Greenhouse Gas Emissions cuts, a set of fuel-based mitigation wedges in Canada

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

To combat climate change, a global transition from fossil fuels to renewable energy and low-carbon systems is necessary. The energy sector plays a pivotal role in this transition. This thesis aims to guide the Canadian oil and gas (O&G) industry in developing investment strategies for transitioning to renewable energy sources, supporting the 2030 Emissions Reduction Plan.

Mitigation wedges provide an accessible framework for understanding emissions-reducing actions. This thesis derives a set of mitigation wedges for transitioning from fossil fuels to renewable energy, which can be applied in designing O&G companies' strategies towards achieving Canada's GHG emissions reductions. Quantitative methods and statistical analysis are applied to a balanced panel dataset collected from the Canada Energy Regulator (CER) website, including information on provinces, territories, and the entire country from 2005 to 2050, with historical data up to 2020.

The study demonstrates that end-use energy demand for natural gas in the industrial and transport sectors and refined petroleum products in the industrial and residential sectors positively impacts GHG emissions reduction in the O&G industry. These four mitigation wedges can significantly contribute to the Canadian O&G industry's GHG emissions target of 42% below 2019 levels. This research offers valuable insights for decision-makers at industry and policy levels to support a successful transition to a low-carbon economy.

Keywords: OLS Multivariate Linear Regression, Fixed-Effects Panel Regression, Mitigation Wedges.

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1. Introduction

The 26th UN Climate Change Conference of the Parties (COP26) took place in Glasgow, U.K., from October 31 to November 13, 2021, followed by the 27th conference in Egypt (COP27, 2022). The mitigation section acknowledged the need for rapid, deep, and sustained reductions in global greenhouse gas (GHG) emissions to limit global warming to 1.5 °C. This includes a 45% reduction in global carbon dioxide emissions by 2030 compared to 2010 levels and reaching net-zero emissions around mid-century, as well as substantial reductions in other GHGs. As 2030 approaches, our way of life faces significant challenges since we have not come close to achieving our climate change targets. The energy transition towards renewable fuels and low-carbon systems is crucial for overcoming this existential threat to the planet.

Although some global companies have started adopting cleaner practices, they represent a small fraction of the oil and gas (O&G) sector, which accounts for 80% of industrial emissions (WEF, 2022). With environmental catastrophes predicted by scientists, it is highly likely that no energy company will be unaffected by clean energy transitions (Pickl, 2019).

O&G companies play an essential role in the energy transition process and have shown interest in energy transition studies published by various governments, institutions, and companies, which offer benefits to support this task. This study focuses on assisting these efforts in Canada by identifying the fossil fuels that should be prioritized for conversion to renewable energy to significantly address GHG emissions targets.

The concept of "mitigation wedges" is used here, defined as a technology, strategy, or action that can be implemented to reduce CO2 or GHG emissions by a specified amount over a specified period, typically 30 or 50 years. By combining several wedges, significant emissions reductions can be achieved, helping stabilize atmospheric GHG concentrations and slowing climate change. This study examines fossil fuel-based mitigation wedges that indicate the type of fossil fuel, the percentage reduction required to achieve 1% less GHG emissions than in 2019, and the sector needing decarbonization.

The World Economic Forum (WEF, 2020) stated that individual responsibility is vital in the energy transition challenge, and effective change can only occur through lifestyle choices and a multistakeholder approach involving a broad coalition of public and private actors. This research proposes a set of fossil fuel-based mitigation wedges obtained from an OLS regression analysis, with results presented alongside an explanation of the interactions occurring among the impacted economic sectors. The primary institutions or companies essential to this fossil fuel transition are identified.

Wealthy companies can hire private consultants for in-depth studies, but the associated risks cannot be fully avoided, and studies are often time-sensitive. Resource-limited, medium or small-sized companies often struggle to hire consultants for such studies, especially in times of inflation. Thus, a practical and cost-effective methodology like this one would be beneficial.

This thesis poses two research questions: 1) Which fuels should the Canadian O&G industry focus on reducing to significantly achieve its GHG emissions target for 2030? 2) Which O&G consumption sectors are most likely to be affected by fuel reductions? To address these questions, this research employs an exploratory, quantitative analysis based on empirical models developed and tested to understand historical variables and provide forecasted interactions among energy consumption variables.

Based on the selected reduced form of a model, four mitigation wedges were established to explore the GHG emissions of Canada's O&G industry in 2030. For each wedge, a description of the fuels transition required to achieve the GHG emissions target is provided. The first wedge involves reducing Refined Petroleum Products (RPP) in the industrial sector. The second wedge calls for restrictions to decrease Natural Gas consumption in the industrial sector. The third wedge targets a reduction in end-use energy demand for Natural Gas in the transport sector. Lastly, the fourth wedge focuses on lowering the end-use energy demand for RPP in the residential sector.

The data for this study, covering the years 2005 to 2020, were sourced from Canada Energy Regulator (CER) energy scenarios, the Canadian government's National Inventory Report on Greenhouse Gas Sources and Sinks, and the 2030 Emissions Reduction Plan – Canada’s Next Steps for Clean Air and a Strong Economy. By using these data and the proposed mitigation wedges, significant GHG emissions reductions can be achieved in Canada. Shareholders can consider the findings of this research when deciding how to allocate their investment capital to support the transition from fossil fuels to renewable energy in Canada's economic sectors.

In conclusion, this research offers a practical methodology for identifying and prioritizing fossil fuel reductions in the Canadian O&G industry to help achieve the country's GHG emissions targets for 2030. By focusing on specific mitigation wedges, stakeholders can develop targeted strategies and investments to facilitate the transition to a low-carbon, sustainable future. This approach can be adapted and updated to account for changes in conditions and verify the validity of the results. The findings presented here provide valuable insights for policymakers, companies, and investors seeking to contribute to the global fight against climate change.

1.1 Background

Energy transition is crucial, and oil and gas companies face a dilemma: whether to shift their focus from their core business to low-carbon energy or to maintain business as usual and maximize returns from oil and gas reserves. This uncertainty revolves around acquiring technology, entering new markets, and securing genuine stakeholder support. Moreover, the O&G industry plays a vital role in helping capital-intensive clean energy technologies mature and reduce uncertainty (Poudineh, 2019).

In Canada, several regulations promote sustainable energy transition. Table 1.1 provides a chronological summary, highlighting the 2030 Emissions Reduction Plan introduced in March 2022.

Table 1.1. Canadian regulation to promote sustainable energy transition.

Regulation	Content
The Energy Efficiency Act (S.C. 1992, c. 36) was released in 1992 and last changed in December 2008.	This Act aims to establish the minimum energy efficiency standards for a broad range of products and equipment in order to decrease overall Canadian energy consumption.
The Canada Foundation for Sustainable Development Technology Act (S.C. 2001, c. 23) was launched in 2001.	To establish a not-for-profit foundation that finances and supports the development and demonstration of clean technologies which provide solutions to issues of climate change, clean air, water and soil quality, and which deliver economic, environmental and health benefits to Canadians.
The Canada Emission Reduction Incentives Agency Act (S.C. 2005, c. 30, s. 87) was released in 2005.	The Act established the Canada Emission Reduction Incentives Agency, whose task it is to come up with incentives to reduce greenhouse gas emissions either through emissions credits or greenhouse gas removal is established.
In 2018, the Canadian federal government introduced regulations to phase out conventional coal-fired electricity across Canada by 2030.	In May of 2021, G7 countries, including the United States and Canada, committed to taking concrete steps towards an end of government investment for unabated international thermal coal power generation projects by the end of 2021. To this respect, the Government of Canada is clarifying today's position on new thermal coal mines and expansion projects in this country with the purpose of providing greater certainty to investors, the mining sector and Canadians generally.
The Greenhouse Gas Pollution Pricing Act in 2018.	It established a federal price on greenhouse gas (GHG) emissions beginning in January 2019 and applying to any province or territory of Canada that

	requests the price, or to any province or territory of Canada that has not implemented a compliant carbon pricing tax[1].
The Impact Assessment Act of 2019, last amended in July 2020, replaces the Canadian Environmental Assessment Act, 2012.	This Act provides the overall architecture for the federal environmental impact assessment regime in Canada. Under the Impact Assessment Act, the Minister of Environment and Climate Change or Governor in Council must determine that the effects within federal jurisdiction likely to be caused by a project are in the public interest, if a project is to move forward. This decision is informed by whether the project contributes to sustainability, whether it hinders or contributes to Canada's ability to meet its commitments in respect of climate change, and other relevant matters.
The Strategic Assessment of Climate Change was revised in October of 2020.	In which the Government of Canada put in place better rules for major projects, Environment and Climate Change Canada (ECCC) developed the strategic assessment of climate change (SACC). It describes the greenhouse gas and climate change information that project proponents need to submit at each phase of a federal impact assessment and requires proponents of projects with a lifetime beyond 2050 to provide a credible plan that describes how the project will achieve net- zero emissions by 2050. The SACC applies to designated projects and guidance for projects regulated by the Canada Energy Regulator will similarly consider the principles and objectives of the SACC. ECCC plans to review and update the SACC every five years.
The Bill C-12 was launched on 26th of June 2021.	This is the Canadian Net-Zero Emissions Accountability Act, which sets out Canada's federal emissions reduction targets in law and creates new mechanisms for legislative oversight of action to meet them.

Following to the Bill C-12 releasing, the "2030 Emissions Reduction Plan – Canada's Next Steps for Clean Air and a Strong Economy" was launched in March of 2022. This plan is the first straightforward roadmap that sets sector-specific emissions reduction targets. By collaborating with stakeholders, governments, businesses, non-profit organizations, and communities across Canada, new opportunities are expected to emerge.

The Canadian government is taking several actions to reduce emissions, presented in Table 1.2.

[1] The carbon pricing was previously implemented in the province of British Columbia in 2008. (https://www2.gov.bc.ca/gov/content/environment/climate-change/clean-economy/carbon-tax) .

Table 1.2. 2030 Emissions Reduction Plan– Canada's Next Steps for Clean Air and a Strong Economy.

Main action name	Main action description
Helping to reduce energy costs for our homes and buildings.	Development of the $150-million Canada Green Buildings Strategy to build off existing initiatives and set out new policy, programs, incentives, and standards needed to drive a massive retrofit of the existing building stock, and construction to the highest zero-carbon standards.
Empowering communities to take climate action.	a) Expanding the Low Carbon Economy Fund through a $2.2-billion renewal to leverage further climate actions from provinces and territories, municipalities, universities, colleges, schools, hospitals, businesses, not-for-profit organizations, and Indigenous communities and organizations. a.1) Support climate action by Indigenous Peoples with a new $180-million Indigenous Leadership Fund to support clean energy and energy efficiency projects led by First Nations, Inuit, and Métis communities and organizations. a.2) A $25-million investment in Regional Strategic Initiatives that will drive economic prosperity and the creation of sustainable jobs in a net-zero economy.
Making it easier for Canadians to switch to electric vehicles.	a)Additional funding of $400 million for zero-emission vehicles (ZEVs) charging stations, in support of the Government's objective of adding 50,000 ZEV chargers to Canada's network. b)The Canada Infrastructure Bank will also invest $500 million in ZEV charging and refueling infrastructure. c)The Government of Canada will provide $1.7 billion to extend the Incentives for Zero-Emission Vehicles (iZEV) program will make it more affordable and easier for Canadians to buy and drive new electric light-duty vehicles. To reduce emissions from medium- and heavy-duty vehicles (MHDVs), the Government of Canada will aim to achieve 35 percent of total MHDV sales being ZEVs by 2030. In addition, the Government will develop a MHDV ZEV regulation to require 100 percent MHDV sales to be ZEVs by 2040.
Driving down carbon pollution from the oil and gas sector.	a) Diversifying our energy mix. b) Offering lower carbon oil and gas to the world. c) **A projected contribution from the oil and gas sector of emission reductions to 31 percent below 2005 levels in 2030 (or to 42 percent below 2019 levels).** d) The Government of Canada's will work with industry, provinces, Indigenous partners, and civil society to define and implement the cap on oil and gas sector emissions. Following consultations, the cap will be designed to lower emissions at a pace and scale needed to achieve net zero by 2050. e) To reduce oil and gas methane by at least 75 percent by 2030, supporting clean technologies to further decarbonize the sector, and working to create sustainable jobs.
Powering the economy with renewable electricity.	a) Electrifying more activities—from vehicles to heating and cooling buildings to various industrial processes. b) Increase the supply of electricity. c) Ensure that all electricity generation has net-zero emissions. d)To establish a Pan-Canadian Grid Council to promote clean electricity infrastructure investments. e) Invest an additional $600 million in the Smart Renewables and Electrification Pathways Program to support renewable electricity and grid modernization projects and $250 million to support predevelopment work for large clean electricity projects.
Helping industries develop and adopt clean technology in their journey to net-zero emissions.	a) Developing a carbon capture, utilization, and storage (CCUS) strategy; introducing an investment tax credit to incentivize the development and adoption of this important technology. b) Investing $194 million to expand the Industrial Energy Management System to support ISO 50001 certification, energy managers, cohort-based training, audits, and energy efficiency–focused retrofits for key small-to-moderate projects.
Investing in nature and natural climate solutions.	Additional $780 million for the Nature Smart Climate Solutions Fund to deliver additional emission reductions from nature-based climate solutions. The Fund supports projects that conserve, restore, and enhance Canada's vast and globally

	significant endowment of wetlands, peatlands, and grasslands to store and capture carbon.
Supporting farmers as partners in building a clean, prosperous future.	a) New investment of $470 million in the Agricultural Climate Solutions: On-Farm Climate Action Fund to help farmers adopt sustainable practices such as cover crops, rotational grazing and fertilizer management, b) also investing $330 million to triple funding for the Agricultural Clean Technology Program which supports the development and purchase among farmers of more energy-efficient equipment, c) also invest $100 million in transformative science for a sustainable sector in a changing climate and to support the sector's role in the transition to a net-zero economy for 2050, including fundamental and applied research, knowledge transfer, and developing metrics.
Maintaining Canada's approach to pricing pollution.	Exploring measures that help guarantee the price of pollution: a) Investment approaches, like carbon contracts for differences, which enshrine future price levels in contracts between the Government and low-carbon project investors, thereby de-risking private sector low-carbon investments. b) Legislative approaches to support a durable price on pollution.

Although Canada has a long history of environmental regulations and sustainable actions, achieving a low-carbon economy remains challenging. As time goes on, regulatory requirements become stricter, influencing stakeholders' actions, which must be practical and adaptable.

To reach Canada's net-zero emissions target by 2050, various players must undertake numerous actions. A significant shift from fossil fuels to renewable energy sources is a multi-step goal that will involve substantial infrastructure changes and challenges, as current facilities and networks are designed for fossil fuel operations. As one of the largest oil and gas producers globally, Canada must substantially reduce its reliance on fossil fuels and transition to cleaner alternatives like renewable electricity and hydrogen from renewable sources.

The energy sector often uses energy scenarios for analysis, which are intended to facilitate strategic dialogue about the future of energy systems. These scenarios help industry experts plan and make investment decisions by providing projections for various parameters under specific assumptions. However, several factors and assumptions affect the forecasted outcomes, leading to uncertainty.

As an alternative, the concept of "stabilization wedges", introduced by Pacala and Socolow (2004), considers technological and behavioral options in a structural energy model assessed through an economic evaluation in an input-output analysis. Numerous studies, including those by Williams et al. (2012), Davis et al. (2013), Köppl (2014), and Mathy et al. (2018), have updated the concept of "mitigation wedges." These wedges, considered practical for addressing upcoming changes across a range of categories such as California's infrastructure and technology path, IPCC's SRES scenarios for the UK, Austria's welfare-generating energy services, and power sector decompositions for a group of countries, are sets of specific actions or strategies aimed at reducing greenhouse gas emissions.

Both energy scenarios and mitigation wedges offer advantages and drawbacks. Energy scenarios provide a comprehensive look at the energy system and potential intervention areas but can be complex and difficult to communicate. Mitigation wedges, conversely, offer an accessible framework for understanding specific emissions-reducing actions but might not capture the energy system's full complexity or interactions between various mitigation strategies.

1.2 Problem statement

To achieve Canada's emissions reduction goals outlined in the 2030 Emissions Reduction Plan and support carbon pollution reduction in the oil and gas sector, it is crucial to identify the fossil fuels with the most significant impact on GHG emissions and the economic sectors involved. This information will help direct investments towards emissions reduction. Mitigation wedges, which detail the types of fossil fuels and the sectors where they are used, can inform plans for transitioning to renewable energy sources to reduce GHG emissions and guide the oil and gas industry.

While energy scenarios remain useful for strategists to design, evaluate, and select company strategies, the high level of uncertainty and assumptions about future economic and technological developments prompt this research to focus on "mitigation wedges" for exploring potential opportunities. The need for simplicity and practicality in the analysis for determining directions in the oil and gas industry makes mitigation wedges an appealing choice in this study.

The mitigation wedges concept analyzes past and current events to quantify the contributions of each fossil fuel used in every sector as part of mitigation strategies. This is particularly important when the interactions of variables involved are complex or not easily understood, as is the case with the energy system. This approach helps companies understand and directly apply the results to their strategies. Furthermore, a simplified system map identifying the most critical fossil fuels to be decarbonized in Canada can provide insights into the changes involved in their decarbonization process.

In contrast to previous studies, this research focuses on fossil fuel categories to be replaced with renewable energy as mitigation wedges. The intention is to directly apply these findings to the oil and gas company's strategy or even support existing regulations in Canada.

1.3 Research questions and objective

This research aims to assist the oil and gas (O&G) industry in developing or adjusting their investment strategies for transitioning from fossil fuels to renewable energy sources, as part of the move towards a low-carbon economy. The research questions are as follows: Which fuels should the Canadian O&G industry focus on transitioning to renewable sources in order to significantly achieve its GHG emissions target for 2030? And which O&G consumption sectors are most likely to be impacted by fuel reductions? The objective is to create a set of mitigation wedges for fossil fuels transitioning to renewable energy, which can be used to achieve the necessary greenhouse gas emissions reductions in Canada. These wedges can be practically applied in the design or updating of an O&G company's strategy towards this goal.

The mitigation wedges were developed in this study through several steps: analyzing pre-existing work; selecting relevant findings for model questions and variables; creating simplified models; identifying the fossil fuel categories to address; determining the affected sectors; and proposing the mitigation wedges for the energy transition that could be followed. This approach allows for a quicker and more practical way to obtain plausible mitigation wedges that can be adapted to changing regulations and results as they emerge.

1.4 Thesis outline

In this chapter, the background including the current regulations associated with the energy transition in Canada, problem statement, research questions, and objective of this study were given. Next, chapter 2 presents the literature review which analyses the academic and media literature that is relevant to the thesis. The topics climate change, energy systems, modelling methodologies, energy transition studies, Canadian energy transition studies and the concept of mitigation wedges are mentioned here. Chapter 3 explains the theoretical framework and hypothesis. Chapter 4 describes the methodology used, chapter 5 presents the results and findings, and finally chapter 6 details the discussion and ends with the conclusions.

2. Literature Review

2.1 Climate change

The frequency and magnitude of events brought by climate change are increasing, highlighting the importance of acting now for the future. As the climate-change-generated global average temperature increases, harmful effects impact nature and humanity. The danger of arriving at a tipping point continues as important events recently affecting this situation are exposed.

Indeed, relevant literatures suggest that in order to limit the global average temperature increase enormous efforts must be made with the energy transition agreed by 175 world leaders in the Paris Agreement (UNCC, 2015) and reaffirmed in the Glasgow Climate Pact (COP 26, 2021). This decade seems our last decade to comply with the first important target, which will lead to a higher chance of keeping peak warming to 1.5°C (high confidence). The "carbon budget" developed by the Intergovernmental Panel on Climate Change (IPCC) estimates that to stay within 1.5˚C of global warming the world can "spend" only a maximum budget of 2600-2900 $GtCO_2$ of anthropogenic emissions, of which 2200 $GtCO_2$ have already been used to date. With current emissions of approximately 42 $GtCO_2$ a year, the remaining budget will be depleted in 10-17 years, after which it is highly probable that the conditions in the Earth will drastically change, thus threating our survival (WEF, 2020).

Unfortunately, although several efforts in adopting technologies have been made, policies implemented, and methodologies applied, results show that there has not been much advancement in the implementation of this process globally. The Energy Transition Index (ETI) 2021, reported by the World Energy Forum (WEF), summarizes insights on the energy performance of 115 countries and their energy transition readiness. This report reveals that there is a long way to go in making real headway and that the Oil and Gas (O&G) countries have an important role in getting us there (WEF report, 2021). Of the total 115 countries monitored, 92 have made progress yet only 68 have improved their scores by more than two percentage points—the increases are minimal. Large emerging economies and energy demand included in the 115 countries, such as China and India, have seen strong improvements as has the United States (US). Meanwhile, scores in Brazil, Canada, Malaysia, Singapore and Turkey have been relatively stable. Energy transition investment is concentrated in China and the US accounting for the large share of investments but, investment outside the top 10 countries is growing steadily.

