Cells(45, 2 + i) + Diff * Sol
```

```
            Cells(55, 2 + i).Value = Cells(55, 2 + i).Value + Diff * Sol
* Factors(5, 1) * 0.0000036
            Cells(65, 2 + i).Value = Cells(65, 2 + i).Value + Diff * Sol
* Factors(5, 2) / ((10) ^ 3)
        ElseIf LimitSol = False And Sol > 0 Then
            XS = Factors(5, 0) - Cells(45, 2 + i)
            Cells(55, 2 + i).Value = Cells(55, 2 + i).Value + XS *
Factors(5, 1) * 0.0000036
            Cells(65, 2 + i).Value = Cells(65, 2 + i).Value + XS *
Factors(5, 2) / ((10) ^ 3)
            Cells(45, 2 + i).Value = Factors(5, 0)
            LimitSol = True
        End If
        'Storage
        If LimitSDR = False And SDR > 0 And (Cells(46, 2 + i) + Diff *
SDR) <= Factors(6, 0) Then
            Cells(46, 2 + i).Value = Cells(46, 2 + i) + Diff * SDR
            Cells(56, 2 + i).Value = Cells(56, 2 + i).Value + Diff * SDR
* Factors(6, 1) * 0.0000036
            Cells(66, 2 + i).Value = Cells(66, 2 + i).Value + Diff * SDR
* Factors(6, 2) / ((10) ^ 3)
        ElseIf LimitSDR = False And SDR > 0 Then
            XS = Factors(6, 0) - Cells(46, 2 + i)
            Cells(56, 2 + i).Value = Cells(56, 2 + i).Value + XS *
Factors(6, 1) * 0.0000036
            Cells(66, 2 + i).Value = Cells(66, 2 + i).Value + XS *
Factors(6, 2) / ((10) ^ 3)
            Cells(46, 2 + i).Value = Factors(6, 0)
            LimitSDR = True
        End If
        'Re-Total
        Cells(47, 2 + i).Value = WorksheetFunction.Sum(Range(Cells(40, 2
+ i), Cells(46, 2 + i)))
        'Recalculate Difference
        Diff = Cells(48, 2 + i).Value - Cells(47, 2 + i).Value
        If LimitNuc = True And LimitNG = True And LimitWat = True And
LimitBio = True And LimitWin = True And LimitSol = True And LimitSDR =
True Then
            MsgBox ("All limits reached")
            Exit Do
        End If
    Loop
Next i

'---MW from total TWh assigned---
For i = 1 To 20
    For j = 0 To 6
    Cells(70 + j, 2 + i).Value = Cells(40 + j, 2 + i).Value * ((10) ^ 6)
/ (Data.Cells(43 + j, 4).Value * YearHours)
    Next j
    Cells(77, 2 + i).Value = WorksheetFunction.Sum(Range(Cells(70, 2 +
i), Cells(76, 2 + i)))
Next i

End Sub
```

A.5 Life Cycle Factor Preference

```
Sub FactorPref()
```

```
'---TWh Yearly Generation Reference---
Set Data = ThisWorkbook.Worksheets("Gen.Data")
YearHours = 8760
For i = 1 To 20
    'Nuclear
    Cells(40, 2 + i).Value = Data.Cells(31, 1 + i).Value *
(Data.Range("D43").Value) * YearHours / (10) ^ 6
    'Natural Gas
    Cells(41, 2 + i).Value = (Data.Cells(4, 1 + i).Value + Data.Cells(12,
1 + i).Value + Data.Cells(20, 1 + i).Value _
                            + Data.Cells(33, 1 + i).Value) *
(Data.Range("D44").Value) * YearHours / (10) ^ 6
    'Waterpower
    Cells(42, 2 + i).Value = (Data.Cells(5, 1 + i).Value + Data.Cells(13,
1 + i).Value + Data.Cells(21, 1 + i).Value _
                            + Data.Cells(34, 1 + i).Value) *
(Data.Range("D45").Value) * YearHours / (10) ^ 6
    'Bioenergy
    Cells(43, 2 + i).Value = (Data.Cells(6, 1 + i).Value + Data.Cells(14,
1 + i).Value + Data.Cells(22, 1 + i).Value _
                            + Data.Cells(35, 1 + i).Value) *
(Data.Range("D46").Value) * YearHours / (10) ^ 6
    'Wind
    Cells(44, 2 + i).Value = (Data.Cells(7, 1 + i).Value + Data.Cells(15,
1 + i).Value + Data.Cells(23, 1 + i).Value _
                            + Data.Cells(36, 1 + i).Value) *
(Data.Range("D47").Value) * YearHours / (10) ^ 6
    'Solar PV
    Cells(45, 2 + i).Value = (Data.Cells(8, 1 + i).Value + Data.Cells(16,
1 + i).Value + Data.Cells(24, 1 + i).Value _
                            + Data.Cells(37, 1 + i).Value) *
(Data.Range("D48").Value) * YearHours / (10) ^ 6
    'Storage & Demand Response
    Cells(46, 2 + i).Value = (Data.Cells(9, 1 + i).Value + Data.Cells(17,
1 + i).Value + Data.Cells(24, 1 + i).Value _
                            + Data.Cells(38, 1 + i).Value) *
(Data.Range("D49").Value) * YearHours / (10) ^ 6
    'Total
    Cells(47, 2 + i).Value = Application.Sum(Range(Cells(40, 2 + i),
Cells(46, 2 + i)))
    'Demand profile
    'Cells(48, 2 + i).Value = DemandProfile(i)
Next i

'Store Reference Total Generation for Future Reference
Dim Ref As Variant, Diff As Double, XS As Double
Set Ref = Range("C47:V47")
Selection = Range("C48:V48").Select
Selection.Value = Ref.Value

If ScenarioName <> "Reference Demand " Then
    For i = 1 To 20
        If Cells(48, 2 + i).Value < DemandProfile(i) Then Cells(48, 2 +
i).Value = DemandProfile(i)
    Next i
End If