Alongside the relatively slow progress towards energy transition, a number of additional relevant factors that negatively affect the transition process have recently arisen as follows. In contrast to the highly pandemic-impacted 2020, a fast rebound of demand for products and services was seen in 2021, marked by the global economy's strong and exceptionally rapid recovery with global GDP growth estimated. Because of the strong correlation between economic growth and energy consumption, the global demand for electricity and oil surpassed the pre-pandemic levels, resulting in the highest prices experienced in years. The February 2022 invasion by Russia of Ukraine brought a surge in the prices of energy, accelerating inflation on top of other factors such as strong consumer demand, restricted supply chains, rising wages, increasing costs of housing and food, and low interest rates. Unfortunately, so far, the need for energy resources at high levels is still present and limited options exist in the market as to where to get it. These facts yield to a lack of price elasticity in energy demand, where the energy demand has changed little to price changes because demand remains so high. The risks of high energy prices, inflationary pressure, and economic issues that are expected to increase volatility have given rise to two main responses. In the countries not directly affected by the Ukraine invasion, those that are O&G producing countries (fossil fuel-based economies) are seeing a resulting slow-down of the energy transition process. At the same time, the European community which is the most directly affected by the Russian gas shortage is putting high effort and increased pressure on speeding up this transition, looking forward to reaching their energy security together with net zero emissions.

2.2 Energy Systems

The energy transition relies on moving energy systems that interact with other systems, from high to low-carbon intensity in order to reach net-zero emissions. Nevertheless, it is not easy to identify and prioritize these systems systems for a number of intersecting reasons.

To begin, energy systems are part of our daily lives, encompassing all utilities such as heating, cooling, ventilation, lighting, and the supply of domestic hot water, among others. The International Atomic Energy Agency (IAEA, 2018) defines energy systems as consisting of the energy supply sector, energy end-use technologies, and the associated infrastructure that converts the energy commodities provided by the energy sector into energy service. These systems are usually highly complex and multivariable, which must always be taken into account. Energy systems are frequently misconceptualized as self-contained systems belonging to industry or governments that, despite having an impact on the environment both locally and at large, are completely disconnected from the community. With the migration of the Millennium Development Goals followed by the Sustainable Development Goals (SDG), the conceptualization of the energy system has been updated as an integrated part of the whole of human activities. However, in our day-to-day practice, this disconnection tends to remain and much work needs to be done to make changes if we want to reach a successful energy transition.

The Oil and Gas sector, as one of the main actors for providing us with utilities, faces the crucial decision of setting strategies to either redirect from their core business towards transition to low-carbon technologies, postpone their adaptation strategy until there is less uncertainty, or continue with business as usual. As mentioned in Chapter 1, the O & G companies are not alone as a large number of stakeholders are involved, including clients, suppliers, traders, shareholders, regulators and society, among the most important. Moreover, several sectors are linked with the energy sector, and the interrelations among these sectors results in multiple and highly complex interactions. In effect the energy systems are multivariable, complex networks that include a wide range of interactions among technical, social, and institutional systems. To consider our energy systems and analyze them in separated parts will leave us falling short in our attempt to address and overcome the barriers that currently impede the energy transition. To properly aid in the accomplishment of the SDGs, energy systems need to be holistically integrated within the rest of human activities. Changes that occur in one component may yield to effects on the complete system in a high non-linear and non-predictable way. Therefore, low-carbon energy systems will require better knowledge of the main drivers to pull, and by how much, in order to push the transition to a global level (Blackburn et al. 2017).

To promote the desired transitioning, it becomes crucial to understand the complex interactions that happen among the systems with the energy one and he application of the institutional theory. The study of the low-carbon energy transition has demonstrated gains by finding a high degree of parallelism existing between the literature on socio-technical regimes and institutions. The systematic application of institutionalism can provide a deeper understanding of socio-technical transitions (Geels and Schot, 2017). The clean energy transition can be supported by treating the energy sector as a socio-technical regime and examining how institutions can accelerate the processes involved in this transition (Andrews-Speed, 2016). This theory was used to study the processes by which structures that include rules, norms and routines, become established as authoritative guidelines for social behavior. It explains how those elements are created, diffused, and adopted (De Jonge, 2015). This theory has shown that geographic locations are the base for the general regulatory, normative, and cultural–cognitive institutional constraints or advantages that shape the international performance of companies (Amal, 2016). It also indicates that when the institutions are self-reinforcing with positive feedback or increasing returns, mainly in their profitability, they are strongly resistant to change (Andrews-Speed, 2016). In both, political and economic institutions, the positive feedback mechanisms and the consequent institutional resilience result in a high degree of path-dependence. In addition, the fact of having a complex inter-locking and inter-dependence between institutions reinforces path-dependency (North, 1990). In consequence, a change in one institution or the introduction of a new institution will generally require change in a number of other connected institutions. The energy industry is strongly connected with several other institutions and these findings will apply. Clearly, there will be much resistance on the part of institutions to change and the use of their power to constrain change, but the institutional theory can provide useful information about factors that have historically influenced a major transition such as this. For instance, the full replacement of one institution by another, or of one set of institutions by another, has happened when a major crisis of confidence in existing institutions takes place. Then, collective action requires trust or social capital to allow a society to come together to address certain collective action problems (W. Neil Adger, 2006). The one we are facing now with climate change is no exception and in terms of transaction cost economics (Williamson, 2013), it will be high. To this respect, trust lowers the transaction costs of solving collective action problems and as long as the institutions and society have clear and reliable solutions to guide them on this path, the process will speed up. Trustworthy energy scenarios can become key to these ends.

A higher complexity degree is given by the fact that, as we all are immersed in the transition, we will have to learn how to deal with the changes under certain limits. Also, it is important to keep in mind that some effects will be time lagged and we won´t fully identify these now but in the future. As an illustrative example of important limits that are present in a transition, Geobey and McGowan (2019) studied the historic data of the Plague in Europe to find out if the resilience of a system could be measured contemporaneously by those within a social system and if it was possible to learn from past efforts to understand the resilience of social systems by those living through their transformations. They found a time lag between quantitative indicators of system resilience and the systemic shocks introduced by the Plague but that those who experienced the epidemic were trying to develop personal understandings of the social changes around them and collective understandings of how to respond to these crises. They learned that there were some limits of what could be understood during the period of social transformation and what was needed to rely on descendants to reveal. These findings can perfectly be transferred to what we are currently facing, with the energy transition.

2.3 Modelling methodologies

A critical part to understanding the energy systems is the modelling that represents these systems' behaviours. In general, applicable modelling has two main parts: the model itself and its associated solving methodology. A model is an approximation to represent a phenomenon in a simplified way, not taking into account some factors yet considering enough of them to achieve an acceptable response in mathematical terms, typically an equation (Jodar and Company, 2022). To solve the model, a wide spectrum of methods can be used to reach a potential solution. Among the most important are deterministic, random, algebraic, and differential methods. The selection of the method varies according to the kind of equations that the model uses and to different fields. Nowadays, there are many algorithms available to mine, alter, manage, retrieve and process data from a variety of sources and perform statistical analysis on. Moreover, business intelligence software can tremendously support the analysis of information.

2.3.1 Stochastic models

Stochastic modelling has been used extensively in the energy transition scenarios, as these models consider a random variable as the uncertainty associated with the model. Moreover, to take advantage of the analysis of massive information, business intelligence software has also been considered to support the modelling. Generally speaking, stochastic models can reflect the changing real-world energy scenarios by providing a range of possible outcomes and the relative likelihood of each. This contrasts with non-stochastic modeling, often called deterministic modeling, which gives the same exact results every time for a particular set of inputs. Stochastic models require the ability to realistically model risks, which can be difficult. Another problem with stochastic models is the fact that specific risks change over time depending on the combination of factors held within the forecasted period, a shortfall which is often ignored. On the side of the business intelligence-based models, the main advantage is that the results generated are more precise and can handle huge amounts of data. Nevertheless, these models are not simple to understand as they are mostly like "closed boxes." They require a deep experience in data analysis, artificial intelligence algorithms, and computational programming to be able to reach suitable models and outcomes. These models are not frequently easy to show as simplified equations and then be used to explain results and encourage stakeholders. As a result, these models are commonly used in closed systems, where the interactions are already known, and it is not needed to understand the new-multiple interactions that will happen.

2.3.2 Econometric models

These models have an empirical base which provides useful tools to analyze the effects of certain factors on dependent variables that are of interest. These models are generated from a data set, named regressors (independent variables) and are fitted by a regression uni- or multivariate treatment. The validity of the resulting empirical models is assessed under a range of statistical tests. The obtained models identify the most significative factors that affect the dependent variable and the magnitude and direction of the effects. In general, empirical models have been applied in a wide range of areas, and in the case of the energy sector these are called econometric models. The main feature of econometric models is that they are constructed with economic data, mainly prices and quantities. The data are time series, cross sections, or a combination of the two, called panel data, with the application of statistical inference. An optimization problem is mostly considered to solve the economic problem set towards a desired maximum or minimum.

These models are extensively used due to the simplicity of the involved equations, which keeps the mathematics at a level that requires algebra only to understand the effects of the studied phenomena or event. However, strong economic and statistical theory is required to properly understand the results. Moreover, modern empirical applications generally share the following common characteristics. Data sets typically have hundreds, thousands or higher numbers of observations. Regressors are not fixed over repeated samples but rather are collected by random sampling, making a mechanism for randomization frequently needed. The data are not normally distributed and the distribution of the errors can change over the time, therefore additional work may be necessary to improve the models' validity (Stock and Watson, 2020).

A popular statistical method used to analyze panel data is Fixed-Effects Panel Regression. With this method, individual-specific or entity-specific fixed effects are included in the regression model to control for unobserved heterogeneity across entities, i.e., for omitted variables in panel data when the omitted variables vary across entities (states) (Stock and Watson, 2020). This approach helps to isolate the effect of the independent variables of interest on the dependent variable, thereby facilitating the analysis.

2.4 Energy transition studies

Next, some of the most relevant modelling examples that have been developed to deal with energy forecasting under uncertainty are presented. As well, the factors that are focused on and the main limitations of these examples are highlighted.

Kanitkar (2020) carried out a review of the main methodologies and tools used in the models to address energy consumption and the forecasting of resource potential and reserves. The work included the study of energy substitution, the forecasting of economic growth, income, energy use and supply linkages for the future. Methods for long-period forecasting can be used to forecast energy demand and emissions. Some examples of these kinds of models are called the IPAT and the STIRPAT equations, where STIR stands for STochastic Impacts by Regression.

To account for uncertainty in the forecasting, Taleb Nassim (2010), popularized the "black swans" mathematical concept as a forecaster that predicts y using knowledge of X and facing uncertainty from the known unknowns $\in$ and the unknown unknowns z. Modeling errors due to $\in$ are stochastic errors and can be incorporated into the model. They deduced from the equations that the forecast errors for nonlinear systems are not constant for all input values. Instead, forecasts can be precise for some values and highly inaccurate for other values.

A selection of examples based on empirical models that have been applied to the energy transition is presented below.

The empirical effects of economic growth, electricity consumption, foreign direct investment (FDI), and financial development on carbon dioxide (CO_2) emissions in Kuwait using time series data from 1980 to 2013 were examined by Salahuddin et al. (2018). Results indicated that these variables have a positive and significant relationship with CO_2 emissions for Kuwait, both in the short and long run.

However, these are not statistically significant. They marked that Kuwait is very rich in renewable resources such as wind and solar and it is rated as excellent in terms of its potential for solar energy due to its very high average daily irradiation and ambient temperatures. The authors suggested reducing unexpected wastage of electricity use brought on by highly subsidized electricity that encourages massive and sprawling consumption of it in the country. They proposed an effort to rationalize electricity consumption to reduce the social and environmental costs of such a highly government-subsidized project. Additionally, as the transport sector has rocketed in the country and, as it is also responsible for a significant proportion of emissions, they stressed out that attention must also be given to reducing emissions from this sector in Kuwait.

Other example is the work of Aydin (2019) who studied the relationship between renewable and non-renewable electricity consumption and economic growth using data from the 1980 to 2015 for the 26 OECD countries Australia, Austria, Belgium, Canada, Chile, Denmark, Finland, France, Greece, Iceland, Ireland, Israel, Italy, Japan, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the United Kingdom, and the United States. The results showed that there is cross-sectional dependence and that there is a bidirectional causality between economic growth and non-renewable electricity consumption. Therefore, there is no causality between economic growth and renewable electricity consumption. This finding is important as it yields to the idea of reaching economic growth without a significative increase of renewable electricity consumption, so far in that group of countries.

Another research done by Xu et al. (2019) stated that a current understanding of the drivers and detractors in the energy transition is limited. Moreover, that factors such as institutional, political, technological and economic factors have not been fully investigated in the literature so far. They reviewed several papers and concluded that no single policy alone can achieve the wanted energy transition. Instead, mentioned that policy makers need to carefully assess the interplay of different policies not only for renewable energy support but also take energy efficiency and climate policy into account in order to avoid distortions. They advised that policy makers need to be aware of the role political economy plays in the dynamics of renewable energy.

As well, the relationship between GHG emissions, financial development, and disaggregated energy consumption (renewable and fossil fuel) among the top 10 countries with the highest CO_2 emissions (Canada, China, Germany, India, Iran, Japan, Korea Republic, Russia, UK and US) was explored by Shi et al. (2019). They applied panel data for the period 1990–2014 within a multivariate framework.

The results indicated a long run relationship between emissions per capita, energy use (renewable and fossil fuel), financial development, GDP per capita and population. The long-run coefficients suggest that a 1% increase in renewable decreases emissions by 0.035%; a 1% increase in financial development reduces emissions by 0.047%; a 1% increase in per capita GDP raises emission by 0.426% and a 1% increase in population increases emission by 0.585%. Additionally, the outcome of the analysis reinforces the contribution of renewable energy use in the carbon emissions' reduction mechanism of these top 10 countries with the highest emissions of CO_2 globally. The result further provides insight to policy makers on the combination of energy mix alongside financial development that can reduce GHG emissions and mitigate climate change and ensure sustainable green environment.

The effect of natural gas, nuclear energy and renewable energy on GDP and carbon emissions in the ten highest CO_2 emitting countries, United States (USA), Canada, India, Iran, Japan, Russia, United Kingdom, South Korea, Germany and China, within a multivariate context for the duration of 1990 to 2014 was studied by Azam et al. (2020) though a multi-variate panel data analysis. These countries have high GDP and are also the greatest suppliers of CO_2 emissions worldwide, with the total CO_2 emission of these regions coming from energy consumption in more than 75%. The panel co-integration test confirmed the existence of a long-run equilibrium correlation among the variables and revealed that natural gas does not contribute to economic growth and CO_2 reduction like nuclear energy and renewable energy. The fact that renewable energy contributes to economic growth in this study for the ten highest CO2 emitting countries from 1990 to 2014 contradicts what Aydin (2019) found for the 26 OECD countries from 1980 to 2015. It may be caused by the much higher levels of nuclear and renewable energy that are used in this group of the ten highest emitting countries.

On the other hand, an interesting analysis of the impact of renewable electricity consumption on economic growth for the panel of ten newly industrialized countries namely Brazil, China, India, Indonesia, Malaysia, Mexico, the Philippines, South Africa, Thailand and Turkey from 1990 to 2015 was carried out by Azam et al. (2021). They employed panel unit root tests, panel heterogeneous cointegration method, panel Fully Modified Ordinary Least Square and the Granger causality method. For this group of countries, it was confirmed that the economic growth, renewable electricity consumption, non-renewable electricity consumption, gross capital formation, labor force and trade openness are co-integrated. It was also found that all studied variables have a positive long-run effect on economic growth, with a 1% increase in renewable and non-renewable electricity consumption increased economic growth by 0.095% and 0.017% respectively. A bidirectional causation between renewable electricity consumption and economic growth in both the short-run and long-run was also found.

An overview of salient studies towards identifying pathways for energy transition focused on the setting of specific targets towards O&G dependent countries, industries or energy scenarios comparisons is given as follows.

Technology is a key element for this transition, to this respect, Lund (2007) explains that extensive technology developments have arisen with three major technological focuses: energy savings on the demand side, efficiency improvements in the energy production processes and the replacement of fossil fuels by alternative renewable energy. Some of these have been applied in countries such as Denmark suggesting substantial advances in their energy transition. Lund called for additional technological improvements to be introduced such as technologies would convert the transportation sector, more and better flexible energy technologies, and improved design of integrated energy system solutions.

In terms of energy transition progress, the O&G rich countries have achieved some positive results. These efforts can be illustrated through the work done by Al-Sarihi and Cherni (2018), who assessed the strengths and weaknesses of Renewable Energy (RE) initiatives in Oman. Based on learning processes, actors' networking and articulation of visions, their findings indicated that RE initiatives, if managed properly, can drive large-scale implementation in Oman.

Griffiths (2017) researched current trends in renewable energy policy in the Gulf Cooperation Council (GCC) countries to identify those that will be the most effective and feasible to speed up renewable energy transition. The results revealed that the GCC have an opportunity to take advantage of renewable energy policy design for acceleration of renewable energy deployment.

An overview carried out for eight of the major companies' role of positioning themselves on the path of energy transition was developed by Pickl (2019). His analysis on measuring their capital allocation into renewable energy and other factors identified five companies (Royal Dutch Shell, Total, BP, Eni, and Equinor) that have undertaken considerable investment into renewable energy and the other three (ExxonMobil, Chevron, and Petrobras) which remain renewable energy with a purely hydrocarbon focus and low activity in terms of renewable strategy. Additionally, a strong linkage between the oil majors' proved oil reserves and their renewable energy strategies was found. So far, these results prove that although there is much research work, proposals and developments available, this hasn´t been properly implemented in practice.

Alternatively, Poudineh (2019) argues that, because of the high level of uncertainty implicit, the strategies of the O&G companies need to be developed with the consideration of a wide set of possible future market conditions (case scenarios), to be flexible enough and evolve quickly to adjust to the response to market fluctuations.

Similarly, Bohra & Shah (2020) developed an optimization framework to allow policymakers to apply a systems approach to all the energy infrastructure in Qatar with the consideration of the industrial, residential, transportation and agriculture sectors. Their goal was to develop an open-source tool that could be used for national-level planning and policymaking, and to use it to generate key technology and policy insights to support the transition of Qatar´s energy infrastructure in the long term. The results provided a blueprint for a cross-sectoral energy transformation including the use of low-carbon transport such as electric cars and public transit, grid scale adoption of solar energy and reverse osmosis for desalination. On the other hand, these showed that hydrogen from the steam reforming of natural gas would be a more profitable export than Liquefied Natural Gas.

The variation of the energy consumption and GDP in the GCC with reference to the group of Organization for Economic Co-operation and Development (OECD) countries was assessed by Howarth et al. (2017). For their estimations they used energy consumption in each sector and total GDP. They computed the energy demand equations per capita energy consumption with power per capita income and time dependency. Their findings highlighted that there is a strong dependence between energy consumption and economic growth in all GCC sectors.

They recommended focusing on both energy efficiency and the need for deeper integration of energy-intensive industry and higher value-added activities and services.

An estimation of effects in the methane emissions and oil prices brought by the increased production in the US high O&G production scenario was carried out by Raimi (2020). Modeling tools and recent data on Greenhouse Gas (GHG) emissions from the O&G sector were used to assess whether continued growth in US oil and natural gas production is likely to increase or decrease domestic and global GHG emissions. The results showed that US-only greenhouse gas emissions are likely to be 2–10% higher under a high production scenario, under a range of assumptions about methane emissions and that the non-US effects may be substantially larger.

On the efficiency in energy use side, Gerarden et al. (2017) assessed relevant literature in the energy-efficient technologies available that offer considerable promise for reducing both the financial costs and environmental damages associated with energy use. They identified three categories of explanations for the apparent underinvestment in these technologies: market failures, behavioral explanations and modeling flaws. The degree to which each explanation contributes to the energy-efficiency gap is relevant for making suitable policies. The decision to invest in disruptive technologies becomes more complex when firms have a strong familiarity with a particular market or process, i.e., O&G, but are unfamiliar with the technologies or services that belong to different markets or processes, i.e., solar, wind or biomass energy generation. However, technology acquisition is a key process in this desired transition that cannot be left out in the energy scenarios and may represent opportunity costs. Collaboration has proved to be an option to acquire selected technologies and to effectively incorporate these within organizations (Dilek, 2013).

A crucial aspect to consider is that decision-making in the energy sector strongly relies on analytical results, and these are provided by forecasts. Ericson (2019) illustrated the main challenges that energy forecasters face and the solutions they employ with the shale gas boom for example. By using a simple typology of energy forecast uncertainties and the setting of domains for the predictions, they manage and explain two important types of uncertainty, the epistemic (unknown unknowns) and the stochastic (known unknowns). They argued that decision-makers in the private, public, and research sectors might benefit from a better understanding of how modelers themselves conceptualize and manage uncertainty.

Gielen et al. (2021) carried out a meta-analysis of 18 energy transition scenarios and they found out that there is consensus over the main strategies: renewable power generation, and the direct and indirect electrification of end-use sectors. There is agreement on most of what needs to be done, though strategies differ, and policy frameworks must be enabled. The authors draw our attention to six targets to focus on: energy intensity, renewables share in primary energy, renewable power generation, electro voltaic cells sales, hydrogen demand, biomass, and reducing global emissions by 50% by 2030. They recommended that strategies be updated regularly to optimize pathways. They recognize that significant structural changes and behavioral changes are needed on top of the technological transition and have developed a set of 32 indicators to characterize these scenarios.

The literature indicates, then, that numerous studies have been developed for the energy transition in the countries with their economies highly dependent on O&G. Nonetheless, as mentioned in section 2.1, when it comes to taking massive investment decisions in both government and fossil fuel companies that operate in these countries much more work is necessary to clearly understand the complex interactions.

To measure and understand the impact of the energy transition in the SDG, the are several scenarios that have been developed by diverse institutions such as government agencies, independent institutes, academic researchers, and private companies. These energy transition scenarios consider a wide variety of methodologies and models. Some of them are updated periodically (usually annually) while other projections come from a one-time publication. Some groups also create "story lines" such as the ones by the IPCC to assess the climate change, and by Shell, that describe the world development qualitatively in addition to the quantitative scenario inputs. Economic growth, population growth, and rate of four technological improvement are often based on exogenous assumptions informed by the projections from the leading organizations in these areas such as the International Monetary Fund, UN Population Division, and International Energy Agency.

For instance, the IPCC has done a great effort on researching and releasing special reports on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (IPPC, 2018). It is currently working on its Sixth Assessment cycle and the Synthesis Report will be the last of the AR6 products, due for release in late 2022 or early 2023.

Another example is the International Renewable Energy Agency (IRENA) has developed its Renewable Energy Roadmap "Remap", a methodology that includes multiple tools, reports, datasets and documents to measure the socio-economic footprint of energy transition roadmaps (Remap, IRENA). This model takes into account energy, economy and environmental factors to evaluate the likely impacts in terms of GDP, employment and human welfare. An analysis was made based on the IRENA REmap energy transition roadmap 2018 to explore a higher deployment of low-carbon technologies, mostly renewable energy and energy efficiency (Garcia-Casals et al., 2019). Results found that by applying appropriate policies, it is possible to reduce over 90% of the energy-related carbon dioxide emissions from the reference case via renewables and energy efficiency coupled with deep electrification of end-uses.

IRENA has also developed its World Energy Transitions to 1.5 degrees pathway outlook (IRENA, 2021) where they highlight that even in the COVID-19 pandemic, renewables-based systems demonstrated remarkable resilience, technical reliability of renewables-based electricity system with high share of solar and wind. The study noted that a consensus has formed that the only realistic option for a climate-safe world is the energy transition grounded in renewable sources and technologies. Likewise, they mention that for the past seven years, more renewable power has been added to the grid annually than fossil fuels and nuclear combined; and renewable power technologies now dominate the global market for new electricity generation capacity as they have become the cheapest sources of electricity in many markets. The IRENA's 1.5°C Scenario showed that electricity generation would grow three-fold in 2050 and the share of renewables would rise to 90%, with the remaining 10% of total electricity generation would be supplied by natural gas (6%) and nuclear (4%). All of these results are stated to be possible with an estimated for a total investment of USD 131 trillion over the next 30 years.

The International Energy Agency launched its World Energy Outlook (WEO, 2021) which makes use of a scenario approach to examine future energy trends relying on the World Energy Model (WEMD, 2021). This sector module-based was used to develop four energy scenarios, the Net Zero Emissions by 2050 Scenario (desirable), the Announced Pledges Scenario (commitments fully achieved on time), the Stated Policies Scenario (conservative) and the Sustainable Development Scenario where key SDGs are achieved becoming a gateway to the outcomes targeted by the Paris Agreement.

To help define and manage successful energy transitions, the World Energy Council (WEC, 2021) developed transition tools which can be used individually or in combination to enable new, timely and actionable insights. The flexibility of the toolkit recognizes different starting points and a no 'one size fits all' approach to a successful transition. They suggest that the tools can be used to support interventions on a global, regional, national, sectoral, and/or cross-sectoral basis. The toolkit consists of the results of surveys done with 696 respondents across six regions and 87 countries, the trends of information and innovation of the World, an evaluation on a World Energy Trilemma Index, and three developed scenarios for future energy pathways.

All of the above energy transition scenarios are generated by independent institutions and the main feature is that these trend to reach the net zero emissions in 2050. On the other hand, if we look at the energy transition scenarios that are developed by O&G companies or government highly dependent on O&G, the general trend is slightly different, as most of them only reach a part of the net zero emissions in 2050 and keep a significant part of the energy mix with the O&G fuels. Some examples are presented as follows.

The U.S. Energy Information Administration released its Annual Energy Outlook 2022 (EIA, 2022). This report examines a range of conditions from 2020 to 2050 largely under assumptions consistent with laws and regulations as of November 2021, current views on economic, demographic and technology trends, among others. Its main highlights are that petroleum and natural gas remain the most-consumed sources of energy in the U.S. through 2050 but renewable energy is the fastest growing with wind and solar incentives, along with falling technology costs and supporting robust competition with natural gas for electricity generation. In tandem, the shares of coal and nuclear power decrease in the U.S. electricity mix and U.S. crude oil production reaches record highs, while natural gas production is increasingly driven by natural gas exports.

Deloitte (Deloitte, 2020) developed a perspective on scenarios for the future of energy through a toolset split in two axes, global dynamics and societal response to climate change. They identified 92 driving forces and 19 associated major uncertainties that span among social, technological, environmental, economic, and political dimensions. Their result was four divergent scenarios which are not are not clear-cut predictions. Rather, they are hypotheses in the form of data-driven stories about tomorrow. They recommend that the ability to identify, understand, and monitor various indicators and signposts will be required to do effective planning and use of the scenarios.

Shell has recently released three scenarios (Shell, 2021): Waves, Islands and Sky 1.5, that explore the consequences of near-term choices, or different speeds of decarbonization. These scenarios took into consideration the current covid19 pandemic and their main messages are that to meet the goal of the Paris agreement, a pace of change in energy use requires to be hugely challenging but remains technically possible and that practical actions today can accelerate progress.

British Petroleum (BP, 2022) released its BP's Energy Outlook 2022 that was focused on three main scenarios: New Momentum, Net Zero and Accelerated. All of these are possible alternatives to happen on global climate actions taken. BP noted that the economic impact of COVID-19 looks to be less severe than previously anticipated and mentioned that its outlook was largely prepared before the invasion of Russia to Ukraine, which pushed the global energy prices higher and created uncertainty about the Russian O&G sector in the last few weeks.

McKinsey launched its Global Energy Perspective 2022 (McKinsey, 2022) assessing energy systems across countries, sectors, and energy products. They explored five scenarios centered around pace of technological progress and level of policy enforcement and due to the date of released, the uncertainties surrounding the conflict in Ukraine were not addressed by these scenarios. The main findings are share of electricity and hydrogen in final consumption may grow to 32% by 2035, and 50% by 2050, renewables are projected to account for 80—90% of power generation globally by 2050, oil demand could peak in the next two to five years, gas demand is projected to grow by 10% in the next decade in all scenarios, energy may attract increasing investment, with most growth being in RES and decarbonization technologies. However, emissions across all scenarios remain far from the requirements for the 1.5º Pathway.

In general, Moriarty and Honnery (2022) mentioned that there is a rising use of energy scenarios (or pathways) as, in earlier decades, forecasts were often single-value complemented with a sensitivity analysis of which the annual EIA forecasts of the US still use this approach, and nowadays, the form that these energy scenarios often take of analyzing the effects of different climate change mitigation policies on energy use and type. For all the scenarios that they reviewed they main questioned, what conclusions can we draw from these forecasts? and are these desirable forecasts for whom? They mentioned that futurists often categorize futures into possible, preferred (or normative), and probable futures, and that every scenario falls into one or a combination of these categories. They reached to the conclusion that it is necessary to reduce the magnitude of energy consumption and the related magnitude of the anthropogenic pressure on the biosphere instead of the increasingly popular 'green growth' solution—rapid substitution of FFs by RE sources and, that future climate cannot be accurately predicted by only using biophysical science methods, social and political concepts are now also needed and ways of integrating these different approaches need to be found, among other conclusions.

Finally, to be able to achieve what is forecast in those energy scenarios, significant effort needs to be done by the actors involved, that is every person in the world at a higher or lower level. The reason why is that some prerequisites to reach the desired outcomes are really hard to achieve, as current lifestyles and business-as-usual will need to be strongly changed. For instance, there must be support for the emerging technologies most likely to become competitive in the short-term. Of course, this will require strong cooperation among the research and the finance institutions, favoring the knowledge and profit sharing over the property-ownership that the technologists and researchers are used to. Another premise set in some scenarios is that investments in O&G must be limited to facilitate a swift decline and a managed transition which, under the current situation with the invasion of Ukraine and the associated fossil fuels shortage, will be extremely difficult to reach. Furthermore, this reduction in O&G positions will seriously affect the revenues, taxes paid, workforce, among others important elements of the O&G and its associated industries with a collateral impact in the economies and social programs resulting from these. An important assumption is the desirability of the electrification of end-use applications in transport and heating mainly, other sectors will also be reshaped. Most notable will be transport as electric vehicles come to account for the majority of the vehicles fleet in 2050. To get this, car manufacturers, electricity appliance producers and distributers must work together with governments to set suitable policies that make it more affordable for the end user pockets. There is also a need of phasing out coal and fossil fuel subsidies that will probable bring serious economic troubles to low-income population. Finally, most of these energy transition scenarios and roadmaps were built under a worldwide or region level but, by considering that every country in the world has different responses to the same change, if a company or institution wants to apply these pathways in a specific country, it may needed to be adapted it to a lower and more specific level and it is likely to bring different outcomes.

2.5 Canadian energy transition studies

In the context of Canada, targets have been set to reduce the country's GHG emissions by 40-45% below 2005 levels by 2030 and to achieve net-zero GHG emissions by 2050, per the Paris agreement. To analyze the feasibility of reaching these targets, a number of energy forecasts and scenario analyses have been developed by institutions within the energy sector. Additionally, several initiatives through laws and funds have been launched by the Canadian government. A brief review of the most relevant of these follows:

As for the worldwide view, the IEA review of energy policy in Canada has revealed a strong pro-attitude in the country towards the energy transition (2022). The country has made a series of international and domestic commitments, putting itself on a path towards an ambitious transformation of its energy system, while remaining a stable and reliable supplier of energy to the world. It just set a target to cut greenhouse gas emissions by 40-45% from 2005 levels by 2030 and legislated a commitment to reach net zero emissions by 2050 at COP26 (2021). The country has promoted people-centered approach to its clean energy transition, with initiatives that include gender equity in clean energy sectors, increasing accesses to clean energy in northern, remote and indigenous communities; and actions to enable just transitions for fossil fuel workers. The electricity supply is one of the cleanest in the world due to significant hydro and nuclear power available. A balanced progress towards national goals for decarbonizing the power sector can be ensured because of large interconnections among provinces and territories. However, steeper emissions reductions are still needed in other sectors, such as O&G production, transport and industry. To this end, Canada has focused its efforts on a number of technologies, including carbon capture, utilization and storage; hydrogen; and small modular nuclear reactors, with a view to serving as a supplier of energy and climate solutions to the world.

Renewables participation in Canada is relevant. Hydropower dominates renewable energy in Canada being the main source for electricity generation and accounted for 14% of Total Final Energy Consumption (TFEC) in 2019. Bioenergy (6% of TFEC in 2018) mainly consists of solid biomass used in industry and in the residential sector, with some contributions by biofuels in transport and small shares of biogas injected in the grid. Wind and solar have experienced rapid growth in the past decade, but still accounted for only 1.2% and 0.2% of TFEC, respectively, in 2019.

At the country level, the Canadian Government launched Generation Energy in 2017 (GEC, 2018), with an open dialogue with stakeholders, experts and individual Canadians. The goal was to envision what a low-carbon energy future would look like for Canada over the course of a generation. It gathered the ideas of more than 380,000 Canadians about Canada's energy future. Then the Minister of Natural Resources formed the Generation Energy Council to prepare a report on the results. The highlights were that, in the face of long-term uncertainties and rapidly changing energy markets worldwide, Canada needs to start out on this journey along two tracks. First, to rapidly transform the energy production, distribution and consumption systems at home so that they are as clean and efficient as possible. Second, the acceleration of the development of low-carbon technologies for use in the existing O&G sector to reduce carbon pollution, cut costs, and create new value-added products and services must continue. The report emphasized that transitioning along these two tracks will not be easy; Canada has long used its abundant natural resources to drive much of its economic prosperity. It noted that the energy transition requires a shift to a more diversified, knowledge-based economy like the ones contributing to growth in other parts of the world with the inclusive consideration of the indigenous in this journey. Specifically, four pathways for the energy transition were identified. First, wasting less energy by increasing energy efficiency could cut about one-third of the Paris emissions commitment for Canada. Second, switching to clean power by changing more of the heating systems, transportation and industrial processes to electricity (clean electrification). The third pathway is using more renewable fuels by expanding the production and using capacity of Canada of cleaner fuels such as biofuels and biogas from plants and waste. The last pathway is producing cleaner O&G through increasing efficiencies, using clean power and cleaner fuels, and introducing new technologies to capture and store carbon emissions. This report set the first collective steps towards the low-carbon energy future in Canada.

In 2021, Canada's GHG emissions projections were estimated under two main scenarios by the Environment and Climate Change Canada (ECCC, 2021). The first scenario was the base case; estimated projections were based on federal, provincial and territorial policies and measures in place as of November 2021 and the scenario assumed no further government action. The second scenario, called the "Additional Measures Case", included federal, provincial and territorial policies and measures that had been announced, including under the Pan-Canadian Framework on Clean Growth and Climate Change, but were not yet fully implemented. These scenarios were built incorporating the statistics on GHG emissions and energy use at that period. By sourcing key assumptions from the available public and private expertise sources, scenarios of emissions projections were developed using E3MC -a detailed, proven energy, emissions and economy model. E3MC has a component named "Energy 2020" which incorporates Canada's energy supply and demand structure, and another component that is a macroeconomic model of the Canadian economy. ECCC updates regularly its models with historical data available from Statistics Canada's Report on Energy Supply and Demand in Canada and Environment and Climate Change Canada's National Inventory Report on Greenhouse Gas Sources and Sinks in Canada.

Regarding to the O&G industry in Canada, the Canadian Energy Research Institute in 2019 developed the Canadian crude oil and natural gas production, supply costs, economic impacts and emissions outlook for the period 2019-2039. The study examined the conventional crude oil and natural gas industries of Canada, including production forecasts and supply costs. It covers onshore and offshore conventional oil, including shale and tight oil activity, conventional natural gas, coalbed methane, tight and shale gas, and the associated natural gas liquids (pentanes plus and condensate only). It does not include oil sands. It is based on factors such as the dynamics of the US crude imports, relatively stable demand from domestic refineries, the pentanes plus and condensate's growth underpinned by the demand from oil sands, the additional pipeline exports to Central Canada to displace foreign oil, and additional exports via the Trans Mountain Pipeline. They forecasted three scenarios: the current policies, the new policies, and sustainable development. Their findings are that the fossil fuel share is forecasted to be for 2025 and 2040, respectively, 79 and 78% in the current policies scenario, 78 and 74% in the new policies, and 77 and 60% in the sustainable development scenario. The WTI is forecasted to be slightly increasing from about 70 USD/bbl in 2018 to about 97 USD/bbl in 2039.

Towards fighting climate change, the Pan-Canadian Framework that represents Canada's commitment was developed in 2016 (CER, 2020). The main goal of the Framework is to place a price on carbon pollution as carbon pricing has proven to be an efficient way to reduce emissions, drive innovation, and encourage people and businesses to pollute less. Additionally, complementary actions are included in the Framework, looking for the reduction of emissions by addressing market barriers where pricing alone is insufficient or not timely enough to reduce emissions in the pre-2030 timeframe. An example of these actions is strengthening the energy efficiency standards and codes for vehicles and buildings. The government of Canada established a national minimum price on carbon pollution starting at $20 per tonne in 2019, yearly increasing in $10 per tonne to $50 in 2022. Then, Canada proposed in a Healthy Environment and a Healthy Economy to increase the price on carbon pollution annually at a rate of $15 per tonne from 2023-2030. Following engagement with provinces, territories and Indigenous leaders, it was accepted. To ensure a comparative framework along all systems in Canada in terms of stringency and effectiveness, a review of carbon pricing systems in Canada was undertaken in 2020-21, led by the Canadian Institute for Climate Choices. Their findings demonstrated that carbon pricing can be a key driver of emissions reductions, however changes in how systems presently operate are necessary to ensure that all carbon pricing systems in Canada are similarly effective in cutting pollution and supporting domestic competitiveness.

Regarding O&G emissions, 22% of total GHG emissions of Canada was accounted by the upstream operations that include O&G exploration, production, and processing in 2021 (UNFCCC, 2021). This industry, in part reinforced by government policies, has made great efforts toward reducing the emissions intensity of its operations. According to Canadian estimates, the emissions intensity of oil sands has fallen by 32% since 1990 and that of upstream natural gas by 13% since 2010. Since oil sands output is expected to drive future growth in Canada's oil production, making emissions reductions from the sector will be critical to achieving climate goals. For this reason, the main

Canadian oil sands companies announced the Oil Sands Pathways to Net Zero initiative in June 2021, with a collective goal to work together with the federal and Alberta governments to achieve net zero emissions from oil sands operations by 2050. Therefore, the sector has become a leading investor in clean technology and innovation, promoting over 64% of all energy Research and Development (R&D) investments in Canada in 2017. Additionally, in 2018, the O&G extraction industry spent 3.6 billion Canadian dollars (CAD) on environmental protection expenditures. This represents, by far, the largest environmental protection expenditure of any sector, representing 37% of total environmental protection expenditures made by businesses in Canada. Federal investments and programming to enhance sustainability include the Clean Growth Program designed to advance emerging clean technologies toward commercial scale so that natural resource operations including upstream O&G can better reduce their environmental impacts on air, land, and water. The program is supporting O&G industry-led RD&D projects to reduce GHG emissions from energy production and use.

Another important organization is the Canadian Climate Institute (CCI), a non-partisan, independently governed climate change policy research organization in Canada. In February 2021, CCI issued the Canada's Net Zero Future report (CCI, 2021), a document detailing analyses of over 60 possible scenarios in which Canada reaches net zero by 2050 and of which three types of possible net zero energy systems in Canada were reached. Scenarios were a fossil fuels plus capturing emissions (negative emissions) energy system, a biofuels energy system, and an electrification plus hydrogen energy system. Their analysis found large drivers for the net zero achievement of Canada both inside and outside the control of the country. The results, in agreement with previous studies and reports, showed that Canada can reach net zero but that it will require strong policies. CCI stated that the current energy mix of Canada is the largest driver of Canada's emissions with about 616 million tonnes (Mt) of CO_2 eq, or 83 per cent of total national emissions. They mentioned that significant improvements in energy efficiency and conservation will be required to the current energy production and consumption in Canada.

The CCI's analysis focused on "final end-use energy" which is the energy consumed at the last point to deliver services such as mobility, heat, or light and included both primary and secondary forms of energy. Primary energy refers to an original source of energy and secondary energy or energy carriers are forms of energy that are made from primary energy. Significant is that secondary forms of energy are only zero-emissions if they are produced in a way that does not emit GHG. Therefore, any remaining Canadian emissions from either primary or secondary energy end-use would have to be offset. CCI analysis found that some solutions showed up consistently across all possible scenarios, which they called “safe bets,” and that these solutions include existing technologies that face no major barriers to scaling, such as electric vehicles, energy efficiency and non-emitting electricity. CCI deems scaling up safe bets as critical to meet the climate goals of Canada, particularly the 2030 target. Other solutions came with more uncertainty regarding the role they might play. These CCI called “wild cards,” which are big-risk technologies with potentially big rewards like direct air carbon capture or hydrogen fuel cells. These “wild cards” could be critical to unlocking the deeper, cost-effective reductions needed to reach the 2050 goal of Canada. However, uncertainty remains on which ones will prove viable, cost-effective, and scalable enough to play a big role.