'Removing Directed and Expiring Capacity
For i = 1 To 20
    'Nuclear
```

```
    Cells(40, 2 + i).Value = Data.Cells(31, 1 + i).Value *
(Data.Range("D43").Value) * YearHours / (10) ^ 6
    'Natural Gas
    Cells(41, 2 + i).Value = (Data.Cells(4, 1 + i).Value + Data.Cells(12,
1 + i).Value) * (Data.Range("D44").Value) * YearHours / (10) ^ 6
    'Waterpower
    Cells(42, 2 + i).Value = (Data.Cells(5, 1 + i).Value + Data.Cells(13,
1 + i).Value) * (Data.Range("D45").Value) * YearHours / (10) ^ 6
    'Bioenergy
    Cells(43, 2 + i).Value = (Data.Cells(6, 1 + i).Value + Data.Cells(14,
1 + i).Value) * (Data.Range("D46").Value) * YearHours / (10) ^ 6
    'Wind
    Cells(44, 2 + i).Value = (Data.Cells(7, 1 + i).Value + Data.Cells(15,
1 + i).Value) * (Data.Range("D47").Value) * YearHours / (10) ^ 6
    'Solar PV
    Cells(45, 2 + i).Value = (Data.Cells(8, 1 + i).Value + Data.Cells(16,
1 + i).Value) * (Data.Range("D48").Value) * YearHours / (10) ^ 6
    'Storage & Demand Response
    Cells(46, 2 + i).Value = (Data.Cells(9, 1 + i).Value + Data.Cells(17,
1 + i).Value) * (Data.Range("D49").Value) * YearHours / (10) ^ 6
    'Total
    Cells(47, 2 + i).Value = Application.Sum(Range(Cells(40, 2 + i),
Cells(46, 2 + i)))
Next i
'Set base Emissions and Cost before difference is alloted
For i = 1 To 20
'---Emissions---
    'TWh*g/GJ*3600000GJ/TWh*MetricTonne/1000000gram
    'i.e. (3.6[GJ*MtCO2e]/[TWh*g])
    'Nuclear
    Cells(50, 2 + i).Value = Cells(40, 2 + i).Value * Factors(0, 1) *
0.0000036
    'Natural Gas
    Cells(51, 2 + i).Value = Cells(41, 2 + i).Value * Factors(1, 1) *
0.0000036
    'Waterpower
    Cells(52, 2 + i).Value = Cells(42, 2 + i).Value * Factors(2, 1) *
0.0000036
    'Bioenergy
    Cells(53, 2 + i).Value = Cells(43, 2 + i).Value * Factors(3, 1) *
0.0000036
    'Wind
    Cells(54, 2 + i).Value = Cells(44, 2 + i).Value * Factors(4, 1) *
0.0000036
    'Solar PV
    Cells(55, 2 + i).Value = Cells(45, 2 + i).Value * Factors(5, 1) *
0.0000036
    'Storage & Demand
    Cells(56, 2 + i).Value = Cells(46, 2 + i).Value * Factors(6, 1) *
0.0000036
    'Total
    Cells(57, 2 + i).Value = Application.Sum(Range(Cells(50, 2 + i),
Cells(56, 2 + i)))
'---COSTS---
    'TWh*LOCE$/MWh*[10^6MWh]/TWh*B$/10^9$
    'Nuclear
    Cells(60, 2 + i).Value = Cells(40, 2 + i).Value * Factors(0, 2) /
((10) ^ 3)
    'Natural Gas
```

```
    Cells(61, 2 + i).Value = Cells(41, 2 + i).Value * Factors(1, 2) /
((10) ^ 3)
    'Waterpower
    Cells(62, 2 + i).Value = Cells(42, 2 + i).Value * Factors(2, 2) /
((10) ^ 3)
    'Bioenery
    Cells(63, 2 + i).Value = Cells(43, 2 + i).Value * Factors(3, 2) /
((10) ^ 3)
    'Wind
    Cells(64, 2 + i).Value = Cells(44, 2 + i).Value * Factors(4, 2) /
((10) ^ 3)
    'Solar PV
    Cells(65, 2 + i).Value = Cells(45, 2 + i).Value * Factors(5, 2) /
((10) ^ 3)
    'Storage & Demand
    Cells(66, 2 + i).Value = Cells(46, 2 + i).Value * Factors(6, 2) /
((10) ^ 3)
    'Total
    Cells(67, 2 + i).Value = Application.Sum(Range(Cells(60, 2 + i),
Cells(66, 2 + i)))
Next i

'Distribution of difference to meet demand (1 TWh at a time)
Dim LowCost As Variant, LCI As Integer, LowEmission As String, LEI As
Integer, C_Diff As Double, E_Diff As Double
Dim CostArr(0 To 6, 0 To 1) As Variant, EmArr(0 To 6, 0 To 1) As Variant,
Limit(6) As Boolean
Dim counter As Double

For i = 0 To 4
    For j = 0 To 6
        Factors(j, i) = Data.Cells(43 + j, 14 + i).Value
    Next j
Next i
'Add respective emissions and costs
For i = 1 To 20

    'set cost and emission arrays
    For x = 0 To 1
    For y = 0 To 6
    CostArr(y, x) = Factors(y, 2 + 2 * x)
    EmArr(y, x) = Factors(y, 1 + 3 * x)
    Next y
    Next x
    'Find difference
    Diff = Cells(48, 2 + i).Value - Cells(47, 2 + i).Value
    C_Diff = LowCostPer * Diff
    E_Diff = LowEmissionPer * Diff
    Do While C_Diff > 0.0001
        'Reset boolean limit checks
        For j = 0 To 6
             If Cells(40 + j, 2 + i) = Factors(j, 0) Then
                Limit(j) = True
            Else
                Limit(j) = False
            End If
        Next j
        'Determine low cost
        counter = 0
        Do
```

```
            counter = counter + 1
            LowCost                                                     =
Application.WorksheetFunction.VLookup(Application.WorksheetFunction.Sma
ll(CostArr, counter), CostArr, 2, 0)
            LCI     =     Application.WorksheetFunction.Match(LowCost,
Application.WorksheetFunction.Index(CostArr, 0, 2), 0)
            'MsgBox ("LowCost: " & LowCost & ", RowNumber: " & LCI & ",
Limit: " & Limit(LCI))
        Loop Until Limit(LCI - 1) = False
        'Apply Difference
        Select Case LowCost
            'Nuclear
            Case "Nuclear"
                If (Cells(40, 2 + i) + C_Diff) <= Factors(0, 0) Then
                    Cells(40, 2 + i).Value = Cells(40, 2 + i) + C_Diff
                    Cells(50,  2  +  i).Value  =  Cells(50,  2  +  i).Value  +
C_Diff * Factors(0, 1) * 0.0000036
                    Cells(60,  2  +  i).Value  =  Cells(60,  2  +  i).Value  +
C_Diff * Factors(0, 2) / ((10) ^ 3)
                ElseIf (Cells(40, 2 + i) + C_Diff) > Factors(0, 0) Then
                    XS = Factors(0, 0) - Cells(40, 2 + i)
                    Cells(50, 2 + i).Value = Cells(50, 2 + i).Value + XS
* Factors(0, 1) * 0.0000036
                    Cells(60, 2 + i).Value = Cells(60, 2 + i).Value + XS
* Factors(0, 2) / ((10) ^ 3)
                    Cells(40, 2 + i).Value = Factors(0, 0)
                    Limit(0) = True
                End If
            'Natural Gas
            Case "Natural Gas"
                If (Cells(41, 2 + i) + C_Diff) <= Factors(1, 0) Then
                    Cells(41, 2 + i).Value = Cells(41, 2 + i) + C_Diff
                    Cells(51,  2  +  i).Value  =  Cells(51,  2  +  i).Value  +
C_Diff * Factors(1, 1) * 0.0000036
                    Cells(61,  2  +  i).Value  =  Cells(61,  2  +  i).Value  +
C_Diff * Factors(1, 2) / ((10) ^ 3)
                ElseIf (Cells(41, 2 + i) + C_Diff) > Factors(1, 0) Then
                    XS = Factors(1, 0) - Cells(41, 2 + i)
                    Cells(51, 2 + i).Value = Cells(51, 2 + i).Value + XS
* Factors(1, 1) * 0.0000036
                    Cells(61, 2 + i).Value = Cells(61, 2 + i).Value + XS
* Factors(1, 2) / ((10) ^ 3)
                    Cells(41, 2 + i).Value = Factors(1, 0)
                    Limit(1) = True
                End If
            'Waterpower
            Case "Hydro"
                If (Cells(42, 2 + i) + C_Diff) <= Factors(2, 0) Then
                    Cells(42, 2 + i).Value = Cells(42, 2 + i) + C_Diff
                    Cells(52,  2  +  i).Value  =  Cells(52,  2  +  i).Value  +
C_Diff * Factors(2, 1) * 0.0000036
                    Cells(62,  2  +  i).Value  =  Cells(62,  2  +  i).Value  +
C_Diff * Factors(2, 2) / ((10) ^ 3)
                ElseIf (Cells(42, 2 + i) + C_Diff) > Factors(2, 0) Then
                    XS = Factors(2, 0) - Cells(42, 2 + i)
                    Cells(52, 2 + i).Value = Cells(52, 2 + i).Value + XS
* Factors(2, 1) * 0.0000036
                    Cells(62, 2 + i).Value = Cells(62, 2 + i).Value + XS
* Factors(2, 2) / ((10) ^ 3)
                    Cells(42, 2 + i).Value = Factors(2, 0)
```

```
                    Limit(2) = True
                End If
            'Bioenergy
            Case "Bioenergy"
                If (Cells(43, 2 + i) + C_Diff) <= Factors(3, 0) Then
                    Cells(43, 2 + i).Value = Cells(43, 2 + i) + C_Diff
                    Cells(53, 2 + i).Value = Cells(53, 2 + i).Value +
C_Diff * Factors(3, 1) * 0.0000036
                    Cells(63, 2 + i).Value = Cells(63, 2 + i).Value +
C_Diff * Factors(3, 2) / ((10) ^ 3)
                ElseIf (Cells(43, 2 + i) + C_Diff) > Factors(3, 0) Then
                    XS = Factors(3, 0) - Cells(43, 2 + i)
                    Cells(53, 2 + i).Value = Cells(53, 2 + i).Value + XS
* Factors(3, 1) * 0.0000036
                    Cells(63, 2 + i).Value = Cells(63, 2 + i).Value + XS
* Factors(3, 2) / ((10) ^ 3)
                    Cells(43, 2 + i).Value = Factors(3, 0)
                    Limit(3) = True
                End If
            'Wind
            Case "Wind"
                If (Cells(44, 2 + i) + C_Diff) <= Factors(4, 0) Then
                    Cells(44, 2 + i).Value = Cells(44, 2 + i) + C_Diff
                    Cells(54, 2 + i).Value = Cells(54, 2 + i).Value +
C_Diff * Factors(4, 1) * 0.0000036
                    Cells(64, 2 + i).Value = Cells(64, 2 + i).Value +
C_Diff * Factors(4, 2) / ((10) ^ 3)
                ElseIf (Cells(44, 2 + i) + C_Diff) > Factors(4, 0) Then
                    XS = Factors(4, 0) - Cells(44, 2 + i)
                    Cells(54, 2 + i).Value = Cells(54, 2 + i).Value + XS
* Factors(4, 1) * 0.0000036
                    Cells(64, 2 + i).Value = Cells(64, 2 + i).Value + XS
* Factors(4, 2) / ((10) ^ 3)
                    Cells(44, 2 + i).Value = Factors(4, 0)
                    Limit(4) = True
                End If
            'Solar
            Case "PV Solar"
                If (Cells(45, 2 + i) + C_Diff) <= Factors(5, 0) Then
                    Cells(45, 2 + i).Value = Cells(45, 2 + i) + C_Diff
                    Cells(55, 2 + i).Value = Cells(55, 2 + i).Value +
C_Diff * Factors(5, 1) * 0.0000036
                    Cells(65, 2 + i).Value = Cells(65, 2 + i).Value +
C_Diff * Factors(5, 2) / ((10) ^ 3)
                ElseIf (Cells(45, 2 + i) + C_Diff) > Factors(5, 0) Then
                    XS = Factors(5, 0) - Cells(45, 2 + i)
                    Cells(55, 2 + i).Value = Cells(55, 2 + i).Value + XS
* Factors(5, 1) * 0.0000036
                    Cells(65, 2 + i).Value = Cells(65, 2 + i).Value + XS
* Factors(5, 2) / ((10) ^ 3)
                    Cells(45, 2 + i).Value = Factors(5, 0)
                    Limit(5) = True
                End If
            'Storage
            Case "Storage & Demand Response"
                If (Cells(46, 2 + i) + C_Diff) <= Factors(6, 0) Then
                    Cells(46, 2 + i).Value = Cells(46, 2 + i) + C_Diff
                    Cells(56, 2 + i).Value = Cells(56, 2 + i).Value +
C_Diff * Factors(6, 1) * 0.0000036
```

```
                    Cells(66, 2 + i).Value = Cells(66, 2 + i).Value +
C_Diff * Factors(6, 2) / ((10) ^ 3)
                ElseIf (Cells(46, 2 + i) + C_Diff) > Factors(6, 0) Then
                    XS = Factors(6, 0) - Cells(46, 2 + i)
                    Cells(56, 2 + i).Value = Cells(56, 2 + i).Value + XS
* Factors(6, 1) * 0.0000036
                    Cells(66, 2 + i).Value = Cells(66, 2 + i).Value + XS
* Factors(6, 2) / ((10) ^ 3)
                    Cells(46, 2 + i).Value = Factors(6, 0)
                    Limit(6) = True
                End If
        End Select
        XS = Cells(47, 2 + i).Value
        'Re-Total
        Cells(47, 2 + i).Value = WorksheetFunction.Sum(Range(Cells(40, 2
+ i), Cells(46, 2 + i)))
        'Recalculate Difference
        C_Diff = C_Diff - (Cells(47, 2 + i).Value - XS)
        If Limit(0) = True And Limit(1) = True And Limit(2) = True And
Limit(3) = True And Limit(4) = True And Limit(5) = True And Limit(6) =
True Then
            MsgBox ("All limits reached")
            Exit Do
        End If
        If Cells(48, 2 + i).Value = Cells(47, 2 + i).Value Then Exit Do
    Loop
    Do While E_Diff > 0.0001
    'Reset boolean limit checks
    For j = 0 To 6
         If Cells(40 + j, 2 + i) = Factors(j, 0) Then
            Limit(j) = True
        Else
            Limit(j) = False
        End If
    Next j
    'Determine low emission
    counter = 0
    Do
        counter = counter + 1
        'MsgBox (counter)
        LowEmission =
Application.WorksheetFunction.VLookup(Application.WorksheetFunction.Sma
ll(EmArr, counter), EmArr, 2, 0)
        LEI = Application.WorksheetFunction.Match(LowEmission,
Application.WorksheetFunction.Index(EmArr, 0, 2), 0)
        'MsgBox ("LowEmission: " & LowEmission & ", RowNumber: " & LEI &
", Limit: " & Limit(LEI))
    Loop Until Limit(LEI - 1) = False
    'Apply Difference
    Select Case LowEmission
        'Nuclear
        Case "Nuclear"
            If (Cells(40, 2 + i) + E_Diff) <= Factors(0, 0) Then
                Cells(40, 2 + i).Value = Cells(40, 2 + i) + E_Diff
                Cells(50, 2 + i).Value = Cells(50, 2 + i).Value + E_Diff
* Factors(0, 1) * 0.0000036
                Cells(60, 2 + i).Value = Cells(60, 2 + i).Value + E_Diff
* Factors(0, 2) / ((10) ^ 3)
            ElseIf (Cells(40, 2 + i) + C_Diff) > Factors(0, 0) Then
                XS = Factors(0, 0) - Cells(40, 2 + i)
```