Another report, the Canada Energy Futures 2021 (EF2021), which explores how possible energy futures might unfold for Canadians over the long term was released in 2021 by the Canada Energy Regulator (CER). To develop it, the CER consulted with industry, various government and non-governmental organizations, and academia. Two main scenarios were considered, where energy supply and demand projections differ based on the level of future action to reduce GHG emissions. EF2021 also includes six additional scenarios that explore what Canada’s electricity system might look like in a net-zero world. The two main scenarios include yearly projections from 2021 to 2050 for all energy commodities, whereas the six electricity scenarios focus only on how Canada will meet given electricity demands under different conditions and include only the forecasted variables in 2030 and 2050. The first one in EF2021 is the Evolving Policies Scenario which assumes that action to reduce GHG emissions from the energy system of Canada continues to increase at a pace similar to recent history, in both Canada and the world; less global demand for fossil fuels; and greater use of low-carbon technologies. The second is the Current Policies Scenario wherein limited action to reduce GHG beyond policies in place today is assumed. These two scenarios provide insights into what the energy system might look like if action to reduce GHG emissions continues to grow at the pace it has in recent years, or if it were to stop at current levels. To reduce GHG emissions of Canada by 40 to 45% below 2005 levels by 2030 and achieving net-zero GHG emissions by 2050 (Canada’s commitment) will likely require more change than we model in the Evolving or Current Policies scenarios. The six scenarios left explore a net-zero future in which electricity is expected to be an important contributor to achieving net-zero emissions.

The analysis of the EF2021 scenarios yields to the following highlights: in the Evolving Policies Scenario, unabated fossil fuel combustion (fossil fuel combustion without CCS) falls 19% from current levels by 2030, 45% by 2040, and 62% by 2050. This scenario projection shows significant changes in Canada's energy system and implies large reductions in GHG emissions; but, due to the remaining unabated fossil fuel demands in 2050, there is an urgent necessity for greater long-term change to reach Canada's target of net-zero emissions by 2050. These changes are, additional to policy, factors such as global energy markets, technology, consumer behavior and preferences. This Evolving Policies Scenario shows total energy use declining, however, electricity demand grows 44% from 2021 to 2050, much of it from new areas such as electric vehicles and hydrogen production, as the electricity system of Canada also gets greener, going from 82% low and non-emitting in 2021 to 95% in 2050. Wind, solar, and battery storage dominate electric capacity additions in all six net-zero electricity scenarios, making up between 82-85% of added capacity. The net-zero electricity scenarios suggest that Canadian power systems will continue to be very distinct across the country, even in a low-carbon future with the ten provinces meeting their electricity demands in diverse ways, with widely varying mixes of types of sources. Also in this scenario, Canadian oil production growth slows over the next decade, peaking at 5.8 million barrels per day (MMb/d) in 2032, up from 5.0 MMb/d in 2021 and after 2032, production declines steadily, reaching 4.8 MMb/d in 2050. Lower global oil prices than the Current Policies Scenario are assumed in the Evolving Policies Scenario. The Brent crude oil price stays at 70 USD/barrel through much of the projection period and Canadian production increases more rapidly, plateauing in 2040 at 6.7 MMbarrels/d. As for natural gas production, in this Evolving Policies Scenario production remains near current levels of approximately 15.5 billion cubic feet per day (Bcf/d) through much of the next two decades, and after 2040, with LNG exports assumed to stay flat, total production begins to decline, falling to 13.1 Bcf/d by 2050.

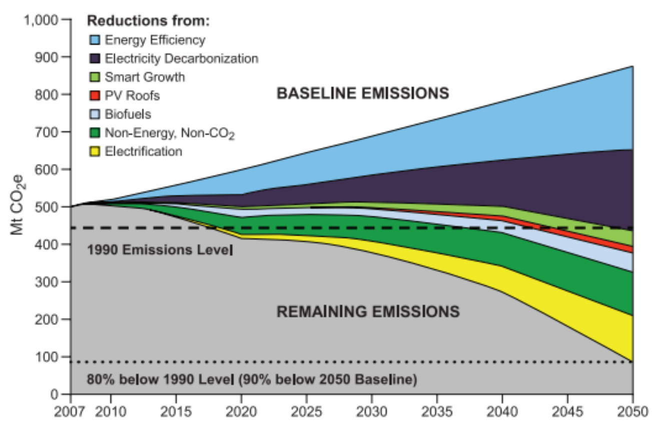
The variables forecasted are primary demand of Canada, energy percentage of share, total Canadian energy use, electricity demand by sector, electricity generation by source (hydro, nuclear, fossil fuel with CCS, wind, solar, hydrogen, and biomass with CCS), cumulative capacity additions, electricity generation share by technology and by province, production of crude oil, oil sands, natural gas, LPG, oil prices, gas prices, fossil fuel demand by type, natural gas demand by sector, among the mostly mentioned in the report. The data and assumptions to generate these scenarios are available in the online resources (CER EF2021-data, 2021).

In summary, GHG emissions are estimated and reported, and energy scenarios and analysis to identify plausible energy transition routes in Canada as a country and by provinces are available. However, most of the research done found a wide spectrum of possible pathways to reach the net zero target and did not provide a unique recommendation as to exactly how to identify where we are and what the options are based on. This fact complicates the communication to stakeholders and a simple and accessible framework for understanding specific actions that can be taken to reduce emissions would be recommended. In this manner, a practical and easy to visualize GHG emissions approach would be desirable to adopt in the O&G industries and related institutions.

2.6 The wedges concept

A simple concept called “stabilization wedges” was developed by Pacala and Socolow (2004). The idea was to identify and implement multiple wedges simultaneously to reach the necessary emissions reductions to mitigate climate change. In this work, they kept the focus on technologies that had the potential to produce a material difference by 2054, and divided a stabilization triangle into seven equal "wedges." They defined that a “wedge” represented an activity that reduced emissions to the atmosphere in an amount that started at zero and increased linearly until it accounted for 1 GtC/year of reduced carbon emissions. Collectively, the wedges thus represented a cumulative total of 25 GtC of reduced emissions over 50 years. The authors stated that “stabilization” at any level required that net emissions do not simply remain constant, but eventually drop to zero. They argued that along the following nearly 50 years, to solve the carbon and climate problem means to deploy the technologies and/or lifestyle changes necessary to fill all seven wedges of the stabilization triangle. The wedges could be achieved from energy efficiency, from the decarbonization of the supply of electricity and fuels (by means of fuel shifting, carbon capture and storage, nuclear energy, and renewable energy), and from biological storage in forests and agricultural soils. They claimed that humanity could solve the carbon and climate problem in the first half of this century simply by scaling up available technology.

This stabilization wedges approach helped to spread the energy transition effort across multiple sectors and technologies, reducing the risk of relying too heavily on any one approach. Williams et al. (2012), used detailed modeling of infrastructure stocks, resource constraints, and electricity system operability to analyze the infrastructure and technology path required to meet California's goal of an 80% Greenhouse Gas Emissions reduction below 1990 levels. The authors built scenarios to explore mitigation options by using a stock-rollover methodology that simulated physical infrastructure at an aggregate level. They found that widespread electrification of transportation and other sectors is required in addition to the technically feasible levels of energy efficiency and decarbonized energy supply existing. The resulting wedges are visualized in Figure 2.1 below as the three biggest drops reached in 2050 where the top three contributions are from energy efficiency (EE) (28%), electricity decarbonization (27%), and electrification of direct fuel uses (16%).



Wedge Category:	Emissions Reduction Mt CO_2e (% of Total) 2030	2050	Types (and Numbers) of Measures Used	Key Attributes in 2050
Energy Efficiency	102 (33%)	223 (28%)	Building EE (18); Vehicle EE (9); Other EE (6)	Energy efficiency improved 1.3% per year on average for 40 years
Electricity Decarbonization	72 (23%)	217 (27%)	High renewables, high nuclear, high CCS, and mixture of the three	90% of generation requirement met with CO_2- free sources. Equivalent decarbonization in each scenario
Smart Growth	13 (4%)	41 (5%)	Reductions in vehicle miles traveled (VMT) (6)	VMT reduced in light duty vehicles (LDV) by 10%; freight trucks 20%; other transportation 20%
Rooftop PV	8 (3%)	21 (3%)	Residential and commercial PV roofs (2)	10% of electricity demand displaced by rooftop PV
Biofuels	18 (6%)	49 (6%)	Transportation biofuels; ethanol, biodiesel, biojet fuel (9); Residential, commercial, industrial biomethane (3)	2% of natural gas use in buildings displaced by biomethane, and 10-20% of petroleum-based fuels for vehicles displaced by biofuels
Non-Energy, Non-CO_2	67 (22%)	116 (15%)	Cement, agriculture, and other (3)	Non-fuel; non-CO_2 GHG emissions reduced 80% below baseline
Electrification	29 (9%)	124 (16%)	Transportation electrification (9); Other end-use electrification (5)	75% of LDV gasoline use displaced by PHEVs & electric vehicles; 30% of fuel use in other transport sectors electrified; 65% electrification of non-heating/ cooling fuel use in buildings; 50% electrification of industrial fuel uses
Baseline Case Emissions	688	875		
Mitigation Case Emissions	380	85		
Total Reduction	308	790		

Figure 2.1 Emission reduction wedges for California in 2050. Source: Williams et al. (2012).

In consequence, three major energy system transformations were identified as necessary to meet the target in California: energy efficiency had to improve by at least 1.3% per year over 40 years;

electricity supply had to be nearly decarbonized, with 2050 emissions intensity less than 0.025 kg CO2e/kWh; and most existing direct fuel uses had to be electrified, with electricity as a 55% of the end-use energy in 2050 versus 15% in 2012.

Davis et al. (2013) extended the wedge concept by redefining the meaning of ‘solve the carbon and climate problem for the next 50 years’ to stress both the scale and urgency of innovating and deploying carbon-emissions-free energy technologies. They explained that cumulative emissions integrate all the emissions released in the past plus those emitted during three distinct phases of mitigation: (1) slowing growth of emissions, (2) stopping growth of emissions, and (3) reducing emissions. The problem, plainly, is that growth of emissions has not stopped (phase 2) or even slowed (phase 1); in fact, emissions have accelerated. Davis et al. projected changes in atmospheric CO_2 and global mean temperature in response to emissions scenarios formed with 16 wedges that were immediately subtracted from the A2 ‘business-as-usual’ marker scenario of the Special Report on Emissions Scenarios of the IPCC. To do this, they performed ensemble simulations using the UK Met Office coupled climate/carbon cycle model, ´HadCM3L´. They concluded that solving the climate problem ultimately requires near-zero emissions and that eliminating emissions over 50 years would require 19 wedges: 9 to stabilize emissions and an additional 10 to completely phase-out emissions. The amounts of carbon-free energy needed to achieve the energy transformation cannot be provided by currently available technologies and systems. An integrated and aggressive set of policies and programs is urgently needed to support energy technology innovation across all stages of research such as development, demonstration, and commercialization. Finally, they mentioned that no matter the number required, wedges can still simplify and quantify the challenge.

Köppl et al. (2014) enhanced the concept of stabilization wedges with respect to energy services integrated in a detailed representation of the energy system. They called the term “mitigation wedges” for the emission reduction options developed in an interdisciplinary bottom-up approach for Austria towards opening the “technology black box.” This concept is different from Pacala and Socolow’s in that the wedges do not aim at a stabilization of GHG emissions but at emission reductions in Austria. The approach embeds the technologies in an integrated structural energy model of the Austrian energy system that starts with energy services and concludes with primary energy flows. To identify the impact at all stages of the mitigation wedges, the energy chain was depicted in a systematic way and energy services were modelled in a bottom-up approach and underpinned by storylines for each mitigation wedge. A catalogue of 25 mitigation wedges was developed for the three demand-side areas (mobility, buildings and manufacturing), and for the supply of electricity and heat. The categories can be grouped into “efficiency wedges” and “fuel shift wedges.” They also quantified the effects of additional investment in the transformation of the energy system as an economic stimulus with corresponding output and employment effects. For example, they included not only the technology but the service provider, Human Resources, and so on. Finally, they claimed that their analysis indicated that a transformation of the energy system could support two objectives: a stimulus in economic growth and employment as well as a step towards reaching mid- and long-term emission reduction targets. They applied the energy service-based approach to a transformation of the energy system in Austria to meet the EU 2020 emission targets. A pragmatic approach was used to compile two feasible portfolios from the catalogue of 25 mitigation wedges that achieve emission savings of 14 Mt CO2 in 2020. One portfolio primarily focuses on energy efficiency options, the other on changes in the fuel mix towards less carbon-intensive fuels. On average, additional investment of about 6 billion € p.a. over a twelve-year period, was estimated to be required.

In 2018, Sandrine et al. (2018) proposed a methodology of an advanced index decomposition analysis based on sectoral energy service indicators and on a specific decomposition in the power sector for quantifying the contribution of different mitigation strategies. Their results revealed the key role of energy efficiency and decarbonization of energy carriers in the industry sector, deployment of renewables in the power sector and, to a lesser extent, coal/gas substitution, and efficiency and energy decarbonization in the transport sector. They called for a deeper understanding of the role a reduction in energy-service demand can play in mitigation scenarios and of the respective contribution for industry of energy efficiency and structural change.

Overall, the research on mitigation wedges has helped to identify a range of potential solutions for reducing greenhouse gas emissions and mitigating climate change. Policy design, industry strategy, and numerous businesses and organizations have used the wedges concept to identify opportunities for reducing their carbon footprint and developing low-carbon products and services. A key mitigation wedge identified both globally and within many countries is transitioning from fossil fuels to renewable energy. The International Energy Agency (IEA), in its annual report on global energy trends, has identified renewable energy as the largest source of new power capacity additions worldwide. The IEA has also recommended that countries prioritize the deployment of renewable energy technologies as a key strategy for reducing greenhouse gas emissions. In Canada, the Canadian Government's climate plan includes a range of measures to support the transition to cleaner energy sources, such as incentives for electric vehicles, funding for renewable energy projects, and support for energy efficiency measures. The government has also committed to achieving net-zero emissions by 2050, which will require a significant shift away from fossil fuels towards renewable energy sources. Thus, a set of mitigation wedges based on fossil fuels to be transitioned to renewable based energy would be supportive in this matter.

Important to note here is that mitigation wedges can be defined as different elements that can be combined to reduce GHG emissions by 1 billion metric tons per year by 2050. These wedges include technologies, actions or strategies like increasing energy efficiency, using renewable energy sources, and implementing carbon capture and storage technologies. These strategies in analogy, can be described as a set of scenarios that can be explored for different possible GHG emissions trajectories that could lead to different levels of climate change impacts. Therefore, mitigation wedges can be used as one approach to reducing emissions and be later taken as the basis of different scenarios, susceptible to carry out further scenario analysis.

Ultimately, the choice between using energy scenarios or mitigation wedges depends on the specific goals and context.

To conclude, in this study mitigation wedges were selected as a complementary approach as a practical and easy-to-visualize approach to support the O&G industry in the achieving of its GHG target requested for the coming years. Though these mitigation wedges cannot fully reduce uncertainty, they can improve credibility around conditions and outcomes that are mutually coherent and statistically well based, which in turn may help foster trust in the energy transition process for Canada and for the world.

3. Theoretical framework and hypotheses

3.1 Theoretical Framework

To answer to the two research questions, namely, findings from the chapter 2 literature review were taken into account, and the Conceptual Framework for the research was constructed. It is visually depicted, as shown in Figure 3.1 below. The Literature review helped to identify which variables have been studied and what relationships have been found to exist among them. Once these facts were known, plausible mitigation wedges to achieve the GHG emissions target could be obtained.

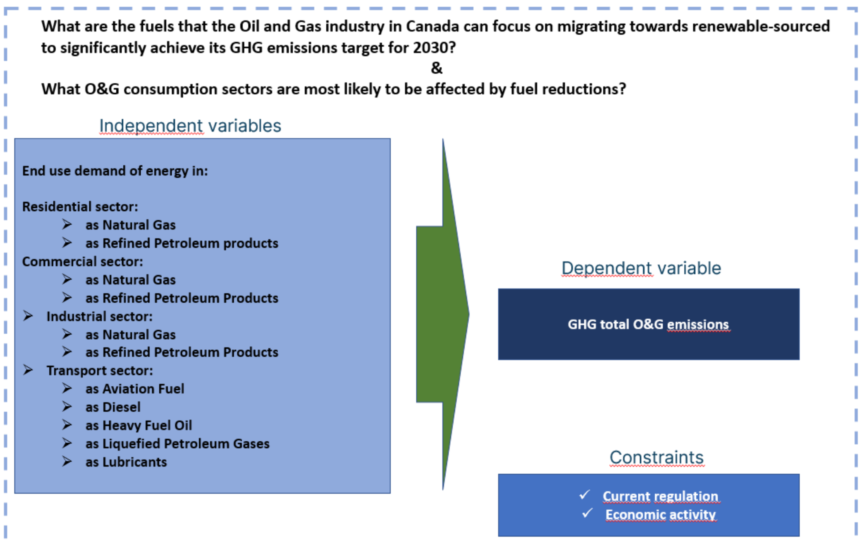


Figure 3.1 Conceptual Framework. Source: Author.

3.2 Hypothesis

The following hypothesis was generated to support the Conceptual Framework. It is presented here, and the methodology employed is detailed in Chapter 4.

With the information available, the studied variables in the O&G industry that have a positive effect on its GHG emissions target are the amount of end use energy coming from every type of fossil fuel. This energy is used in the economic sectors in Canada: residential, industrial, commercial and transport. This hypothesis proposes the relationship among these variables and supports in answering the research questions described in section 1.3 as follows.

Hypothesis: The Refined Petroleum Products and Natural Gas in the industrial, transport, and residential sectors present the largest opportunities for O&G industry GHG emissions reductions in Canada.

By testing this hypothesis, the main factors that have a significant effect on the GHG emissions in the O&G industry will be identified. Then, a reduced form of models that consider only these main factors can be obtained. The significance that each fossil fuel consumption has on the GHG emissions for the O&G industry can be estimated. Finally, the economic sectors that are most important in meeting this target can also be identified.

Important to notice is that the energy provided by renewable sources (hydropower, nuclear, wind and solar mainly) will be in the form of electricity with its associated energy production efficiencies and conditions. This means that particular attention needs to be paid to the industrial processes that require energy at extreme conditions of pressure or temperature, such as steel, iron, smelting, oil and gas refining, or cement production, which can only be met by fossil, geothermal or nuclear sources. Therefore, further research on this consideration will be worthwhile.

4. Methodology

The methodology used for this research is explained in this chapter. The research approach, dataset, the selection of variables, statistical methods, tests associated with the hypothesis, and the construction of the mitigation wedges steps are presented in the following sections.

4.1 Research approach

As mentioned, an exploratory, quantitative analysis was conducted. Empirical models were developed and tested to understand the effects of the regressors (i.e. end use energy) on the dependent variable (i.e. the GHG total O&G emissions). A reduced form of the model was fixed for the most important variables that significantly affect these GHG emissions. A set of plausible mitigation wedges to occur was obtained and a description was given for each wedge.

To maintain consistency across the thesis document, the dependent variable is also called “response” and the independent variables are also called “regressors” or factors that have an effect on the dependent variable or response.

4.2 Dataset

The dataset used for quantitative analyses in this study was built from two main sources: the Energy Future 2021 (EF 2021) scenarios published by the Canada Energy Regulator (CER, 2021) and the Canada’s annual greenhouse gas (GHG) inventory (Annex of the National greenhouse gas emissions, 2022). This dataset has a panel structure, which involves repeated observations of different individual values over a period of time across the provinces and territories of Canada. This panel data supports the analysis on how different regions generate GHG emissions while consuming different fossil fuels during the time period. The dataset relies solely on publicly available information.

4.2.1 Selection of data

Aligned with the hypothesis to be tested, the dependent variable under study is total GHG emissions generated by the O&G industry in Canada, with target for 2030 set by the Bill-C12 -a target which may be subject to revisions at future climate talks including COP27. The regressors selected, the fossil fuels, were based on their linkage to the emission factors that were used to estimate the GHG emissions. Emission factors are the coefficients used to estimate the emissions of pollutants to the air generated per unit of fuel and have associated sector-specific methodologies. The Energy Future 2021 scenarios were a total of 44 variables, and these are provided below in Table 4.1. The regressors selected from these variables were the energy end use by type of fuel (Natural Gas, Refined Petroleum Products, Aviation Fuel, Diesel, Heavy Fuel Oil, Liquefied Petroleum Gases, Lubricants, and Motor Gasoline) at the economic sectors: residential, commercial, industry and transport.

Table 4.1. Variables included in the analysis.