```
        Cells(50, 2 + i).Value = Cells(50, 2 + i).Value + XS *
Factors(0, 1) * 0.0000036
        Cells(60, 2 + i).Value = Cells(60, 2 + i).Value + XS *
Factors(0, 2) / ((10) ^ 3)
        Cells(40, 2 + i).Value = Factors(0, 0)
        Limit(0) = True
      End If
    'Natural Gas
    Case "Natural Gas"
      If (Cells(41, 2 + i) + E_Diff) <= Factors(1, 0) Then
        Cells(41, 2 + i).Value = Cells(41, 2 + i) + E_Diff
        Cells(51, 2 + i).Value = Cells(51, 2 + i).Value + E_Diff
* Factors(1, 1) * 0.0000036
        Cells(61, 2 + i).Value = Cells(61, 2 + i).Value + E_Diff
* Factors(1, 2) / ((10) ^ 3)
      ElseIf (Cells(41, 2 + i) + C_Diff) > Factors(1, 0) Then
        XS = Factors(1, 0) - Cells(41, 2 + i)
        Cells(51, 2 + i).Value = Cells(51, 2 + i).Value + XS *
Factors(1, 1) * 0.0000036
        Cells(61, 2 + i).Value = Cells(61, 2 + i).Value + XS *
Factors(1, 2) / ((10) ^ 3)
        Cells(41, 2 + i).Value = Factors(1, 0)
        Limit(1) = True
      End If
    'Waterpower
    Case "Hydro"
      If (Cells(42, 2 + i) + E_Diff) <= Factors(2, 0) Then
        Cells(42, 2 + i).Value = Cells(42, 2 + i) + E_Diff
        Cells(52, 2 + i).Value = Cells(52, 2 + i).Value + E_Diff
* Factors(2, 1) * 0.0000036
        Cells(62, 2 + i).Value = Cells(62, 2 + i).Value + E_Diff
* Factors(2, 2) / ((10) ^ 3)
      ElseIf (Cells(42, 2 + i) + C_Diff) > Factors(2, 0) Then
        XS = Factors(2, 0) - Cells(42, 2 + i)
        Cells(52, 2 + i).Value = Cells(52, 2 + i).Value + XS *
Factors(2, 1) * 0.0000036
        Cells(62, 2 + i).Value = Cells(62, 2 + i).Value + XS *
Factors(2, 2) / ((10) ^ 3)
        Cells(42, 2 + i).Value = Factors(2, 0)
        Limit(2) = True
      End If
    'Bioenergy
    Case "Bioenergy"
      If (Cells(43, 2 + i) + E_Diff) <= Factors(3, 0) Then
        Cells(43, 2 + i).Value = Cells(43, 2 + i) + E_Diff
        Cells(53, 2 + i).Value = Cells(53, 2 + i).Value + E_Diff
* Factors(3, 1) * 0.0000036
        Cells(63, 2 + i).Value = Cells(63, 2 + i).Value + E_Diff
* Factors(3, 2) / ((10) ^ 3)
      ElseIf (Cells(43, 2 + i) + C_Diff) > Factors(3, 0) Then
        XS = Factors(3, 0) - Cells(43, 2 + i)
        Cells(53, 2 + i).Value = Cells(53, 2 + i).Value + XS *
Factors(3, 1) * 0.0000036
        Cells(63, 2 + i).Value = Cells(63, 2 + i).Value + XS *
Factors(3, 2) / ((10) ^ 3)
        Cells(43, 2 + i).Value = Factors(3, 0)
        Limit(3) = True
      End If
    'Wind
    Case "Wind"
```

```
            If (Cells(44, 2 + i) + E_Diff) <= Factors(4, 0) Then
                Cells(44, 2 + i).Value = Cells(44, 2 + i) + E_Diff
                Cells(54, 2 + i).Value = Cells(54, 2 + i).Value + E_Diff
* Factors(4, 1) * 0.0000036
                Cells(64, 2 + i).Value = Cells(64, 2 + i).Value + E_Diff
* Factors(4, 2) / ((10) ^ 3)
            ElseIf (Cells(44, 2 + i) + C_Diff) > Factors(4, 0) Then
                XS = Factors(4, 0) - Cells(44, 2 + i)
                Cells(54, 2 + i).Value = Cells(54, 2 + i).Value + XS *
Factors(4, 1) * 0.0000036
                Cells(64, 2 + i).Value = Cells(64, 2 + i).Value + XS *
Factors(4, 2) / ((10) ^ 3)
                Cells(44, 2 + i).Value = Factors(4, 0)
                Limit(4) = True
            End If
        'Solar
        Case "PV Solar"
            If (Cells(45, 2 + i) + E_Diff) <= Factors(5, 0) Then
                Cells(45, 2 + i).Value = Cells(45, 2 + i) + E_Diff
                Cells(55, 2 + i).Value = Cells(55, 2 + i).Value + E_Diff
* Factors(5, 1) * 0.0000036
                Cells(65, 2 + i).Value = Cells(65, 2 + i).Value + E_Diff
* Factors(5, 2) / ((10) ^ 3)
            ElseIf (Cells(45, 2 + i) + C_Diff) > Factors(5, 0) Then
                XS = Factors(5, 0) - Cells(45, 2 + i)
                Cells(55, 2 + i).Value = Cells(55, 2 + i).Value + XS *
Factors(5, 1) * 0.0000036
                Cells(65, 2 + i).Value = Cells(65, 2 + i).Value + XS *
Factors(5, 2) / ((10) ^ 3)
                Cells(45, 2 + i).Value = Factors(5, 0)
                Limit(5) = True
            End If
        'Storage
        Case "Storage & Demand Response"
            If (Cells(46, 2 + i) + E_Diff) <= Factors(6, 0) Then
                Cells(46, 2 + i).Value = Cells(46, 2 + i) + E_Diff
                Cells(56, 2 + i).Value = Cells(56, 2 + i).Value + E_Diff
* Factors(6, 1) * 0.0000036
                Cells(66, 2 + i).Value = Cells(66, 2 + i).Value + E_Diff
* Factors(6, 2) / ((10) ^ 3)
            ElseIf (Cells(46, 2 + i) + C_Diff) > Factors(6, 0) Then
                XS = Factors(6, 0) - Cells(46, 2 + i)
                Cells(56, 2 + i).Value = Cells(56, 2 + i).Value + XS *
Factors(6, 1) * 0.0000036
                Cells(66, 2 + i).Value = Cells(66, 2 + i).Value + XS *
Factors(6, 2) / ((10) ^ 3)
                Cells(46, 2 + i).Value = Factors(6, 0)
                Limit(6) = True
            End If
        End Select
        XS = Cells(47, 2 + i).Value
        'Re-Total
        Cells(47, 2 + i).Value = WorksheetFunction.Sum(Range(Cells(40, 2
+ i), Cells(46, 2 + i)))
        'Recalculate Difference
        E_Diff = E_Diff - (Cells(47, 2 + i).Value - XS)
        If Limit(0) = True And Limit(1) = True And Limit(2) = True And
Limit(3) = True And Limit(4) = True And Limit(5) = True And Limit(6) =
True Then
            MsgBox ("All limits reached")
```

```
            Exit Do
        End If
        If Cells(48, 2 + i).Value = Cells(47, 2 + i).Value Then Exit Do
    Loop
'MsgBox ("Year: " & 2015 + i)

'Retotal emissions and costs
Cells(57, 2 + i).Value = WorksheetFunction.Sum(Range(Cells(50, 2 + i),
Cells(56, 2 + i)))
Cells(67, 2 + i).Value = WorksheetFunction.Sum(Range(Cells(60, 2 + i),
Cells(66, 2 + i)))

Next i

'Range("C48:V48").Clear
'---MW from total TWh assigned---
For i = 1 To 20
    For j = 0 To 6
    Cells(70 + j, 2 + i).Value = Cells(40 + j, 2 + i).Value * ((10) ^ 6)
/ (Data.Cells(43 + j, 4).Value * YearHours)
    Next j
    Cells(77, 2 + i).Value = WorksheetFunction.Sum(Range(Cells(70, 2 +
i), Cells(76, 2 + i)))
Next i
End Sub
```

A.6 Life Cycle Factor Preference with Variable Cost