No	Variable	Name of variable log-diff transformed	Description	Units
1	GHG_OG_Total	GHG_OG_Totaldiff	Total Green House Gases Emissions by the Oil and Gas industries	kT CO_2 eq
2	GHG_OG_PRI	GHG_OG_PRIdiff	Green House Gases Emissions from Petroleum Refining Industry	kT CO_2 eq
3	GHG_OG_OGE	GHG_OG_OGEdiff	Green House Gases Emissions from Oil and Gas Extraction	kT CO_2 eq
4	PED_NG	pedndiff	Primary Energy Demand of Natural Gas	Petajoules
5	PED_RPP	pedrdiff	Primary Energy Demand of Refined Petroleum Products	Petajoules
6	End_Use_Res_NG	enduerngdiff	End use demand of energy in Residential sector as Natural Gas	Petajoules
7	End_Use_Res_RPP	enduerrppdiff	End use demand of energy in Residential sector as Refined Petroleum products	Petajoules
8	End_Use_Com_NG	enduecngdiff	End use demand of energy in Commercial sector as Natural Gas	Petajoules
9	End_Use_Com_RPP	enduecrppdiff	End use demand of energy in Commercial sector as Refined Petroleum Products	Petajoules
10	End_Use_Ind_NG	endueingdiff	End use demand of energy in Industrial sector as Natural Gas	Petajoules
11	End_Use_Ind_RPP	endueirppdiff	End use demand of energy in Industrial sector as Refined Petroleum Products	Petajoules
12	End_Use_Tran_AviFuel	enduetafdiff	End use demand of energy in Transport sector as Aviation Fuel	Petajoules
13	End_Use_Tran_Diesel	enduetddiff	End use demand of energy in Transport sector as Diesel	Petajoules
14	End_Use_Tran_HeavyFuelO	enduethfodiff	End use demand of energy in Transport sector as Heavy Fuel Oil	Petajoules

15	End_Use_Tran_LPG	Enduetlpgdiff	End use demand of energy in Transport sector as Liquefied Petroleum Gases	Petajoules
16	End_Use_Tran_Lubricants	enduetldiff	End use demand of energy in Transport sector as Lubricants	Petajoules
17	End_Use_Tran_Gasoline	enduetgdiff	End use demand of energy in Transport sector as Motor Gasoline	Petajoules
18	End_Use_Tran_NG	enduetngdiff	End use demand of energy in Transport sector as Natural Gas	Petajoules
19	EndUseP_Trans_Gasoline	ptgdiff	End use price of energy in Transport sector as Motor Gasoline	Canadian dollars per gigajoule[2]
20	EndUseP_Trans_Diesel	ptddiff	End use price of energy in Transport sector as Diesel	Canadian dollars per gigajoule
21	EndUseP_Resi_Electricity	prediff	End use price of energy in Residential sector as electricity	Canadian dollars per gigajoule
22	EndUseP_Resi_Natural Gas	prndiff	End use price of energy in Residential sector as Natural Gas	Canadian dollars per gigajoule
23	EndUseP_Resi_Oil	prodiff	End use price of energy in Residential sector as Crude Oil	Canadian dollars per gigajoule
24	EndUseP_Ind_NG	pindiff	End use price of energy in Industrial sector as Natural Gas	Canadian dollars per gigajoule
25	EndUseP_Ind_Oil	piodiff	End use price of energy in Industrial sector as Crude Oil	Canadian dollars per gigajoule
26	EndUseP_Com_Electricity	pcediff	End use price of energy in Commercial sector as electricity	Canadian dollars per gigajoule
27	EndUseP_Com_Natural Gas	pcndiff	End use price of energy in Commercial sector as Natural Gas	Canadian dollars per gigajoule
28	EndUseP_Com__Oil	pcodiff	End use price of energy in Commercial sector as Crude Oil	Canadian dollars per gigajoule
29	ElecGen_Bio_Geo	Egbdiff	Electricity Generated by Biomass and Geotherm	Petajoules
30	ElecGen_Solar	egsdiff	Electricity Generated by the Sun	Petajoules
31	ElecGen_Wind	egudiff	Electricity Generated by wind	Petajoules
32	ElecGen_NG	egndiff	Electricity generated by Natural Gas as primary fuel	Gigawatt hours
33	ElecGen_Oil	egodiff	Electricity generated by Crude Oil as primary fuel	Gigawatt hours
34	COP.Total	copdiff	Crude Oil production	Thousand Barrels per day
35	NGP.Total	ngpdiff	Natural Gas production	Billion Cubic Feet per day
36	Can.US_ExchRate	cuediff	Canada-US Exchange Rate	CAD$ / US$
37	Brent	brentdiff	Crude Oil reference price	US$ per Barrel
38	CanLightSweet	clsdiff	Canadian light sweet crude oil reference price	Canadian dollars per Barrel
39	HenryHub	hhdiff	Gas reference price	US$ per Million of cubic feet
40	NovaInventoryTransfer	nitdiff	Nova Inventory Transfer (NIT)[3]	US$/MMBtu
41	WTI	wtidiff	Crude Oil reference price	US$ per barrel

[2] In 2010 Canadian dollars terms (i.e. adjusting for inflation).

[3] NIT is the pricing point used for natural gas sourced from the Western Canadian Sedimentary Basin (WCSB). As the natural gas trading hub located in Alberta, NIT is the commercial mechanism that overlays the Nova Gas Transmission Ltd. (NGTL) pipeline network, and is connected to several export markets and storage.

42	WesternCanSelect	wcsdiff	Western Canadian Select crude oil[4]	Canadian dollars per barrel
43	EleCap_Pfuel_NG	ecndiff	Electricity generating capacity by Natural Gas	Megawatts
44	EleCap_Pfuel_Oil	ecodiff	Electricity generating capacity by Crude Oil	Megawatts

4.2.2 Sources of data

The potential regressors and responses used in this research from the EF 2021 contain data for the years from 2005 through 2020, and cover the 10 provinces and 3 territories of Canada; the responses GHG emissions for the O&G industry were reported by the Government of Canada in its Canada's National Inventory Report on Greenhouse Gas Sources and Sinks in Canada. Finally, the GHG emissions targets for the O&G industry set in 2030 were obtained from the Emissions Reduction Plan – Canada's Next Steps for Clean Air and a Strong Economy and recently agreed by Canada in the COP27.

4.3 Data processing

The available data were gathered, as mentioned, to take into consideration the elasticity, that is the measurement of how responsive a variable is to a change in another, the base-10 logarithm (log) was selected for the regression applied and so to transform the variables. Due to the variety of the economic activities carried out among the provinces of Canada, there is a wide range of values in the data. To increase reliability in the data frame when zero values are presented, as log of 0 is undefined, all the zeros in the data were substituted to a value of 1. By doing this, the mentioned error is avoided and the log of 1 is zero, keeping the null existence of the value in the analysis. The problem of missing data was dealt with using the same mentioned substitution approach during data processing. Fortunately, most of the data were available except for the GHG emissions in the Petroleum Refining Industry (RPI) of New Brunswick for the years from 2014 through 2020. Values were estimated from the GHG emissions inventory for New Brunswick source where both the Petroleum Refining Industries and the Mining emissions were missing. Due to the variable situation of the Mining activity reported in this province, the Mining emissions were taken as an average of

[4] API's heavy crude oil (Average 20°API) exporting to the Far East is collectively referred as Western Canadian Select (WCS): http://www.advantagepetroleum.com/OurBusiness/show.php?id=158 and https://crudemonitor.ca/crudes/assay.php?acr=WCS&crudename=Western%20Canadian%20Select .

the reported data in years 2005 to 2013 which were available in the analyzed period. The estimation for the RPI was done as the difference between the Stationary Combustion Sources and all the implicit factors except the RPI.

In addition, the nature of the panel data results in having a time series in which the variable "time" has, first, a strong effect on the dependent variable or response, and second, on unobserved variables that differ from one province to the next (e.g. prevailing carbon tax policies) but do not change over time. To eliminate these province (region) and time effects to allow for clear analysis of the causal relationships among variables, an adjustment was introduced: differences between the variable at the year "t" and the variable at one previous year "t-1" (1-year lag difference) as well as the variable at the province "i" and the variable at other province "i-1" were applied to all variables used.

4.3.1 Variables definition

To support the purpose of study a key stage was to determine the effects of end use energy consumption by sector and type of fossil fuel on the GHG emissions of this industry in Canada. Therefore, the GHG emissions variable is the main dependent variable. The national greenhouse gas (GHG) inventory of Canada reported the anthropogenic (human-caused) emissions by sources and removals by sinks. From this report the GHG emissions for the O&G industry were taken as:

> **GHG total emissions generated by the O&G industry** = GHG emissions from the oil and gas extraction (OGE) operations + GHG emissions from the Petroleum Refining Industry (PRI) + GHG emissions from the O&G Fugitive Sources + GHG emissions from the Chemical Industry (Ammonia Production + Nitric Acid Production + Adipic Acid Production + Petrochemical Production) -------(1)

Where:

GHG emissions from the O&G Fugitive Sources = Oil and Natural Gas[5] + Venting + Flaring ---------(2)

The GHG emissions from the O&G Fugitive Sources refer to the release of gases into the atmosphere that are not intended to be released during normal operations of industrial facilities, such as

[5] Updated method for estimating emissions from pneumatics, compressor seals and equipment leaks in the oil and gas sector (National Inventory Report 1990 –2020: Greenhouse Gas Sources and Sinks in Canada, 2022).

refineries, chemical plants, and other manufacturing facilities which are included in the OGE, PRI and Chemical Industry emissions. These fugitive emissions can come from leaks, spills, or other unintended releases of gases, such as methane, volatile organic compounds (VOCs), sulfur dioxide (SO_2), and nitrogen oxides (NOx). These emissions are released through pneumatics, compressor seals and equipment leaks, venting and flaring in the O&G industry and depend greatly on the volume of oil and natural gas processed; any reduction in the processed volume will bring a reduction in the O&G Fugitive Sources when these emissions are present. Additionally, the GHG emissions from the Chemical Industry have relatively small magnitude in comparison with the rest of GHG emissions. For these reasons, these two types of emissions were not analyzed separately from the GHG total emissions by the O&G industry.

The rest of variables defined and included in the analysis were selected under two main considerations: findings from previous relevant studies (World Energy Outlook (2021), Annual Energy Outlook of EIA (2021) and the methodology to estimate the GHG emissions reported in the inventory of Canada. The data frame has a multivariate context for the period from 2005 through 2020, and its variables were presented in Table 4.1.

4.3.2 Observations at a Province level

The O&G activity across the provinces of Canada has wide variation with respect to provincial economic activity. For the oil and gas extraction (OGE) operations, the provinces of Alberta, British Columbia, Saskatchewan and Newfoundland and Labrador have significative activity in this OGE category. The Petroleum Refining Industry (PRI) is present in the provinces of New Brunswick, Ontario, Alberta, Quebec, Saskatchewan, Newfoundland and Labrador, and British Columbia. As for the province of Nova Scotia, there was a reduction to zero emissions in this PRI category since 2014 because it does not have any refinery; Imperial Oil's Dartmouth refinery closed in 2013 and the facility now operates as an oil products terminal. To avoid outliers, the province of Prince Edward Island was not taken into consideration in the data frame as this province does not have O&G activities.

Regarding with the three territories of Canada, low population and GHG emissions by O&G industry are present there, thus, to avoid outliners these territories were not taken into account for the analysis.

4.4 Statistical tests

4.4.1 Descriptive statistic

For an overview of the variables included in the sample, the maximum, minimum, mean, median, and standard deviation were estimated. In addition, plot histograms of the variables are an aid to visualize whether or not a normal distribution exists.

For each variable, the maximum and minimum values give a reference of the range of the data. The mean is the average or the most common value in all the numbers that are part of the defined variable, this is also referred to as an expected value. The median is the middle value of the sorted list of numbers that conform the variable. The standard deviation can show the range of this variable, assuming the data has a normal distribution. It is important to state that the normal distribution of the sample is desirable for most of the variables considered, as this avoids oriented long-tail problems that can lead to errors in the estimations of the fitted models obtained.

To avoid multicollinearity, that is high interdependence among the regressors which cause problems in the estimation of the regression models, an important consideration taken is the fact of not having, at least theoretically, two or more variables that could have correlated each other. The correlation matrix is commonly used to quick view this problem.

4.4.2 Ordinary Least Squares (OLS) with multiple regressors

A series of OLS regression models were sequentially obtained and selected by applying the following steps. First, the effects of every one of the independent variables on the dependent ones were checked. These results were compared with what was expected based on literature. Next, the variables observed were transformed as detailed in section 4.3 data processing. As said, it is a panel data that includes variables across provinces and time, thus these effects were controlled by applying base-10 logarithm and simple difference formulas to each variable set. Additionally, these variables differentiating helped to deal with stationarities when present.

This can be expressed for the variable "Y" for provinces i and time t as follows.

$$Ydiff = \sum_{t=1}^{n}[\log(Y_t^i - Y_{t-1}^i)] \quad + \sum_{i=1}^{m}[\log(Y_t^i - Y_t^{i-1})] \text{ ---------}(3)$$

Fixed-Effects Panel Regression can be obtained by OLS regression with the variables transformed in this manner. The data used in this study gathered energy demand, use, generation, O&G production, prices, and GHG O&G emissions of nine provinces over time periods, training and testing. Training period include the years used to run the OLS regression and develop the model, from 2005 through 2016. Testing period include the years used to test the accuracy of the model to forecast, from 2017 through 2020. As both time and province differences among the variables are important factors, the panel regression is a two-dimensional analysis which estimates outcomes from multiple provinces (i) across time horizon (t).

The OLS multivariate regression can be formulated as follows.

$$Y\text{diff} = \beta 0 + \beta 1 X1\text{diff} + \beta 1 X2\text{diff} + \ldots + \beta \text{n} X\text{ndiff} + uit \text{ ------------}(4)$$

Where Y is the response, $\beta 0$ is the constant term, βs are the coefficients of the regressors, Xi are the regressors and $u$it is the error term.

Fixed-Effects are a commonly estimated models when panel data is available. It is assumed that there are some omitted variables that correlated with explanatory variables in the model and the fixed model provides a mean for controlling omitted variable bias. These omitted variables must not change along the variable "time," which means that their effects on the response will be the same at all times. Another feature in fixed models is that the error term must not be correlated with other variables.

Then, OLS regression was sequentially applied to improve the fitness of the models that were chosen for each chosen dependent variable. The most important factors were identified with the statistical significance of each variable on these models, estimated by their p-values, and of all the variables in the model as a joint significance, tested by the F-statistic.

4.4.3 Robustness of the model

The robustness of the models obtained was validated through a series of statistical tests that include: Variance Inflation Factor (VIF), testing of residuals (Normal Q-Q plot and Jarque-Bera test), heteroskedasticity (Breush-Pagan Test) and error autocorrelation was also checked (Durbin Watson Test). The variables used were set to avoid, within the possible limits, any reverse causality or endogeneity explained in 4.4.2.

A VIF is used to detect multicollinearity in the OLS regression model. This means that there is correlation between regressors in the model, a fact that can adversely affect the results obtained with the regression model. The VIF calculates values that must be 1 or lower than 5 to be moderately correlated.

The testing of the normal distribution of the residuals, which is one of the assumptions for the OLS regression model, includes a normal Q-Q plot ("quantile-quantile" plot), which is used to assess whether or not the residuals follow a normal distribution. Additionally, the Jarque-Bera test is used to assess normality of the residuals. This is a type of Lagrange multiplier test and its p-value must be lower than 0.05 not to reject the null hypothesis that the data is normally distributed.

Another key assumption in OLS, known as homoscedasticity, is that the residuals are distributed with equal variance at each level of the regressor. The contrary is named as heteroscedasticity. The Breusch-Pagan test is useful to determine whether or not heteroscedasticity is present in a regression model. The null hypothesis of homoscedasticity present cannot be rejected unless the p-value of the test is higher than some significance level (i.e. $\alpha = .05$). By so, it is concluded that heteroscedasticity is not present in the regression model and its results become unreliable.

In addition, another main assumption in OLS regression is that there is no correlation between consecutive residuals. To determine if this assumption is met the statistical hypothesis test Durbin-Watson is performed. If the result of the test has a value between 1.5 and 2.5, then autocorrelation is likely not a cause for concern.

Following the models that were more proven to be robust enough, a testing step was developed with the fitted models obtained. A data estimation of the models with the dataset "testing" that include the variables for the period 2017-2020 was carried out. The results were compared against the "testing" dataset by calculating their Root Mean Squared Errors (RMSE) as follows:

$$RMSE = \frac{\sqrt{\sum(P_i - O_i)^2}}{n} \text{--------------} (5)$$

where:

Pi is the predicted value for the ith observation in the dataset, Oi is the observed value for the ith observation in the dataset and, n is the size of the sample.

The best fitted model was then selected based on the lowest RMSE calculated and the most important factors were identified though the regressors that were statistically significant in these models.

4.4.4 Test of the hypothesis

Hypothesis: The Refined Petroleum Products and Natural Gas in the industrial, transport, and residential sectors present the largest opportunities for O&G industry GHG emissions reductions in Canada.

The following statistical test was designed to identify if the end use energy generated from each one of the fossil fuels have an impact on the GHG emissions in the O&G industry (using the differentiated form), stated in the hypothesis as follows:

m1_GHG_OG_Total = $\beta_0 + \beta_1$* End use demand of energy in Residential sector as Natural Gas + $\beta_2 *$ End use demand of energy in Residential sector as Refined Petroleum products + $\beta_3 *$ End use demand of energy in Commercial sector as Natural Gas + $\beta_4 *$ End use demand of energy in Commercial sector as Refined Petroleum Products + $\beta_5 *$ End use demand of energy in Industrial sector as Natural Gas + $\beta_6 *$ End use demand of energy in Industrial sector as Refined Petroleum Products + $\beta_7 *$ End use demand of energy in Transport sector as Aviation Fuel + $\beta_8 *$ End use demand of energy in Transport sector as Diesel + $\beta_9 *$ End use demand of energy in Transport sector as Heavy Fuel Oil + $\beta_{10} *$ End use demand of energy in Transport sector as Liquefied Petroleum Gases + $\beta_{11} *$ End use demand of energy in Transport sector as Lubricants + $\beta_{12} *$ End use demand of energy in Transport sector as Motor Gasoline + $\beta_{13} *$ End use demand of energy in Transport sector as Natural Gas + ε ---------------------------------(6)

4.5 Mitigation wedges

The reduced form of the model obtained identifies the key elements that are the categories of the mitigation wedges to be estimated. To estimate these wedges, the following steps were followed:

1.The baseline level of GHG emissions in the O&G industry was defined from the historic data 2005 - 2020 in Canada, with base on year 2019 (the target for the oil and gas sector action set in the 2030

Emissions Reduction Plan). This baseline was the reference point to measure the impact of the mitigation efforts.

2.The potential mitigation elements were identified as the significant regressors found in the reduced form of the model. These significant regressors are the “potential fuel-decarbonization strategies” that could help significantly reduce GHG emissions in the O&G industry.

3.The emissions reductions that each element could achieve were quantified based on the coefficient that each one has on the reduced form of the model. This helped to determine which “potential fuel-decarbonization strategies” are most effective and which ones are less.

4.The emissions reductions were estimated and divided into wedges to help visualize the impact of each “strategy”. Each wedge represents a specific amount of emissions reductions that can be achieved through a particular “strategy”.

5. Results and Findings

This chapter presents the data frame descriptive statistics (according to the statistical methods outlined in chapter 4), the OLS regression model that best fit to test the hypothesis, the robustness of the model results and the mitigation wedges definitions, with the implications of each one are detailed.

5.1 Descriptive statistics

The begin, the main descriptive statistics of the panel data variables used in the study are shown in Table 5.1 below. The data used consist of 144 observations with 41 variables distributed among dependent and independent variables, according to the hypothesis tested, and nine regional variables corresponding to the provinces of Canada, considered within a 15-year time period (2005-2020).

Table 5.1. Descriptive statistics of variables in data frame.

No	Variable	Unit	Min	Max	Median	Mean	Standard Deviation
1	GHG_OG_Total	kT CO_2 eq	15	134893	2874	19231	36625.43
2	GHG_OG_PRI	kT CO_2 eq	1	7271	1124	1923.9	1833.94
3	GHG_OG_OGE	kT CO_2 eq	1	92374	311.5	9581.7	23189.26
4	PED_NG	Petajoules	16.75	2742.23	237.71	482.38	681.07
5	PED_RPP	Petajoules	98.63	1511.54	241.94	530.14	493.96
6	End_Use_Res_NG	Petajoules	0.137	383.45	23.88	75.63	109.89
7	End_Use_Res_RPP	Petajoules	0.24	52.94	5.08	10.82	12.72
8	End_Use_Com_NG	Petajoules	0	281.56	61.74	72.71	78.92
9	End_Use_Com_RPP	Petajoules	1.85	208.82	8.273	23.90	33.35
10	End_Use_Ind_NG	Petajoules	2.33	1965.89	136.43	273.37	476.88
11	End_Use_Ind_RPP	Petajoules	9.70	855.85	90.07	201.99	241.48
12	End_Use_Tran_AviFuel	Petajoules	0.71	101.99	12.02	29.40	29.09
13	End_Use_Tran_Diesel	Petajoules	11.75	244.03	53.45	88.00	75.79
14	End_Use_Tran_HeavyFuelO	Petajoules	0.001	42.097	1	7.249	10.22
15	End_Use_Tran_LPG	Petajoules	0.001	8.34	0.18	1.34	2.01
16	End_Use_Tran_Lubricants	Petajoules	0.003	3.75	0.08	0.27	0.53
17	End_Use_Tran_Gasoline	Petajoules	20.65	565.02	71.30	155.44	157.44
18	End_Use_Tran_NG	Petajoules	0.001	1.66	0.64	0.63	0.50
19	EndUseP_Trans_Gasoline	CAD per gigajoule[6]	29.89	50.69	40.16	40.24	4.34
20	EndUseP_Trans_Diesel	CAD per gigajoule	27.88	48.81	37.18	37.48	4.48

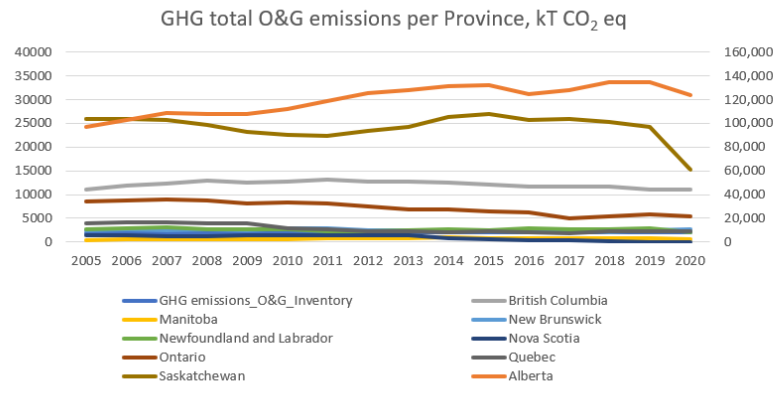
[6] In 2010 Canadian dollars terms (i.e. adjusting for inflation).