```
Sub FactorPrefVar()
'---TWh Yearly Generation Reference---
Set Data = ThisWorkbook.Worksheets("Gen.Data")
YearHours = 8760
For i = 1 To 20
    'Nuclear
    Cells(40,   2   +   i).Value   =   Data.Cells(31,   1   +   i).Value   *
(Data.Range("D43").Value) * YearHours / (10) ^ 6
    'Natural Gas
    Cells(41, 2 + i).Value = (Data.Cells(4, 1 + i).Value + Data.Cells(12,
1 + i).Value + Data.Cells(20, 1 + i).Value _
                            +   Data.Cells(33,   1   +   i).Value)   *
(Data.Range("D44").Value) * YearHours / (10) ^ 6
    'Waterpower
    Cells(42, 2 + i).Value = (Data.Cells(5, 1 + i).Value + Data.Cells(13,
1 + i).Value + Data.Cells(21, 1 + i).Value _
                            +   Data.Cells(34,   1   +   i).Value)   *
(Data.Range("D45").Value) * YearHours / (10) ^ 6
    'Bioenergy
    Cells(43, 2 + i).Value = (Data.Cells(6, 1 + i).Value + Data.Cells(14,
1 + i).Value + Data.Cells(22, 1 + i).Value _
                            +   Data.Cells(35,   1   +   i).Value)   *
(Data.Range("D46").Value) * YearHours / (10) ^ 6
    'Wind
    Cells(44, 2 + i).Value = (Data.Cells(7, 1 + i).Value + Data.Cells(15,
1 + i).Value + Data.Cells(23, 1 + i).Value _
                            +   Data.Cells(36,   1   +   i).Value)   *
(Data.Range("D47").Value) * YearHours / (10) ^ 6
    'Solar PV
    Cells(45, 2 + i).Value = (Data.Cells(8, 1 + i).Value + Data.Cells(16,
1 + i).Value + Data.Cells(24, 1 + i).Value _
                            +   Data.Cells(37,   1   +   i).Value)   *
(Data.Range("D48").Value) * YearHours / (10) ^ 6
```

```
    'Storage & Demand Response
    Cells(46, 2 + i).Value = (Data.Cells(9, 1 + i).Value + Data.Cells(17,
1 + i).Value + Data.Cells(24, 1 + i).Value _
                            +   Data.Cells(38,   1   +   i).Value)   *
(Data.Range("D49").Value) * YearHours / (10) ^ 6
    'Total
    Cells(47,  2  +  i).Value  =  Application.Sum(Range(Cells(40,  2  +  i),
Cells(46, 2 + i)))
    'Demand profile
    'Cells(48, 2 + i).Value = DemandProfile(i)
Next i

'Store Reference Total Generation for Future Reference
Dim Ref As Variant, Diff As Double, XS As Double
Set Ref = Range("C47:V47")
Selection = Range("C48:V48").Select
Selection.Value = Ref.Value



'Removing Directed and Expiring Capacity
For i = 1 To 20
    'Nuclear
    Cells(40,   2   +   i).Value   =   Data.Cells(31,   1   +   i).Value   *
(Data.Range("D43").Value) * YearHours / (10) ^ 6
    'Natural Gas
    Cells(41, 2 + i).Value = (Data.Cells(4, 1 + i).Value + Data.Cells(12,
1 + i).Value) * (Data.Range("D44").Value) * YearHours / (10) ^ 6
    'Waterpower
    Cells(42, 2 + i).Value = (Data.Cells(5, 1 + i).Value + Data.Cells(13,
1 + i).Value) * (Data.Range("D45").Value) * YearHours / (10) ^ 6
    'Bioenergy
    Cells(43, 2 + i).Value = (Data.Cells(6, 1 + i).Value + Data.Cells(14,
1 + i).Value) * (Data.Range("D46").Value) * YearHours / (10) ^ 6
    'Wind
    Cells(44, 2 + i).Value = (Data.Cells(7, 1 + i).Value + Data.Cells(15,
1 + i).Value) * (Data.Range("D47").Value) * YearHours / (10) ^ 6
    'Solar PV
    Cells(45, 2 + i).Value = (Data.Cells(8, 1 + i).Value + Data.Cells(16,
1 + i).Value) * (Data.Range("D48").Value) * YearHours / (10) ^ 6
    'Storage & Demand Response
    Cells(46, 2 + i).Value = (Data.Cells(9, 1 + i).Value + Data.Cells(17,
1 + i).Value) * (Data.Range("D49").Value) * YearHours / (10) ^ 6
    'Total
    Cells(47,  2  +  i).Value  =  Application.Sum(Range(Cells(40,  2  +  i),
Cells(46, 2 + i)))
Next i

If ScenarioName <> "Reference Demand " Then
    For i = 1 To 20
        If Cells(47, 2 + i).Value < DemandProfile(i) Then Cells(48, 2 +
i).Value = DemandProfile(i)
    Next i
End If

'Set base Emissions and Cost before difference is alloted
For i = 1 To 20
'---Emissions---
    'TWh*g/GJ*3600000GJ/TWh*MetricTonne/1000000gram
    'i.e. (3.6[GJ*MtCO2e]/[TWh*g])
    'Nuclear
    Cells(50, 2 + i).Value = Cells(40, 2 + i).Value * Factors(0, 1) *
0.0000036
    'Natural Gas
```

```
    Cells(51, 2 + i).Value = Cells(41, 2 + i).Value * Factors(1, 1) *
0.0000036
    'Waterpower
    Cells(52, 2 + i).Value = Cells(42, 2 + i).Value * Factors(2, 1) *
0.0000036
    'Bioenergy
    Cells(53, 2 + i).Value = Cells(43, 2 + i).Value * Factors(3, 1) *
0.0000036
    'Wind
    Cells(54, 2 + i).Value = Cells(44, 2 + i).Value * Factors(4, 1) *
0.0000036
    'Solar PV
    Cells(55, 2 + i).Value = Cells(45, 2 + i).Value * Factors(5, 1) *
0.0000036
    'Storage & Demand
    Cells(56, 2 + i).Value = Cells(46, 2 + i).Value * Factors(6, 1) *
0.0000036
    'Total
    Cells(57, 2 + i).Value = Application.Sum(Range(Cells(50, 2 + i),
Cells(56, 2 + i)))
'---COSTS---
    'TWh*LOCE$/MWh*[10^6MWh]/TWh*B$/10^9$
    'Nuclear
    Cells(60, 2 + i).Value = Cells(40, 2 + i).Value * Factors(0, 2) /
((10) ^ 3)
    'Natural Gas
    Cells(61, 2 + i).Value = Cells(41, 2 + i).Value * Factors(1, 2) /
((10) ^ 3)
    'Waterpower
    Cells(62, 2 + i).Value = Cells(42, 2 + i).Value * Factors(2, 2) /
((10) ^ 3)
    'Bioenery
    Cells(63, 2 + i).Value = Cells(43, 2 + i).Value * Factors(3, 2) /
((10) ^ 3)
    'Wind
    Cells(64, 2 + i).Value = Cells(44, 2 + i).Value * Factors(4, 2) /
((10) ^ 3)
    'Solar PV
    Cells(65, 2 + i).Value = Cells(45, 2 + i).Value * Factors(5, 2) /
((10) ^ 3)
    'Storage & Demand
    Cells(66, 2 + i).Value = Cells(46, 2 + i).Value * Factors(6, 2) /
((10) ^ 3)
    'Total
    Cells(67, 2 + i).Value = Application.Sum(Range(Cells(60, 2 + i),
Cells(66, 2 + i)))
Next i

'Distribution of difference to meet demand (1 TWh at a time)
Dim LowCost As Variant, LCI As Integer, LowEmission As String, LEI As
Integer, C_Diff As Double, E_Diff As Double, c_dif As Double, e_dif As
Double
Dim CostArr(0 To 6, 0 To 1) As Variant, EmArr(0 To 6, 0 To 1) As Variant,
Limit(6) As Boolean
Dim counter As Double, count As Integer

'Add respective emissions and costs

For i = 1 To 20
    count = 0
    For x = 0 To 4
        For y = 0 To 6
            Factors(y, x) = Data.Cells(43 + y, 14 + x).Value
        Next y
```

```
    Next x

    'Find difference
    Diff = Cells(48, 2 + i).Value - Cells(47, 2 + i).Value
    C_Diff = LowCostPer * Diff
    E_Diff = LowEmissionPer * Diff
    Do While C_Diff > 0.0001
        If C_Diff < 1 Then
            c_dif = C_Diff
        Else
            c_dif = 1
        End If
        count = count + 1
        'set cost and emission arrays
        For x = 0 To 1
        For y = 0 To 6
        CostArr(y, x) = Factors(y, 2 + 2 * x)
        EmArr(y, x) = Factors(y, 1 + 3 * x)
        Next y
        Next x
        'MsgBox (CostArr(0, 0) & vbTab & CostArr(0, 1) & vbCrLf &
CostArr(1, 0) & vbTab & CostArr(1, 1) & vbCrLf & CostArr(2, 0) & vbTab &
CostArr(2, 1) & vbCrLf & CostArr(3, 0) & vbTab & CostArr(3, 1) & vbCrLf
& CostArr(4, 0) & vbTab & CostArr(4, 1) & vbCrLf & CostArr(5, 0) & vbTab
& CostArr(5, 1) & vbCrLf & CostArr(6, 0) & vbTab & CostArr(6, 1) & vbCrLf)

        'Reset boolean limit checks
        For j = 0 To 6
             If Cells(40 + j, 2 + i) = Factors(j, 0) Then
                Limit(j) = True
            Else
                Limit(j) = False
            End If
        Next j
        'Determine low cost
        counter = 0
        Do
            counter = counter + 1
            LowCost                                                    =
Application.WorksheetFunction.VLookup(Application.WorksheetFunction.Sma
ll(CostArr, counter), CostArr, 2, 0)
            LCI      =      Application.WorksheetFunction.Match(LowCost,
Application.WorksheetFunction.Index(CostArr, 0, 2), 0)
        Loop Until Limit(LCI - 1) = False
        'MsgBox ("Year: " & i & vbTab & "TWh Count: " & count & vbCrLf &
"LowCost: " & LowCost & ", RowNumber: " & LCI & ", Limit: " & Limit(LCI)
& ", Cost: " & CostArr(LCI - 1, 0) & "$/MWh")
        'Apply Difference
        Select Case LowCost
            'Nuclear
            Case "Nuclear"
                If (Cells(40, 2 + i) + c_dif) <= Factors(0, 0) Then
                    Cells(40, 2 + i).Value = Cells(40, 2 + i) + c_dif
                    Cells(50, 2 + i).Value = Cells(50, 2 + i).Value +
c_dif * Factors(0, 1) * 0.0000036
                    Cells(60, 2 + i).Value = Cells(60, 2 + i).Value +
c_dif * Factors(0, 2) / ((10) ^ 3)
                    Factors(0, 2) = Factors(0, 2) * VarCost
                ElseIf (Cells(40, 2 + i) + c_dif) > Factors(0, 0) Then
                    XS = Factors(0, 0) - Cells(40, 2 + i)
                    Cells(50, 2 + i).Value = Cells(50, 2 + i).Value + XS
* Factors(0, 1) * 0.0000036
                    Cells(60, 2 + i).Value = Cells(60, 2 + i).Value + XS
* Factors(0, 2) / ((10) ^ 3)
```

```
                    Cells(40, 2 + i).Value = Factors(0, 0)
                    Factors(0, 2) = Factors(0, 2) * VarCost
                    Limit(0) = True
                End If
            'Natural Gas
            Case "Natural Gas"
                If (Cells(41, 2 + i) + c_dif) <= Factors(1, 0) Then
                    Cells(41, 2 + i).Value = Cells(41, 2 + i) + c_dif
                    Cells(51, 2 + i).Value = Cells(51, 2 + i).Value +
c_dif * Factors(1, 1) * 0.0000036
                    Cells(61, 2 + i).Value = Cells(61, 2 + i).Value +
c_dif * Factors(1, 2) / ((10) ^ 3)
                    Factors(1, 2) = Factors(1, 2) * VarCost
                ElseIf (Cells(41, 2 + i) + c_dif) > Factors(1, 0) Then
                    XS = Factors(1, 0) - Cells(41, 2 + i)
                    Cells(51, 2 + i).Value = Cells(51, 2 + i).Value + XS
* Factors(1, 1) * 0.0000036
                    Cells(61, 2 + i).Value = Cells(61, 2 + i).Value + XS
* Factors(1, 2) / ((10) ^ 3)
                    Cells(41, 2 + i).Value = Factors(1, 0)
                    Factors(1, 2) = Factors(1, 2) * VarCost
                    Limit(1) = True
                End If
            'Waterpower
            Case "Hydro"
                If (Cells(42, 2 + i) + c_dif) <= Factors(2, 0) Then
                    Cells(42, 2 + i).Value = Cells(42, 2 + i) + c_dif
                    Cells(52, 2 + i).Value = Cells(52, 2 + i).Value +
c_dif * Factors(2, 1) * 0.0000036
                    Cells(62, 2 + i).Value = Cells(62, 2 + i).Value +
c_dif * Factors(2, 2) / ((10) ^ 3)
                    Factors(2, 2) = Factors(2, 2) * VarCost
                ElseIf (Cells(42, 2 + i) + c_dif) > Factors(2, 0) Then
                    XS = Factors(2, 0) - Cells(42, 2 + i)
                    Cells(52, 2 + i).Value = Cells(52, 2 + i).Value + XS
* Factors(2, 1) * 0.0000036
                    Cells(62, 2 + i).Value = Cells(62, 2 + i).Value + XS
* Factors(2, 2) / ((10) ^ 3)
                    Cells(42, 2 + i).Value = Factors(2, 0)
                    Factors(2, 2) = Factors(2, 2) * VarCost
                    Limit(2) = True
                End If
            'Bioenergy
            Case "Bioenergy"
                If (Cells(43, 2 + i) + c_dif) <= Factors(3, 0) Then
                    Cells(43, 2 + i).Value = Cells(43, 2 + i) + c_dif
                    Cells(53, 2 + i).Value = Cells(53, 2 + i).Value +
c_dif * Factors(3, 1) * 0.0000036
                    Cells(63, 2 + i).Value = Cells(63, 2 + i).Value +
c_dif * Factors(3, 2) / ((10) ^ 3)
                    Factors(3, 2) = Factors(3, 2) * VarCost
                ElseIf (Cells(43, 2 + i) + c_dif) > Factors(3, 0) Then
                    XS = Factors(3, 0) - Cells(43, 2 + i)
                    Cells(53, 2 + i).Value = Cells(53, 2 + i).Value + XS
* Factors(3, 1) * 0.0000036
                    Cells(63, 2 + i).Value = Cells(63, 2 + i).Value + XS
* Factors(3, 2) / ((10) ^ 3)
                    Cells(43, 2 + i).Value = Factors(3, 0)
                    Factors(3, 2) = Factors(3, 2) * VarCost
                    Limit(3) = True
                End If
            'Wind
            Case "Wind"
                If (Cells(44, 2 + i) + c_dif) <= Factors(4, 0) Then
```