	EndUseP_Resi_Electricity	CAD per gigajoule					
21	EndUseP_Resi_Natural Gas	CAD per gigajoule	4.36	51.46	14.89	16.37	7.95
22	EndUseP_Resi_Oil	CAD per gigajoule	22.10	41.43	29.86	30.77	4.20
23	EndUseP_Ind_NG	CAD per gigajoule	1.66	14.84	6.41	6.91	2.91
24	EndUseP_Ind_Oil	CAD per gigajoule	18.96	48.24	29.75	30.08	6.01
25	EndUseP_Com_Natural Gas	Canadian dollars per gigajoule	2.42	20.70	10.71	10.55	3.72
26	EndUseP_Com__Oil	CAD per gigajoule	19.39	38.73	27.45	27.60	3.99
27	ElecGen_Bio_Geo	Petajoules	1	5856.07	506.50	914	1145.11
28	ElecGen_Solar	Petajoules	0.26	2168	1	112.90	432.68
29	ElecGen_Wind	Petajoules	1	14436.8	765.5	1904.1	3002.44
30	ElecGen_NG	Gigawatt hours	30.49	45033.64	2025.60	6380.12	10036.88
31	ElecGen_Oil	Gigawatt hours	1	4200.75	309.81	581.12	805.09
32	COP.Total	Thousand Barrels per day	0.50	3983.031	34.679	399.082	889.53
33	NGP.Total	Billion Cubic Feet per day	0.002	13.38	1	2.06	3.38
34	Brent	US$ per Barrel	41.00	128.41	79.31	84.56	28.15
35	CanLightSweet	CAD per Barrel	34.00	100.01	63.38	68.39	20.45
36	HenryHub	US$/Million of cubic feet	2	11.30	4.30	5.08	2.87
37	NovaInventoryTransfer	US$/MMBtu	1.27	9.49	3.37	3.90	2.62
38	WTI	US$ per barrel	39	120.12	80.14	80.12	25.18
39	WesternCanSelect	CAD per barrel	26.40	97.39	61.30	60.84	22.20
40	EleCap_Pfuel_NG	Megawatts	31.05	10903.63	562.49	2124.25	2948.73
41	EleCap_Pfuel_Oil	Megawatts	1	1594.63	222.30	404.47	536.83

Table 5.1 presents the GHG total O&G emissions with a mean of 19,231 kT CO_2 eq for the nine provinces. Also shown are GHG emissions from Refined Petroleum Products (RPP), O&G Extraction operations (OGE), fugitive, and petrochemical plants. The case of Alberta has peaks of fugitive emissions which are higher than the GHG emissions from RPP and OGE.

Trends in GHG total O&G emissions reported by every one of the provinces of Canada used in this analysis from 2005 to 2020 appear in Figure 5.1 below. The GHG total O&G emissions variable is directly linked with the O&G operations in each region. Alberta, presented on the right axis, has the highest GHG total O&G emissions in the country as a result of having the largest share of the nation’s O&G activity. It is followed by Saskatchewan, British Columbia, Ontario, and then the rest of the provinces which all have significantly lower emissions than Alberta.

Figure 5.1. GHG total O&G emissions per Province.



The GHG total O&G emission variable is mainly influenced by the fossil fuel energy consumption in the different sectors at the end users front. In Table 5.1, the magnitude of the mean and maximum values is useful to observe that the use of Natural Gas (NG) and Refined Petroleum Product (RPP) in the industrial sector have the highest demand. These two variables, NG and RPP, are followed by the gasoline and diesel used in the transport sector. The NG consumption is also high in the residential and commerce sectors. Figure 5.2 collects the NG end use grouped for the residential, commercial, and industrial sectors. In this figure, Alberta is on the second axis as it still has the highest energy end used. Ontario follows due to the high industrial activity and population in this region.

Figure 5.2. Natural Gas end use energy in sectors Residential, Commercial, and Industrial.

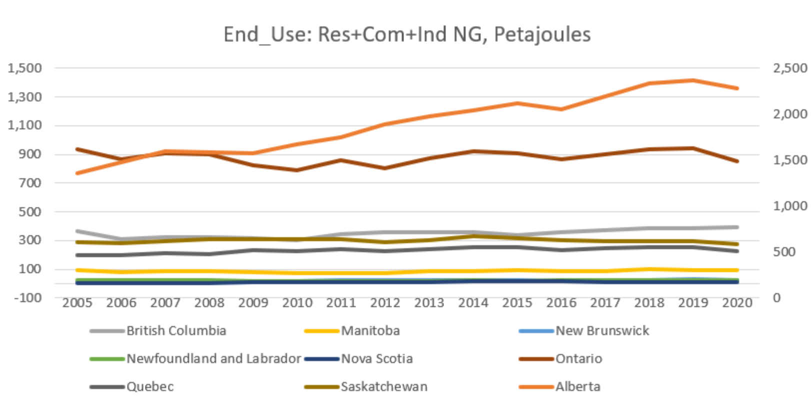
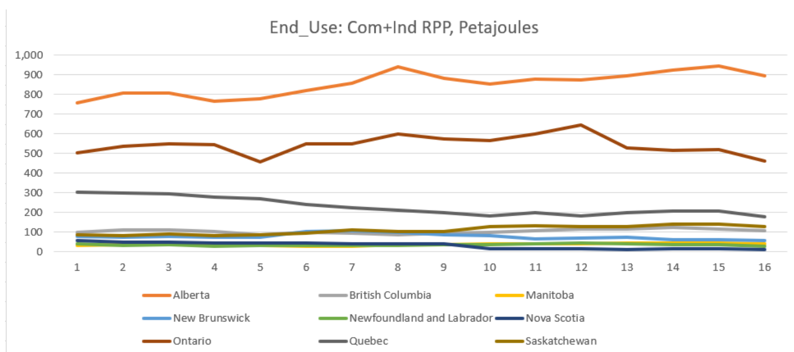


Figure 5.3 plots the RPP end use grouped for the commercial and industrial sectors. Alberta still has the highest energy end used. However, this time Ontario is closer and is followed by Quebec. Alberta has five refineries which have a total crude processing capacity of 542.4 Mb/d (28.5% of Canada's total refining capacity). Ontario has the second largest refining capacity after Alberta, with four refineries with a total capacity of 393 thousand barrels per day (Mb/d). Next is Quebec, with two large refineries currently operating and a combined capacity of 372 thousand barrels per day (Mb/d). New Brunswick, as mentioned before, has the largest refinery in Canada with a capacity of 320 thousand barrels per day (Mb/d). Nevertheless, New Brunswick produces RPPs in excess of its needs and operates primarily for exports to the U.S. and neighbouring provinces.

Figure 5.3. Refined Petroleum Products end use energy in sectors Commercial and Industrial.



The data from Table 5.1 (pg. 51 and 52) were converted to histograms which can be found in Appendix A. Oil and Gas production were included as a reference, as are the origin of these products. Overall, it can be seen that the variables GHG, related with NG and RPP, follow a right-oriented distribution (right-tailed). This means that Alberta has a high effect on this distribution.

The correlation matrix is presented in Appendix B. It was developed to check the impacts of every one of the regressors on the dependent variables and compare the results with what was expected. Although the focus of the study is on fossil fuels, literature suggests that an overall view of the variables that may present interactions and the estimation of their correlation coefficients is useful to have an idea of the presence or absence of dependence among these variables. The correlation coefficients that are equal to or higher than 0.9 are highlighted in yellow, and the ones at 0.8 in light yellow color. These are the variables that are highly correlated in the dataset. The table illustrates that GHG emissions total for O&G and for OGE are highly correlated with the oil and gas production, and consequently with the Primary Energy Demand of Natural Gas (NG) and end use of NG in the industry sector. As expected, due to the high volumes of NG used in this sector, the electricity generated by NG is correlated with its Primary Energy Demand (PED) and the end use of NG and RPP in the industrial sector. Additionally, the electricity capacity generation from NG is correlated with the end use of NG in the residential and commercial sectors. This correlation is due to the fact that in Alberta, Saskatchewan, and Ontario there are several natural gas-fired power stations, and a high population and urban activity are seen in Ontario, Alberta, and British Columbia.

5.2 Test Results of the Hypothesis

To recall, the hypothesis stated that *the Refined Petroleum Products and Natural Gas in the industrial, transport, and residential sectors present the largest opportunities for O&G industry GHG emissions reductions in Canada* and the results confirmed the hypothesis as follows.

The results for the OLS best fit regression model obtained to test the hypothesis are presented in Table 5.3. Next, the effects of the analyzed variables on the GHG total O&G emissions are explained and various implications for design are discussed.

To explore the effect on the GHG total O&G emissions by the 13 potential independent variables selected, each one of these variables was added and tested in the regression model. A series of sequential models was obtained, and a selection of the best fitted was done.

The variables that, due to their low statistical significance, were not selected are the following:

- End use demand of energy in Residential sector as Natural Gas.
- End use demand of energy in Commercial sector as Natural Gas.
- End use demand of energy in Commercial sector as Refined Petroleum Products.
- End use demand of energy in Transport sector as Aviation Fuel.
- End use demand of energy in Transport sector as Diesel.
- End use demand of energy in Transport sector as Heavy Fuel Oil.
- End use demand of energy in Transport sector as Liquefied Petroleum Gases.
- End use demand of energy in Transport sector as Lubricants.
- End use demand of energy in Transport sector as Motor Gasoline.

Finally, the model that best fit was named M10. The equation for this model is as follows:

GHG emissions O&G Total = -0.005574 + (0.053203 * enduerrppdiff) + (0.161955*endueingdiff) + (0.421870*endueirppdiff) + (0.062665*enduetngdiff) ---(12)

Where:

Enduerrppdiff => End use demand of energy in Residential sector as Refined Petroleum Products [Petajoules]

Endueingdiff => End use demand of energy in Industrial sector as Natural Gas [Petajoules]

Endueirppdiff => End use demand of energy in Industrial sector as Refined Petroleum Products [Petajoules]

Enduetngdiff => End use demand of energy in Transport sector as Natural Gas [Petajoules]

As well, Table 5.3 summarizes the results of model M10.

Table 5.3. Panel regression results for the Hypothesis (GHG emissions O&G Total as dependent variable).

Independent variables	Coefficients	t-statistics	p-value
Enduerrppdiff	0.053203	1.783	0.07775
Endueingdiff	0.161955	3.392	0.00102
Endueirppdiff	0.421870	5.912	5.4087e-8
Enduetngdiff	0.062665	6.979	4.15e-10

Model M10 has an adjusted R^2 of 0.5255, meaning that the four regressors, EndUse_Ind_RPP, EndUse_Ind_NG, EndUse_Resi_RPP, and EndUse_Trans_NG, explain 52.55% of the variation in the GHG emissions by O&G in Canada.

As mentioned in chapter 4, the F-Test of overall significance in this regression is a test of whether or not this linear regression model provides a better fit to a dataset than a model with no predictor variables. Model M10 has an accepted p-value of 2.2 e-16 which it is much lower than 0.01 value. Therefore, it can be said that these four independent variables jointly have an effect on the dependent variable, the GHG emissions by O&G in Canada. Thus, the corresponding coefficients of the M10 model are statistically significant, and the variables can be said that are the most important factors affecting the dependent variable.

In consequence, the reduced form of the M10 model reveals that end use demand of energy in the residential sector as Refined Petroleum Products, end use demand of energy in the industrial sector as Natural Gas, end use demand of energy in the industrial sector as Refined Petroleum Products and end use demand of energy in the transport sector as Natural Gas have a long run positive effect on GHG emissions reduction in Canada. Thus, the outcomes confirm the hypothesis and answer the research questions, "What are the fuels that the Oil and Gas industry in Canada can focus on reducing so as to significantly achieve its GHG emissions target for 2030?" and, "What O&G consumption sectors are most likely to be affected by fuel reductions?".

Per order of significance, the associated coefficients express that the GHG emissions by O&G in Canada are significantly affected by the end use demand of Refined Petroleum Products in the industrial sector, Natural Gas in the industrial sector, Natural Gas in the transport sector, and Refined Petroleum Products in the residential sector.

The manner in which the end use energy from these fossil fuels needs to be changed to reduce the GHG emissions for the O&G industry is described as follows:

The GHG emissions by O&G in Canada will be expected to go down by 1% if:

- the end use demand of energy as Natural Gas in the industrial sector goes down by 0.16%,
- there is a decrease of 0.06% in the end use demand of energy as Natural Gas in the transport sector,
- the end use demand of energy as Refined Petroleum Products in the industrial sector decreases in 0.42%, and
- a reduction of 0.05% in the end use demand of energy as Refined Petroleum Products in the residential sector is presented.

5.3 Robustness of the Hypothesis model

The Variance Inflation Factors (VIF) of the four regressors was estimated and all the values are lower than a value of five, indicating that the fitted regression model shows no multicollinearity, thus all the regressors are not highly correlated to each other. Hence, the selected regressors do provide unique or independent information in the regression model.

The residuals were estimated and their distribution is plotted in Figure 5.5a in a histogram (below). Skewness and kurtosis metrics are included. To visualize the curve distribution symmetry of the residuals, the normal Q-Q plot ("quantile-quantile" plot), Jarque-Bera, and Breusch-Pagan tests are presented in Figure 5.6a. The histogram shows a light left-skewed tail, but most of the residuals follow a normal distribution. Skewness is -0.285 and, as a small negative value, indicates that the tail is on the left side of the distribution, which extends towards more negative values, confirming the histogram plot. Kurtosis is 5.837 and since this is greater than 3, indicates that the distribution has more values in the tails compared to a normal distribution. The Jarque-Bera test statistic is 34.556 and the p-value of the test is 3.1e-8, therefore it fails to reject the null hypothesis that the data are normally distributed. Additionally, since the observed deviations from the symmetry that the residuals follow to the left-tail are slight, in general, it can be considered that they mostly follow a trend towards the normal distribution. Accordingly, this assumption for the OLS regression model can be kept. The normal Q-Q plot shows within a range of -1 to +1 quantiles. Lastly, the Breusch-Pagan test has a p-value of 0.089, which is not lower than 0.05, thus the null hypotheses cannot be rejected and homoscedasticity is present. These results support the assumptions taken of the model M10, allowing that it is statistically confident to reproduce the dependent variable.

Figure 5.5a Distribution of the residuals (histogram).

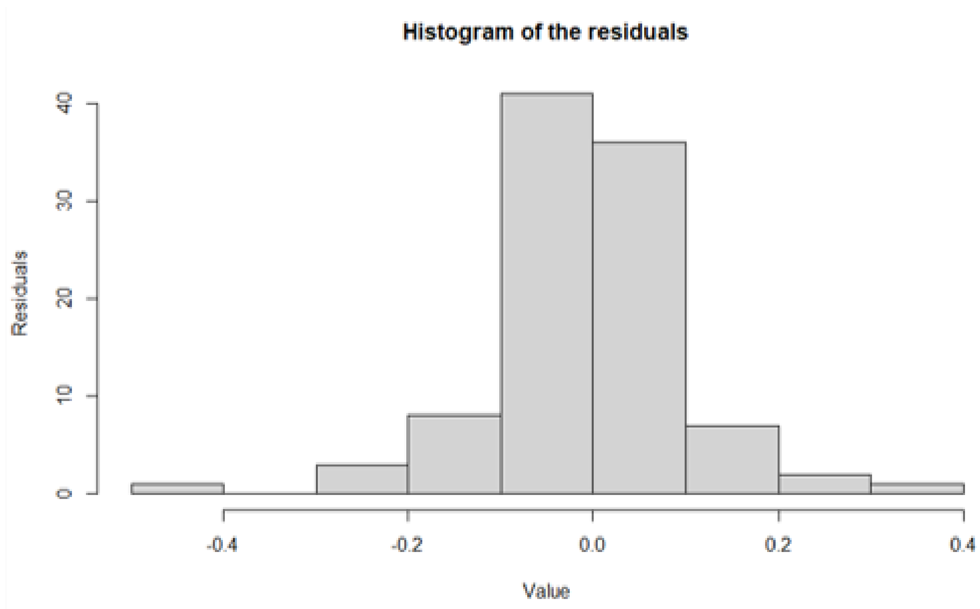
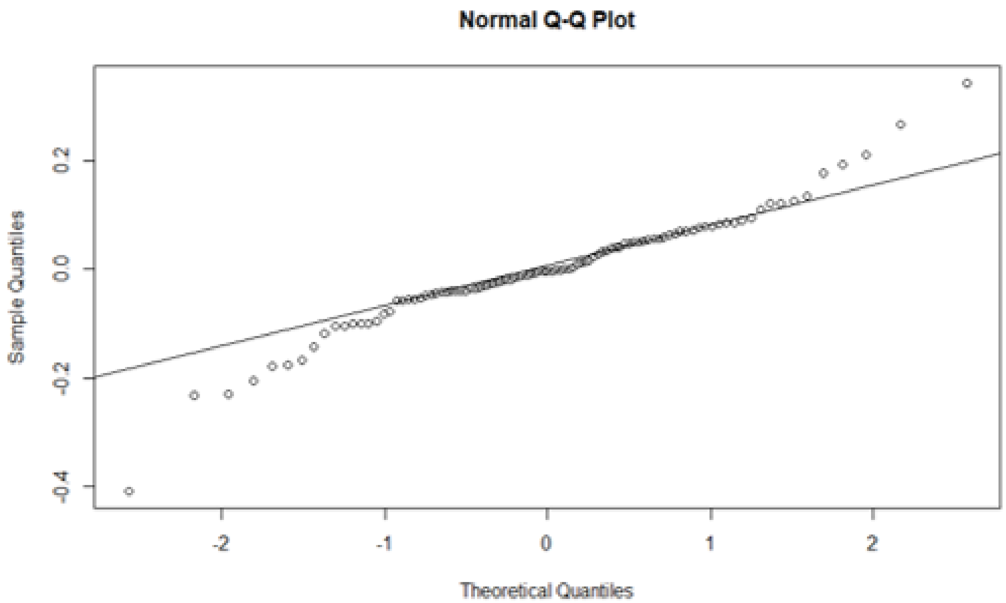


Figure 5.6a Normal Q-Q plot of the residuals.



Finally, the M10 model obtained with the training data frame was used to estimate the values of the GHG emissions for the O&G industry registered from 2017 to 2020, named the testing data frame. The results were evaluated with the RMSE, which has a value of 2,000 kT CO_2 eq. This represents 11% of the average value for all the GHG emissions O&G Total values in the data frame. In consequence, M10 can be confidently used for this variable estimation.

5.4 Implications of the reduced form of the model (M10)

The resulting M10 model has four regressors as the main variables implied for generating the GHG emissions by the O&G industry. These variables, detailed below, are fossil fuels used in certain sectors that provide associated services into those sectors. The common uses of the fossil fuels in the sectors identified in the model are described as follows:

Enduerrppdiff => Use of Refined Petroleum Products (RPP) in the Residential sector [Petajoules]

In 2020, RPP used in the residential sector amounted to approximately 10% of total RPP end use in Canada (Natural Resources Canada, 2020).

The use of RPP in the residential sector varies depending on the region and the availability of other fuel sources such as natural gas or renewable energy, and these products typically include:

Heating oil, a type of fuel oil used for heating homes and buildings. It is commonly used in furnaces, boilers, and other heating systems.

Propane, a type of Liquefied Petroleum Gas (LPG) used for heating and cooking in rural areas where natural gas is not available.

Gasoline, primarily used as a transportation fuel, but also used for some small engines such as lawnmowers and other equipment used for residential purposes.

Diesel fuel, used frequently for backup generators and other equipment used in residential settings.

Kerosene, a type of fuel oil used for heating and lighting in some rural areas where other fuel sources are not available.

Endueingdiff => Use of Natural Gas in the Industrial sector [Petajoules]

Natural Resources Canada reported during 2020 that the industrial sector was the largest consumer of Natural Gas, amounting to approximately 40% of total NG end used in Canada (Natural Resources Canada, 2020).

Natural gas is a widely used energy source for a several industrial applications. It provides a reliable and cost-effective fuel source. Some of the most common uses of natural gas in the industrial sector include:

Heat and power generation in boilers, turbines, and engines to generate heat and electricity for industrial processes.

Chemical production as a raw feedstock for the production of chemicals such as methanol, ammonia, and hydrogen, and also as a fuel in chemical processes such as steam reforming.

Metal production as a fuel in furnaces for the production of metals such as steel, aluminum, and copper.

Food processing such as baking and dairy processing for heating and sterilization.

Paper and pulp production, as a fuel for boilers and turbines in paper and pulp production facilities.

Glass production, as a fuel in glass production for melting and shaping the glass.

Cement production, as a fuel in kilns for cement production.

Transportation, as a transportation fuel in the form of compressed natural gas (CNG) and liquefied natural gas (LNG) for trucks, buses, and ships.

Endueirppdiff => Use of Refined Petroleum Products in the Industrial sector [Petajoules]

The refined petroleum products used in the industrial sector of Canada depend on the specific industry and the type of equipment and machinery being used. In 2020, the consumption of RPP in the industrial sector accounted for approximately 23% of total RPP used in Canada (Natural Resources Canada, 2020). Among the most common refined petroleum products used in the industrial sector of Canada are:

Diesel fuel in heavy-duty trucks, locomotives, and other large machinery in the transportation and construction industries.

Gasoline, used primarily as a transportation fuel and also in some industrial applications such as small engines and generators.

Propane, used as a fuel for forklifts, heating, and as a feedstock for some industrial processes such as plastics manufacturing.

Jet fuel, used in the aviation industry for commercial and military aircraft.

Heating oil, used as a fuel for heating large industrial buildings and equipment such as boilers and furnaces.

These RPPs are used also as lubricants, hydraulic fluids, and other industrial oils to keep machinery running smoothly.

Enduetngdiff => Use of Natural Gas in the Transport sector [Petajoules]

In Canada, the Natural gas used in the transport sector is limited, but it is increasingly being used in recent years. The consumption of NG in the transport sector in 2020 was less than 1% of total NG used in Canada. NG can be used in two main forms: compressed natural gas (CNG) and liquefied natural gas (LNG). Common uses of natural gas in the transport sector in Canada include:

In heavy-duty trucks, which are commonly used in the freight and transportation industries. These trucks can be powered by either CNG or LNG, which provide a lower-emission alternative to diesel fuel.

In transit buses, which are used in public transportation systems across Canada. CNG is the most common form of natural gas used in buses, although some cities are also using LNG-powered buses.

In waste collection trucks, which are often powered by CNG. This is a popular use of natural gas in the transport sector as these trucks operate in densely populated urban areas and their use of natural gas can significantly reduce emissions and improve air quality.

In some marine vessels, such as ferries and cargo ships. This is a growing trend as the marine sector looks to reduce emissions and comply with environmental regulations.

By acknowledging their typical uses, the implications that each one of the reductions suggested by the M10 model would have in the sectors can be deduced, and these are described in chapter 6.

Overall, it is important to note that the use of natural gas in the transport sector in Canada is seen as a way to reduce greenhouse gas emissions and improve air quality, particularly in urban areas. However, as natural gas is still a fossil fuel, the long-term solution requires a transition to renewable energy sources.

5.5 Mitigation wedges

Once the reduced form of the model (M10) was obtained and proven to be confident, the four key elements identified as statistically significant were set as the categories of the mitigation wedges. The steps described in section 4.5 were then carried out:

1. The baseline was defined as the GHG emissions in the O&G industry in 2019, as said, what was set as the baseline for the oil and gas sector target in the 2030 Emissions Reduction Plan.

2. The mitigation categories were defined as the regressors of the reduced form of the model M10, recalling these as follows:

Enduerrppdiff => Use of Refined Petroleum Products in Residential sector [Petajoules]

Endueingdiff => Use of Natural Gas in Industrial sector [Petajoules]

Endueirppdiff => Use of Refined Petroleum Products in Industrial sector [Petajoules]

Enduetngdiff => Use of Natural Gas in Transport sector [Petajoules]

3. The emissions reductions that each element could achieve were quantified based on the coefficient that each one has on the reduced form of the model. These were presented in Table 5.3. The coefficients determined the order of priority regarding the "potential fuel-decarbonization strategies" to be most effective, and are shown in order in Table 5.4.

Table 5.4. Mitigation wedges categories and order of priority.

Order of priority	Independent variables	Coefficients
1	Endueirppdiff	0.421870
2	Endueingdiff	0.161955
3	Enduetngdiff	0.062665
4	Enduerrppdiff	0.053203

4. The emissions reductions were estimated by taking the results of 1% reduction in GHG emissions to the 42% of 2019 target for 2030 and dividing into four wedges to help visualize the impact of each "strategy." Each wedge represents a specific amount of emissions reductions that can be achieved through a particular "strategy" and the results are displayed in Figure 5.7 and Table 5.5 below.

Figure 5.7 Mitigation wedges for GHG emissions O&G in Canada.

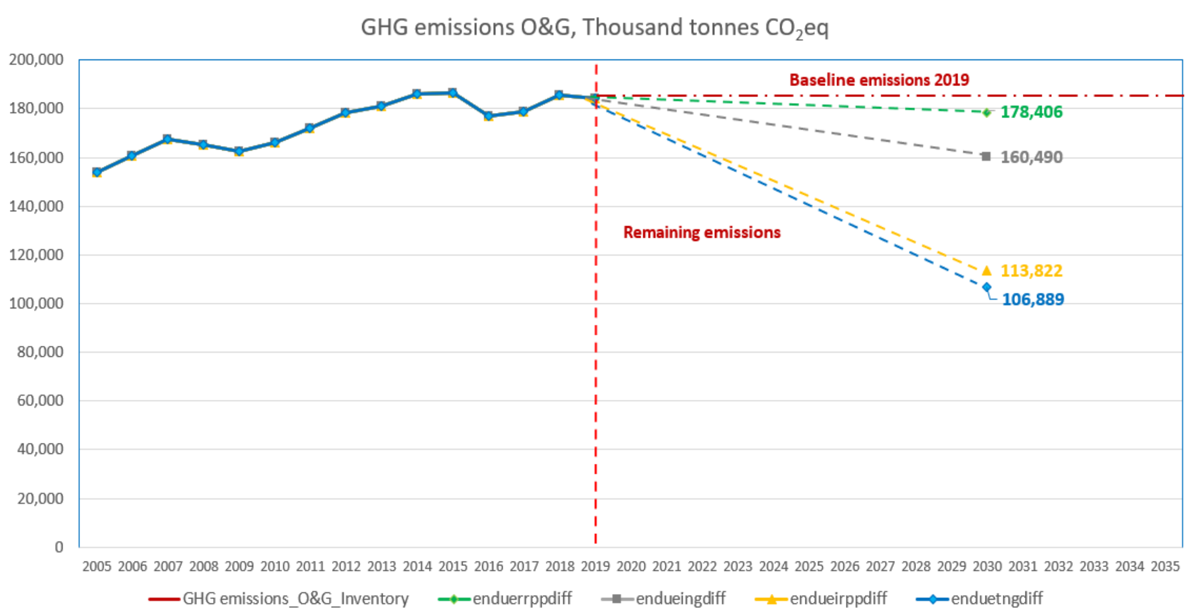


Table 5.5. Mitigation wedges (GHG emissions O&G Total in Canada).

Wedge category: Fossil fuel used in economic sector	GHG emissions O&G reductions, Thousand tonnes CO_2e (% of total) In 2030	Key actions to take towards 2030
Refined Petroleum Products in residential sector	5,886 (7.6%)	• Promote energy-efficient housing. • Provide incentives for renewable energy. • Promote electric and hybrid vehicles. • Increase public awareness. • Implement energy-saving policies. • Encourage alternative heating sources. • Carbon pricing.
Natural Gas in industrial sector	17,916 (23.1%)	• Energy efficiency improvements. • Fuel switching. • Process improvements. • Carbon pricing. • Government policies and incentives. • Collaborative efforts.
Refined Petroleum Products in industrial sector	46,669 (60.3%)	• Energy efficiency improvements. • Fuel switching. • Process improvements. • Carbon pricing. • Government policies and incentives. • Collaborative efforts.
Natural Gas in transport sector	6,932 (9%)	• Increase the use of electric vehicles. • Increase the use of biofuels. • Increase the use of hydrogen fuel cell vehicles. • Encourage active transportation. • Improve infrastructure for alternative fuels. • Carbon pricing.
Base case emissions	184,292	
Mitigation case emissions	106,889	
Total reduction emissions	**77,403**	

The key actions for reducing the use of these fossil fuels in the specified sectors in Canada require a combination of policy interventions, incentives for consumers, and public awareness campaigns.

Some of the actions have already implemented yet need to be strengthened. Key actions that can be taken include the following:

Refined Petroleum Products in residential sector.

- **Promote energy-efficient housing**[7]: Encouraging the construction of energy-efficient homes can help reduce the demand for refined petroleum products in the residential sector. Building codes can be updated to promote the use of energy-efficient materials, such as insulation, and appliances.
- **Provide incentives for renewable energy**[7]: Government incentives, such as tax rebates, can encourage homeowners to install renewable energy sources, such as solar panels or wind turbines, which can help reduce the use of refined petroleum products.
- **Promote electric and hybrid vehicles**[7]: Encouraging the use of electric or hybrid vehicles can help reduce the demand for refined petroleum products in the transportation sector, which can indirectly reduce the demand for refined petroleum products in the residential sector.
- **Increase public awareness**: A public awareness campaign can educate homeowners about the benefits of reducing their use of refined petroleum products, including cost savings and environmental benefits. This can be done through various channels such as TV or social media.
- **Implement energy-saving policies**[8]: Governments can introduce policies that require energy-efficient appliances and buildings. For instance, mandatory energy labeling and certification can be implemented for buildings, and minimum energy efficiency standards can be introduced for appliances.
- **Encourage alternative heating sources**[7,9]: Encouraging the use of alternative heating sources such as geothermal, biomass, or electric heating can help reduce the demand for refined petroleum products in the residential sector.

[7] Included in "The Emissions Reduction Plan– Canada's Next Steps for Clean Air and a Strong Economy".
[8] Considered in "The Energy Efficiency Act (S.C. 1992, c. 36) was released in 1992 and last changed in December 2008".
[9] Included in "The Canada Foundation for Sustainable Development Technology Act (S.C. 2001, c. 23) was launched in 2001".

- **Carbon pricing**[10]: Implementing a carbon price on natural gas emissions would incentivize industries to reduce their use of the fossil fuel and explore cleaner alternatives.

Natural Gas in industrial sector.

- **Energy efficiency improvements**[8]: One of the most effective ways to reduce the use of natural gas in the industrial sector is to improve energy efficiency. This can be achieved through the use of more efficient equipment, better insulation, and other energy-saving measures.
- **Fuel switching**[7]: Another option is to switch from natural gas to a cleaner energy source, such as renewable energy or electricity. For example, industries that use natural gas for heating could switch to electric heat pumps or geothermal systems.
- **Process improvements**[7]: Industries can also implement process improvements to reduce their natural gas consumption. This could include optimizing production processes or reducing waste. The certification in the Industrial Energy Management System to support ISO 50001 encourages optimization of the processes involved in industry.
- **Carbon pricing**[10]: Implementing a carbon price on natural gas emissions would incentivize industries to reduce their use of the fossil fuel and explore cleaner alternatives.
- **Government policies and incentives**[7]: The Canadian government could introduce policies and incentives to encourage industries to transition to cleaner energy sources. These could include subsidies for renewable energy technologies or tax breaks for energy-efficient equipment.
- **Collaborative efforts**: Collaborative efforts between industries, government, and research institutions could help identify opportunities to reduce natural gas use and develop new technologies and processes that reduce emissions.

Refined Petroleum Products in industrial sector.

- **Energy efficiency improvements**[8]: As with reducing natural gas use, improving energy efficiency is one of the most effective ways to reduce the use of refined petroleum products in the industrial sector. This could include upgrading equipment and processes to be more energy efficient, and implementing energy management systems to optimize energy use.

[10] "The Greenhouse Gas Pollution Pricing Act in 2018" takes into account this strategy.

- **Fuel switching**[7]: Another option is to switch from refined petroleum products to cleaner energy sources, such as renewable energy or electricity. For example, industries that use diesel fuel for heavy-duty trucks could switch to electric vehicles or vehicles powered by hydrogen fuel cells.
- **Process improvements**[7]: Industries can also implement process improvements to reduce their use of refined petroleum products. This could include optimizing production processes or reducing waste. The certification in the Industrial Energy Management System to support ISO 50001 encourages optimization of the processes involved in the industry.
- **Carbon pricing**[10]: Implementing a carbon price on emissions from refined petroleum products would incentivize industries to reduce their use of these fossil fuels and explore cleaner alternatives.
- **Government policies and incentives**[7]: The Canadian government could introduce policies and incentives to encourage industries to transition to cleaner energy sources. These could include subsidies for renewable energy technologies or tax breaks for energy-efficient equipment.
- **Collaborative efforts**: Collaborative efforts between industries, government, and research institutions could help identify opportunities to reduce the use of refined petroleum products and develop new technologies and processes that reduce emissions.

Natural Gas in transport sector.

- **Increase the use of electric vehicles**[7]: One of the most effective ways to reduce the use of natural gas in the transport sector is to increase the use of electric vehicles. This could include passenger cars, buses, and trucks.
- **Increase the use of biofuels**[7]: Biofuels, such as biodiesel or ethanol, can be used as an alternative to natural gas in the transport sector. These fuels are made from renewable sources and can help to reduce greenhouse gas emissions.
- **Increase the use of hydrogen fuel cell vehicles**[7]: Hydrogen fuel cell vehicles emit only water as a byproduct and can be powered by hydrogen produced from renewable sources. As the technology improves, hydrogen fuel cell vehicles could become an increasingly viable alternative to natural gas-powered vehicles.
- **Encourage active transportation**: Encouraging active transportation, such as walking, cycling, or using public transit, can help to reduce the use of natural gas-powered vehicles.

- **Improve infrastructure for alternative fuels**[7]: Governments could invest in the infrastructure needed to support alternative fuels, such as electric vehicle charging stations, hydrogen refueling stations, and biofuel production facilities.
- **Carbon pricing**[10]: Implementing a carbon price on emissions from natural gas-powered vehicles would incentivize the use of alternative fuels and encourage the transition to cleaner transportation options.

The execution of these “potential strategies” is intended to support achieving the GHG emissions target set by the Canadian government for the O&G industry. Of course, these actions cannot be addressed by the O&G industry on its own. Firstly, the residential, industrial, and transport sectors need to work together with the energy industry and government to ensure that the energy to be reduced can be supplied by other alternative renewable sources as electricity via either via traditional grid power or by onsite generated power. Secondly, the effect of these changes on society and the economy will need to be analyzed and feasible solutions identified to be applied when the changes are implemented. As a relevant example of this analysis, the balance among the jobs that will be in play with this energy transition will need to be taken into consideration since it will generate an economic impact that would need to be compensated. All these points, at least, will need to be holistically analyzed to carry out the actions that the optimization solution resulted in.

6. Discussion and conclusion

This chapter first presents a summary of the results obtained. Next, the associated implications are detailed. Then, the main limitations of the study are exposed, and finally, suggested future research is mentioned with the purpose of being able to continue this work.

6.1 Summary of results

This thesis provided a practical proposal for the estimation of mitigation wedges, giving a contribution to the manner in which this approach can be used in the O&G industry strategy definition or in energy policy analysis. The study results indicated that to effectively achieve the GHG emissions target in Canada for 2030, the O&G industry with involved institutions would need to design a collaborative strategy with the industrial, transport, and residence sectors to significantly reduce the use of Refined Petroleum Products and Natural Gas. To support this strategy, in parallel, the Canadian government would need to strengthen the application of the current Canadian regulation and to identify key amendments targeted to specific regions of Canada that would need to be soon launched. Mitigation wedges have been widely developed in literature and consulting. This study has presented a practical method for generating and updating these wedges for fossil fuels. The reduced form of a model (M10) model represents a main contribution of this work. The M10 model can be used by the energy transition community and by the oil and gas practitioners as the basis to generate alternative scenarios.

2030 will be the first deadline for the energy transition agreed in the Paris Agreement (UNCC, 2015), reaffirmed in the last UN conference of the Parties of the UNFCCC in the Arab Republic of Egypt (COP 27, 2022). Despite the great efforts made, there is a long way to go in making real headway (WEF report, 2021). In this mission, O&G countries have an important role, but it is shared with the rest of the economic sectors, government, and society in getting us there. This need for inter-collaboration was reinforced by the findings of this research. The research questions driving the thesis aimed to (i) identify the fossil fuels that the Oil and Gas industry in Canada can focus on migrating towards renewable-sourced to significantly achieve its GHG emissions target for 2030, and (ii) to highlight the sectors that would be impacted. Recalling the hypothesis, it was generated as "The Refined Petroleum Products and Natural Gas in the industrial, transport, and residential sectors present the largest opportunities for O&G industry GHG emissions reductions in Canada".

The GHG emissions for the O&G industry along with end use energy consumptions by type of fuel and sector of eight provinces of Canada (all except Manitoba and Prince Edward Island) were gathered for the study for the years 2005 to 2020. To test the first hypothesis, Fixed-Effects Panel Regression was applied. A series of OLS regression models were sequentially obtained with the 2005-2016 data transformed. These models were developed to understand the effects of the end use energy on the dependent variable, the GHG total O&G emissions. A final reduced form of the model, named M10, was obtained for the most important variables that significantly affect these GHG emissions. The robustness of the M10 model was validated through a series of statistical tests. Then, to test the M10 model's efficacy in forecasting the testing period, GHG total O&G emissions values for 2017-2020 were estimated, and an RMSE was calculated, ensuring that M10 model is confident enough to estimate GHG total O&G emissions for this period.

The mitigation wedges were then estimated using the regressors of the M10 model, following the steps defined in chapter 4, to reach the GHG total O&G emissions target for year 2030. The four mitigation wedges were obtained and set as plausible strategies to reduce GHG emissions and prioritized in Table 5.4. The impact of each one of the mitigation wedges in the reduction of the GHG emissions is visualized in Figure 5.7. The associated actions of each one of the strategies (mitigation wedges) were explained and summarized in Table 5.5.

The results of the OLS regression analyses confirmed that there must be a reduction in end used energy from fossil fuels (RPP and NG) in the economic sectors (industrial, transport and residential) in order to achieve the GHG emissions target of the oil and gas industry of going down by at least 42% below 2019 levels. The result of this first test demonstrated that the GHG emissions by O&G in Canada will be expected to go down by 1% if:

1) the end use demand of energy as Natural Gas in the industrial sector goes down by 0.16%;

2) there is a decrease of 0.06% in the end use demand of energy as Natural Gas in the transport sector;

3) the end use demand of energy as Refined Petroleum Products in the industrial sector decreases by 0.42%; and

4) a reduction of 0.05% in the end use demand of energy as Refined Petroleum Products in the residential sector is presented.

Overall, these results showed that there is a positive effect of the end use demand of energy as NG in the industrial and transport sectors, as well as RPP in the industrial and residential sectors to reduce GHG emissions generated by the O&G industry. These findings reinforce what Andrews-Speed (2016) has emphasized, namely that the industrial sector is one of the players that strongly drives the process involved in the energy transition. Findings are also in line with studies from Garcia-Casals et al. (2019), World Energy Outlook (2021), World Energy Council (2021), Annual Energy Outlook of EIA (2022), three scenarios of Shell (2021), and BP's Energy Outlook (2022). These other energy scenarios demonstrated the direct effect of the fossil-fuel energy used and GHG emissions released.

Moreover, as noted earlier, the results of M10's outputs confirm that new business models of collaborative strategies among the O&G industry with other companies in the industry, transport, and residential sectors must be searched out. Because these stakeholders cannot act on their own, of course government, financial sector, non-profit institutions, and society --the final user-- must also take part in these collaborative strategies.

Specifically, to achieve the goal of 42% less than the maximum value of GHG emissions registered in 2019, the proposed mitigation wedges yield to:

1) Lower the end used energy of Refined Petroleum Products (RPP) in the residential sector to 2.23% of its 2019 values;

2) Reduce to 6.80% the end used energy of Natural Gas (NG) in the industrial sector of the values registered in 2019;

3) Cut by 17.72% the end used energy of RPP in the industrial sector of the 2019 use; and

4) Decrease to 2.63% of the end used energy of NG in the transport sector of its value in 2019.

These four mitigation wedges would reduce a total estimated of 77,403 Mt CO_2e (2019 base) to be migrated to non-emitting sources by 2030.