```
                    Cells(44, 2 + i).Value = Cells(44, 2 + i) + c_dif
                    Cells(54, 2 + i).Value = Cells(54, 2 + i).Value +
c_dif * Factors(4, 1) * 0.0000036
                    Cells(64, 2 + i).Value = Cells(64, 2 + i).Value +
c_dif * Factors(4, 2) / ((10) ^ 3)
                    Factors(4, 2) = Factors(4, 2) * VarCost
                ElseIf (Cells(44, 2 + i) + c_dif) > Factors(4, 0) Then
                    XS = Factors(4, 0) - Cells(44, 2 + i)
                    Cells(54, 2 + i).Value = Cells(54, 2 + i).Value + XS
* Factors(4, 1) * 0.0000036
                    Cells(64, 2 + i).Value = Cells(64, 2 + i).Value + XS
* Factors(4, 2) / ((10) ^ 3)
                    Cells(44, 2 + i).Value = Factors(4, 0)
                    Factors(4, 2) = Factors(4, 2) * VarCost
                    Limit(4) = True
                End If
            'Solar
            Case "PV Solar"
                If (Cells(45, 2 + i) + c_dif) <= Factors(5, 0) Then
                    Cells(45, 2 + i).Value = Cells(45, 2 + i) + c_dif
                    Cells(55, 2 + i).Value = Cells(55, 2 + i).Value +
c_dif * Factors(5, 1) * 0.0000036
                    Cells(65, 2 + i).Value = Cells(65, 2 + i).Value +
c_dif * Factors(5, 2) / ((10) ^ 3)
                    Factors(5, 2) = Factors(5, 2) * VarCost
                ElseIf (Cells(45, 2 + i) + c_dif) > Factors(5, 0) Then
                    XS = Factors(5, 0) - Cells(45, 2 + i)
                    Cells(55, 2 + i).Value = Cells(55, 2 + i).Value + XS
* Factors(5, 1) * 0.0000036
                    Cells(65, 2 + i).Value = Cells(65, 2 + i).Value + XS
* Factors(5, 2) / ((10) ^ 3)
                    Cells(45, 2 + i).Value = Factors(5, 0)
                    Factors(5, 2) = Factors(5, 2) * VarCost
                    Limit(5) = True
                End If
            'Storage
            Case "Storage & Demand Response"
                If (Cells(46, 2 + i) + c_dif) <= Factors(6, 0) Then
                    Cells(46, 2 + i).Value = Cells(46, 2 + i) + c_dif
                    Cells(56, 2 + i).Value = Cells(56, 2 + i).Value +
c_dif * Factors(6, 1) * 0.0000036
                    Cells(66, 2 + i).Value = Cells(66, 2 + i).Value +
c_dif * Factors(6, 2) / ((10) ^ 3)
                    Factors(6, 2) = Factors(6, 2) * VarCost
                ElseIf (Cells(46, 2 + i) + c_dif) > Factors(6, 0) Then
                    XS = Factors(6, 0) - Cells(46, 2 + i)
                    Cells(56, 2 + i).Value = Cells(56, 2 + i).Value + XS
* Factors(6, 1) * 0.0000036
                    Cells(66, 2 + i).Value = Cells(66, 2 + i).Value + XS
* Factors(6, 2) / ((10) ^ 3)
                    Cells(46, 2 + i).Value = Factors(6, 0)
                    Factors(6, 2) = Factors(6, 2) * VarCost
                    Limit(6) = True
                End If
        End Select
        XS = Cells(47, 2 + i).Value
        'Re-Total
        Cells(47, 2 + i).Value = WorksheetFunction.Sum(Range(Cells(40, 2
+ i), Cells(46, 2 + i)))
        'Recalculate Difference
        C_Diff = C_Diff - (Cells(47, 2 + i).Value - XS)
        If Limit(0) = True And Limit(1) = True And Limit(2) = True And
Limit(3) = True And Limit(4) = True And Limit(5) = True And Limit(6) =
True Then
```

```
            MsgBox ("All limits reached")
            Exit Do
        End If
        If Cells(48, 2 + i).Value = Cells(47, 2 + i).Value Then Exit Do
    Loop
    Do While E_Diff > 0.0001
        If E_Diff < 1 Then
            e_dif = E_Diff
        Else
            e_dif = 1
        End If
    'Reset boolean limit checks
    For j = 0 To 6
         If Cells(40 + j, 2 + i) = Factors(j, 0) Then
            Limit(j) = True
        Else
            Limit(j) = False
        End If
    Next j
    'Determine low emission
    counter = 0
    Do
        counter = counter + 1
        'MsgBox (counter)
        LowEmission                                                  =
Application.WorksheetFunction.VLookup(Application.WorksheetFunction.Sma
ll(EmArr, counter), EmArr, 2, 0)
        LEI      =      Application.WorksheetFunction.Match(LowEmission,
Application.WorksheetFunction.Index(EmArr, 0, 2), 0)
        'MsgBox ("LowEmission: " & LowEmission & ", RowNumber: " & LEI &
", Limit: " & Limit(LEI))
    Loop Until Limit(LEI - 1) = False
    'Apply Difference
    Select Case LowEmission
        'Nuclear
        Case "Nuclear"
            If (Cells(40, 2 + i) + e_dif) <= Factors(0, 0) Then
                Cells(40, 2 + i).Value = Cells(40, 2 + i) + e_dif
                Cells(50, 2 + i).Value = Cells(50, 2 + i).Value + e_dif
* Factors(0, 1) * 0.0000036
                Cells(60, 2 + i).Value = Cells(60, 2 + i).Value + e_dif
* Factors(0, 2) / ((10) ^ 3)
                Factors(0, 2) = Factors(0, 2) * VarCost
            ElseIf (Cells(40, 2 + i) + e_dif) > Factors(0, 0) Then
                XS = Factors(0, 0) - Cells(40, 2 + i)
                Cells(50, 2 + i).Value = Cells(50, 2 + i).Value + XS *
Factors(0, 1) * 0.0000036
                Cells(60, 2 + i).Value = Cells(60, 2 + i).Value + XS *
Factors(0, 2) / ((10) ^ 3)
                Cells(40, 2 + i).Value = Factors(0, 0)
                Factors(0, 2) = Factors(0, 2) * VarCost
                Limit(0) = True
            End If
        'Natural Gas
        Case "Natural Gas"
            If (Cells(41, 2 + i) + e_dif) <= Factors(1, 0) Then
                Cells(41, 2 + i).Value = Cells(41, 2 + i) + e_dif
                Cells(51, 2 + i).Value = Cells(51, 2 + i).Value + e_dif
* Factors(1, 1) * 0.0000036
                Cells(61, 2 + i).Value = Cells(61, 2 + i).Value + e_dif
* Factors(1, 2) / ((10) ^ 3)
                Factors(1, 2) = Factors(1, 2) * VarCost
            ElseIf (Cells(41, 2 + i) + e_dif) > Factors(1, 0) Then
                XS = Factors(1, 0) - Cells(41, 2 + i)
```

```
                Cells(51, 2 + i).Value = Cells(51, 2 + i).Value + XS *
Factors(1, 1) * 0.0000036
                Cells(61, 2 + i).Value = Cells(61, 2 + i).Value + XS *
Factors(1, 2) / ((10) ^ 3)
                Cells(41, 2 + i).Value = Factors(1, 0)
                Factors(1, 2) = Factors(1, 2) * VarCost
                Limit(1) = True
            End If
        'Waterpower
        Case "Hydro"
            If (Cells(42, 2 + i) + e_dif) <= Factors(2, 0) Then
                Cells(42, 2 + i).Value = Cells(42, 2 + i) + e_dif
                Cells(52, 2 + i).Value = Cells(52, 2 + i).Value + e_dif
* Factors(2, 1) * 0.0000036
                Cells(62, 2 + i).Value = Cells(62, 2 + i).Value + e_dif
* Factors(2, 2) / ((10) ^ 3)
                Factors(2, 2) = Factors(2, 2) * VarCost
            ElseIf (Cells(42, 2 + i) + e_dif) > Factors(2, 0) Then
                XS = Factors(2, 0) - Cells(42, 2 + i)
                Cells(52, 2 + i).Value = Cells(52, 2 + i).Value + XS *
Factors(2, 1) * 0.0000036
                Cells(62, 2 + i).Value = Cells(62, 2 + i).Value + XS *
Factors(2, 2) / ((10) ^ 3)
                Cells(42, 2 + i).Value = Factors(2, 0)
                Factors(2, 2) = Factors(2, 2) * VarCost
                Limit(2) = True
            End If
        'Bioenergy
        Case "Bioenergy"
            If (Cells(43, 2 + i) + e_dif) <= Factors(3, 0) Then
                Cells(43, 2 + i).Value = Cells(43, 2 + i) + e_dif
                Cells(53, 2 + i).Value = Cells(53, 2 + i).Value + e_dif
* Factors(3, 1) * 0.0000036
                Cells(63, 2 + i).Value = Cells(63, 2 + i).Value + e_dif
* Factors(3, 2) / ((10) ^ 3)
                Factors(3, 2) = Factors(3, 2) * VarCost
            ElseIf (Cells(43, 2 + i) + e_dif) > Factors(3, 0) Then
                XS = Factors(3, 0) - Cells(43, 2 + i)
                Cells(53, 2 + i).Value = Cells(53, 2 + i).Value + XS *
Factors(3, 1) * 0.0000036
                Cells(63, 2 + i).Value = Cells(63, 2 + i).Value + XS *
Factors(3, 2) / ((10) ^ 3)
                Cells(43, 2 + i).Value = Factors(3, 0)
                Factors(3, 2) = Factors(3, 2) * VarCost
                Limit(3) = True
            End If
        'Wind
        Case "Wind"
            If (Cells(44, 2 + i) + e_dif) <= Factors(4, 0) Then
                Cells(44, 2 + i).Value = Cells(44, 2 + i) + e_dif
                Cells(54, 2 + i).Value = Cells(54, 2 + i).Value + e_dif
* Factors(4, 1) * 0.0000036
                Cells(64, 2 + i).Value = Cells(64, 2 + i).Value + e_dif
* Factors(4, 2) / ((10) ^ 3)
                Factors(4, 2) = Factors(4, 2) * VarCost
            ElseIf (Cells(44, 2 + i) + e_dif) > Factors(4, 0) Then
                XS = Factors(4, 0) - Cells(44, 2 + i)
                Cells(54, 2 + i).Value = Cells(54, 2 + i).Value + XS *
Factors(4, 1) * 0.0000036
                Cells(64, 2 + i).Value = Cells(64, 2 + i).Value + XS *
Factors(4, 2) / ((10) ^ 3)
                Cells(44, 2 + i).Value = Factors(4, 0)
                Factors(4, 2) = Factors(4, 2) * VarCost
                Limit(4) = True
```

```
            End If
        'Solar
        Case "PV Solar"
            If (Cells(45, 2 + i) + e_dif) <= Factors(5, 0) Then
                Cells(45, 2 + i).Value = Cells(45, 2 + i) + e_dif
                Cells(55, 2 + i).Value = Cells(55, 2 + i).Value + e_dif
* Factors(5, 1) * 0.0000036
                Cells(65, 2 + i).Value = Cells(65, 2 + i).Value + e_dif
* Factors(5, 2) / ((10) ^ 3)
                Factors(5, 2) = Factors(5, 2) * VarCost
            ElseIf (Cells(45, 2 + i) + e_dif) > Factors(5, 0) Then
                XS = Factors(5, 0) - Cells(45, 2 + i)
                Cells(55, 2 + i).Value = Cells(55, 2 + i).Value + XS *
Factors(5, 1) * 0.0000036
                Cells(65, 2 + i).Value = Cells(65, 2 + i).Value + XS *
Factors(5, 2) / ((10) ^ 3)
                Cells(45, 2 + i).Value = Factors(5, 0)
                Factors(5, 2) = Factors(5, 2) * VarCost
                Limit(5) = True
            End If
        'Storage
        Case "Storage & Demand Response"
            If (Cells(46, 2 + i) + e_dif) <= Factors(6, 0) Then
                Cells(46, 2 + i).Value = Cells(46, 2 + i) + e_dif
                Cells(56, 2 + i).Value = Cells(56, 2 + i).Value + e_dif
* Factors(6, 1) * 0.0000036
                Cells(66, 2 + i).Value = Cells(66, 2 + i).Value + e_dif
* Factors(6, 2) / ((10) ^ 3)
                Factors(6, 2) = Factors(6, 2) * VarCost
            ElseIf (Cells(46, 2 + i) + e_dif) > Factors(6, 0) Then
                XS = Factors(6, 0) - Cells(46, 2 + i)
                Cells(56, 2 + i).Value = Cells(56, 2 + i).Value + XS *
Factors(6, 1) * 0.0000036
                Cells(66, 2 + i).Value = Cells(66, 2 + i).Value + XS *
Factors(6, 2) / ((10) ^ 3)
                Cells(46, 2 + i).Value = Factors(6, 0)
                Factors(6, 2) = Factors(6, 2) * VarCost
                Limit(6) = True
            End If
        End Select
        XS = Cells(47, 2 + i).Value
        'Re-Total
        Cells(47, 2 + i).Value = WorksheetFunction.Sum(Range(Cells(40, 2
+ i), Cells(46, 2 + i)))
        'Recalculate Difference
        E_Diff = E_Diff - (Cells(47, 2 + i).Value - XS)
        If Limit(0) = True And Limit(1) = True And Limit(2) = True And
Limit(3) = True And Limit(4) = True And Limit(5) = True And Limit(6) =
True Then
            MsgBox ("All limits reached")
            Exit Do
        End If
        If Cells(48, 2 + i).Value = Cells(47, 2 + i).Value Then Exit Do
    Loop
'MsgBox ("Year: " & 2015 + i)

'Retotal emissions and costs
Cells(57, 2 + i).Value = WorksheetFunction.Sum(Range(Cells(50, 2 + i),
Cells(56, 2 + i)))
Cells(67, 2 + i).Value = WorksheetFunction.Sum(Range(Cells(60, 2 + i),
Cells(66, 2 + i)))

Next i
```

```
'Range("C48:V48").Clear
'---Final Factor Declaration---
If VarCost <> 1 Then
    For i = 0 To 4
        For j = 0 To 6
            Cells(2 + j, 24 + i).Value = Factors(j, i)
        Next j
    Next i
End If

'---MW from total TWh assigned---
For i = 1 To 20
    For j = 0 To 6
    Cells(70 + j, 2 + i).Value = Cells(40 + j, 2 + i).Value * ((10) ^ 6)
/ (Data.Cells(43 + j, 4).Value * YearHours)
    Next j
    Cells(77, 2 + i).Value = WorksheetFunction.Sum(Range(Cells(70, 2 +
i), Cells(76, 2 + i)))
Next i

End Sub
```

Appendix B: List of Assumptions

Major assumptions carried by this work include:

1. For the reference scenario it is assumed the IESO OPO [15] forecasted capacities for each technology will hold true, this creates a business as usual scenario
2. Peak electricity demand is assumed to account for roughly 6 hours every workday, which works out to 17% for the year
3. Unless otherwise stated in the scenario, the model assumes that life cycle impacts remain static throughout the temporal horizon of 2016 to 2035
4. For hydroelectric, wind and solar, the it is assumed that these renewable fuel sources have negligible emissions
5. Bioenergy combustion is assumed to be carbon dioxide neutral
6. A single life cycle cost and life cycle emission factor is assumed for each electricity supply technology
7. The Technology capacity factor is based on historical data and is a static model input
8. Assumptions carried by the IESO in the OPO [15] to develop the alternate demand profiles are inherited by this model