The thesis results are also in line with Geels and Scot (2007): "what looks like a regime shift at one level may be viewed merely as an incremental change in inputs for a wider regime at another level," meaning that the energy system must be analyzed overall. The proposed actions in each one of the mitigation wedges are mostly aligned with the current regulation for the energy transition launched by the Canadian Government. However, complementary actions would thus be needed to be able to achieve the set target of at least 42% below 2019 levels in GHG emissions. Given that it seems implausible to achieve quite significant drops in the reduction in the end use energy by NG and RPP in the industrial, NG in the transport, and in RPP in the residential sectors under the current conditions by 2030, the is urgent need to launch amendments to the current regulation. These would benefit from being focused on strengthening the specific participation of each region in Canada, according to its impact on fossil fuels reduction in consumption.

Analysis of the associated obstacles to reach the 2030 targets for the industry sector highlights a main limitation nowadays in the Energy Intensive Processes (EIP) of the manufacturing sector like the steel and iron, O&G refining, cement production and smelting. Specifically, the technology developments required to achieve the extreme conditions that these processes need (i.e. high temperatures and pressures) are not yet to commercial scale (EIP, 2014). To be able to meet the need for such extreme conditions would require nuclear power, green hydrogen or geothermal energy, in combination with carbon capture, utilization and storage. Therefore, it is probable that the set target of 30% of the 2019 emissions will not be achieved. Current "2030 Emissions Reduction Plan–Canada's Next Steps for Clean Air and a Strong Economy" would have to emphasize the support of clean technologies for the EIP to further decarbonize the oil and gas sector, powering the economy with renewable electricity, and helping industries develop and adopt clean technology in their journey to net-zero emissions.

This research has focused on a practical proposal to estimate mitigation wedges for Canada, in order to achieve its GHG emissions target for the O&G industry with an energy consumption perspective. The analysis is straight line, and the variables consider a range of certainty. The generated wedges offer a prioritized focus on the fossil fuels to be decarbonized for the O&G industry and economic sectors with its associated difficulties and risks; managers are encouraged to apply the proposed approach in their decision analysis. These possibilities will facilitate the identification of possible stakeholders, in addition to the O&G companies, to carry out the energy transition that is sought. In parallel, financial incentives can also be identified for the Canadian government to work on either reinforcing or developing new ones. Overall, fossil fuels end use energy must be reduced but, of all the sectors, the industrial sector plays a most relevant role. Therefore, main attention should be given to this sector, specifically to the NG and RPP fuels. To do so, there is a large amount of energy (implicit) that will need to be swapped from fossil to renewable sources. These considerations also imply that the current policies, regulations and incentives will need to be strongly emphasized to get positive but stronger outputs. A close monitoring and updating of these results will be a must. After all, the O&G industry and all the economic sectors, together with society and government, are the pioneers of this energy transition.

6.2 Limitations

Although a strong effort has been made to ensure that the best results have been obtained in this research, a number of limitations could not be fully addressed. Non-expected facts that disturb the outcomes may appear, and the simplified model did not consider any mathematical concept that deals with this kind of unknown uncertainty (Taleb N. N., 2010). Of course, this can be a serious issue but, in such a case, the methodology used in this study is easily adaptable such that an updated model could be generated with the disturbing event included as historic. If more time is available, a good limitation to address in this research would be to add to the variables related with prices in the dataframe, along with applying synthetic control methods to identify the effects of the carbon tax policy on the prices and the end use energy (J. D. Baker, 2022). An important limitation of this proposal is on the side of the model towards extrapolating beyond the territorial limits of Canada. The model would need to be calibrated for use with other country's input data. Lastly, in order for the model to be capable of processing higher data loads, it would have been beneficial to include Artificial Intelligence (AI) algorithms or stochastic modeling to fit an alternative M10 model and evaluate its effectiveness in the forecasting and, on the side of the results found, it would be interesting to explore the use of Artificial Intelligence tools to test an improvement in the confidence of the forecasted values. AI approaches can be applied to improve the estimation of the GHG emissions released in the O&G sector which yields a closer estimation of the real reductions of these emissions. With respect to the results on the industrial sector, a study on the available technology to reach the extreme conditions needed and an estimated roadmap would be highly helpful. Finally, the advantages of all of these tools may be synergized positively through a proper combination of the algorithms.

6.3 Future research

The results found in this study, as well as some of the limitations observed, call for future studies on this topic. Among the short-term opportunities that seem of immediate relevance for further research are the following:

1) Cost estimation of each of the wedges - each has particularities that will impact on the cost for implementing the wedges in each sector.

2) Feasibility studies through the identification and modelling of key constraints tied to each wedge -these ought to consider that some of the alternatives are not easily deployable in remote or northern communities.

3) Estimation of time for the implementation - associated with the ease or difficulty of implementing the wedges immediately and the assumptions of future developments in technology, which will play a relevant role.

4) Further detailed analysis within each of the four broad categories that are estimated. For instance, with transportation the different contributions of increased use of electric vehicles, biofuels, hydrogen fuel cell vehicles, encouraged active transportation, improved infrastructure for alternative fuels, and carbon pricing could be estimated.

5) Jurisdiction-by-jurisdiction implications. A clear example is that Alberta and Quebec have different baselines to work from and it might be useful to look at how different strategies might be appropriate for different provinces.

As mentioned in 2.6, the wedges concept section, these mitigation wedges can provide the basis of a further scenario analysis. Accordingly, a number of complementary scenarios should be obtained from different assumptions about potential risks and benefits of a particular potential investment.

6.4 Closing remarks

This research developed a tool to help decision makers in the O&G industry, and the impacted sectors, navigate their pathway opportunities in fossil fuels decarbonization in reaching the GHG emissions target for 2030.

As the study results showed, there is a pressing need for technology developments (emerging from laboratories and pilot projects to the commercial stage) to be applied in the EIP in order that these processes can be powered by green hydrogen or other alternative sources (e.g., geothermal). Nuclear energy is not well adopted in several provinces in Canada, and it is not an option, though it would also be plausible to use. The cuts in the RPP and NG that this study founded if the 2030 target for GHG emissions in the O&G industry is to be met – 60.3% and 23.1%, respectively, reduction in end use energy by RPP and NB in the industrial; 9% reduction in NG in the transport sector, and 7.6% reduction RPP in the residential sector – calls for substantially increased support. Specifically, higher incentives are needed to reduce use of Refined Petroleum Products and Natural Gas in the industry (where possible and not EIP), Natural Gas in the transport, and Refined Petroleum Products in the residential. Directed and aligned collaboration among these three sectors, society and government should be stressed to rapidly and sustainability accelerate the availability of enough equipment and infrastructure. To do this, considered elements in a set of implemented regulations in Canada need to be stressed. This set includes "The Emissions Reduction Plan– Canada's Next Steps for Clean Air and a Strong Economy;" "The Energy Efficiency Act (S.C. 1992, c. 36) released in 1992 and last changed in December 2008;" "The Canada Foundation for Sustainable Development Technology Act (S.C. 2001, c. 23) launched in 2001;" and "The Greenhouse Gas Pollution Pricing Act in 2018."

Additionally, an important effort in powering further advances in the engineering of more powerful and adaptable photovoltaic panels, cells, used for solar power generation and storage, turbine blades used in hydro and wind power generation electricity should be done with academic, research agencies, business incubators and commercial services worldwide. Integrated electricity grid with sources, sinks, and massive transmission lines should be accelerated, built with the associated incorporation of novel artificial intelligence applications to solve supply, storage and distribution problems. Finally, the transition is feasible, however significant challenges need to be overcome. Otherwise, we will all pay for the delay.

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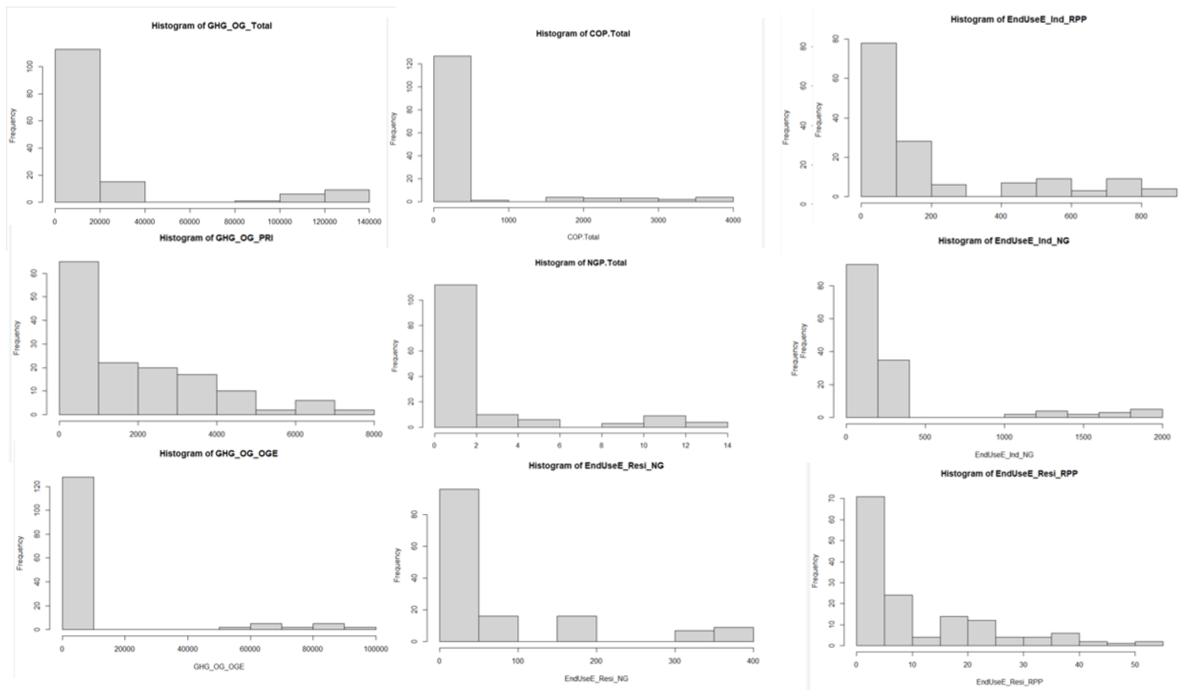
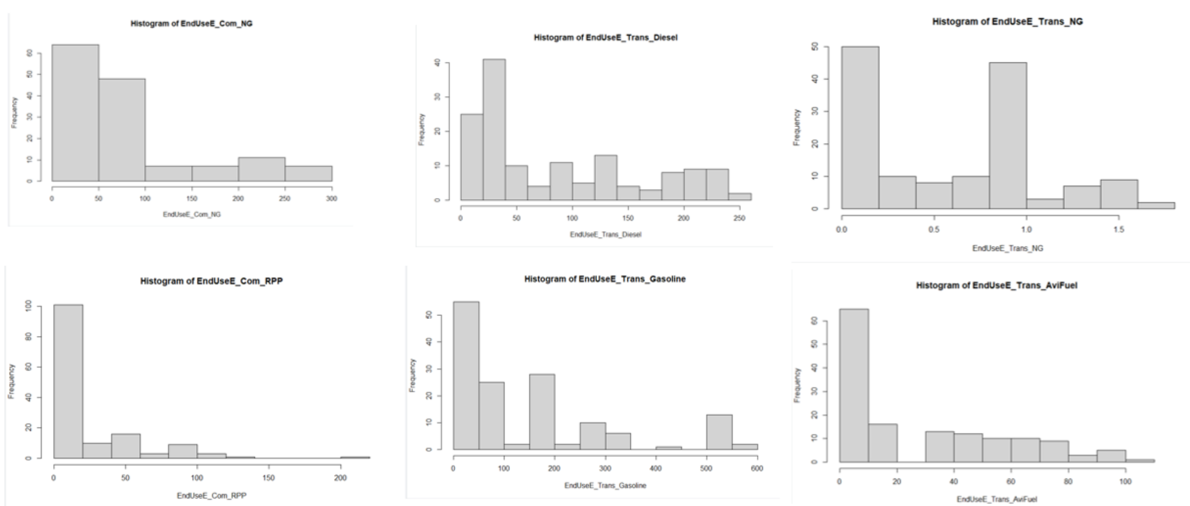
Appendix A – Histograms of data frame variables:

Oil and Gas production, GHG total O&G emissions, NG, RPP, Diesel, Gasoline and Aviation Fuel end use energy in the residential, commercial, and industrial sectors.





Appendix B –Correlation matrix of the data frame.

	PED_NG	PED_RPP	End_Use_Res_NG	End_Use_Res_RPP	End_Use_Com_NG	End_Use_Com_RPP	End_Use_Ind_NG	End_Use_Ind_RPP	End_Use_Tran_AviFuel	End_Use_Tran_Diesel	End_Use_Tran_HeavyFuelO	End_Use_Tran_LPG	End_Use_Tran_Lubricants	End_Use_Tran_Gasoline	End_Use_Tran_NG	EndUseP_Trans_Gasoline	EndUseP_Trans_Diesel	EndUseP_Resi_Natural.Gas	EndUseP_Resi_Oil	EndUseP_Ind_NG	EndUseP_Ind_Oil	EndUseP_Com_Natural.Gas	EndUseP_Com_Oil	ElecGen_Bio_Geo
PED_NG	1	0.81603301	0.67185694	-0.0483322	0.744379	0.8994879	0.9621526	0.9591221	0.365538164	0.795058168	-0.02807804	0.392678278	0.258882707	0.447739331	0.13976731	-0.39912682	-0.372160036	-0.45885948	-0.03259	-0.2696624	0.14916971	-0.563909	0.084731644	0.39436414
PED_RPP	0.816033	1	0.88160534	0.4293019	0.9363324	0.8168375	0.6635373	0.9215397	0.72902596	0.9836734	0.29635976	0.704397861	0.580611888	0.867528405	0.185111225	-0.269767503	-0.285419263	-0.33512473	0.087096	-0.0061263	-0.0969546	-0.3204569	0.109004022	0.38389314
End_Use_Res_NG	0.6718569	0.88160534	1	0.3369125	0.9593725	0.6237125	0.4496828	0.7658043	0.634098375	0.864004537	0.232512409	0.853531885	0.707600964	0.858402366	0.178546557	-0.235952044	-0.29302511	-0.33537413	0.180558	-0.012609	-0.0741317	-0.3256992	0.201776106	0.27285781
End_Use_Res_RPP	-0.048332	0.4293019	0.3369125	1	0.3545857	0.1174542	-0.1936369	0.169126	0.450275052	0.386183161	0.387171136	0.343780688	0.431762608	0.648148142	0.153823749	0.0217117	0.008900184	0.389131171	-0.02955	0.43622678	-0.4979467	0.39213196	-0.11555144	-0.1260874
End_Use_Com_NG	0.744379	0.93633244	0.95937253	0.35458574	1	0.6688753	0.5447185	0.8285179	0.690039591	0.929195083	0.283960823	0.787378711	0.659924819	0.886422263	0.151597429	-0.263533526	-0.311327985	-0.39534148	0.144002	-0.0475679	-0.0086331	-0.3649158	0.156342325	0.31400377
End_Use_Com_RPP	0.8994879	0.81683749	0.62371246	0.11745423	0.6688753	1	0.864744	0.9195858	0.380753933	0.788069565	-0.00618015	0.347286977	0.303144076	0.468831897	0.105068907	-0.346858532	-0.325431525	-0.31894701	-0.07012	-0.127746	0.00792928	-0.440154	0.016921875	0.32747439
End_Use_Ind_NG	0.9621526	0.66353733	0.44968285	-0.1936369	0.5447185	0.864744	1	0.8780148	0.219718486	0.64521057	-0.11137084	0.172180299	0.060073364	0.224021446	0.114027859	-0.385495429	-0.335241537	-0.42711096	-0.09568	-0.3113431	0.20649808	-0.5523542	0.040887778	0.39837376
End_Use_Ind_RPP	0.9591221	0.92153968	0.76580431	0.16912602	0.8285179	0.9195858	0.8780148	1	0.474078955	0.886217454	0.043820634	0.491077828	0.374603448	0.616156046	0.14302481	-0.392289704	-0.369607623	-0.41543906	-0.03439	-0.1541853	0.00744075	-0.4921837	0.040349525	0.33571884
End_Use_Tran_AviFuel	0.3655382	0.7290206	0.63409837	0.45027505	0.6900396	0.3807539	0.2197185	0.474079	1	0.768843473	0.654198096	0.749517464	0.568355135	0.841912273	0.218981916	0.110737632	0.02923873	-0.15924498	0.320939	0.15192016	-0.1049322	0.04489013	0.282824136	0.58037756
End_Use_Tran_Diesel	0.7950582	0.9836734	0.86400454	0.38618316	0.9291951	0.7880696	0.6452106	0.8862175	0.768843473	1	0.363681055	0.725343694	0.577454128	0.870496868	0.139303445	-0.212635361	-0.240834894	-0.37038921	0.159453	-0.0302772	-0.0097183	-0.3228287	0.180335777	0.46098426
End_Use_Tran_HeavyFuelO	-0.028078	0.29635976	0.23251241	0.38717114	0.2839608	-0.00618	-0.1113708	0.0438206	0.654198096	0.363681055	1	0.547108339	0.348097196	0.485225124	-0.14700165	0.245728634	0.180834215	0.070969663	0.287679	0.26726836	-0.0601474	0.3515297	0.246322176	0.56287225
End_Use_Tran_LPG	0.3926783	0.70439786	0.85353189	0.34378069	0.7873787	0.347287	0.1721803	0.4910778	0.749517464	0.725343694	0.547108339	1	0.650456595	0.81483007	0.103203047	0.024416977	-0.082046774	-0.19677697	0.353206	0.11170461	-0.0466869	-0.0417961	0.36204598	0.47660352
End_Use_Tran_Lubricants	0.2588827	0.58061189	0.70760096	0.43176261	0.6599248	0.3031441	0.0600734	0.3746034	0.568355135	0.577454128	0.348097196	0.650456595	1	0.719576497	0.056998828	-0.036691231	-0.110210595	-0.12180892	0.210123	0.14832756	-0.1550517	-0.0605353	0.156754695	0.10970186
End_Use_Tran_Gasoline	0.4477393	0.86752841	0.85840237	0.64814814	0.8864223	0.4688319	0.2240214	0.616156	0.841912273	0.870496868	0.485225124	0.81483007	0.719576497	1	0.190632158	-0.094033619	-0.153658321	-0.20640943	0.205161	0.13235724	-0.2049965	-0.0945129	0.144603208	0.27344111
End_Use_Tran_NG	0.1397673	0.18511122	0.17854656	0.15382375	0.1515974	0.1050689	0.1140279	0.1430248	0.218981916	0.139303445	-0.14700165	0.103203047	0.056998828	0.190632158	1	0.016986792	0.060205685	0.07651805	-0.00309	0.11425148	-0.2327619	-0.0939545	-0.00937904	0.01975482
EndUseP_Trans_Gasoline	-0.399127	-0.2697675	-0.23595204	0.0217117	-0.263534	-0.346859	-0.3854954	-0.3922897	0.110737632	-0.21263536	0.245728634	0.024416977	-0.03669123	-0.09403362	0.016986792	1	0.916469885	0.222307454	0.68073	0.1604048	0.28639887	0.2858211	0.602131322	0.12497359
EndUseP_Trans_Diesel	-0.37216	-0.28541926	-0.29302511	0.00890018	-0.311328	-0.325432	-0.3352415	-0.3696076	0.02923873	-0.24083489	0.180834215	-0.082046774	-0.11021059	-0.15365832	0.060205685	0.916469885	1	0.183152867	0.720966	0.13553267	0.31868237	0.24870468	0.629309356	0.11008011
EndUseP_Resi_Natural.Gas	-0.458859	-0.33512473	-0.33537413	0.38913117	-0.395341	-0.318947	-0.427111	-0.4154391	-0.15924498	-0.37038921	0.070969663	-0.196776973	-0.12180892	-0.20640943	0.07651805	0.222307454	0.183152867	1	-0.05867	0.54729965	-0.2783111	0.75916609	-0.01146288	-0.1447977
EndUseP_Resi_Oil	-0.032589	0.0870963	0.18055817	-0.0295549	0.1440021	-0.070117	-0.0956788	-0.0343884	0.320939037	0.159453354	0.287678821	0.353205774	0.21012295	0.205161149	-0.00308939	0.680730267	0.720965634	-0.05867086	1	-0.0615589	0.52095698	0.00205483	0.958437973	0.36339426
EndUseP_Ind_NG	-0.269662	-0.00612633	-0.012609	0.43622678	-0.047568	-0.127746	-0.3113431	-0.1541853	0.151920164	-0.03027723	0.267268356	0.111704612	0.148327563	0.132357237	0.114251484	0.160404805	0.135532666	0.547299655	-0.06156	1	-0.4197564	0.57970174	-0.10800542	-0.0140879
EndUseP_Ind_Oil	0.1491697	-0.09695464	-0.0741317	-0.4979467	-0.008633	0.0079293	0.2064981	0.0074407	-0.10493224	-0.00971831	-0.06014741	-0.04668695	-0.15505171	-0.20499647	-0.23276191	0.286398872	0.31868237	-0.27831107	0.520957	-0.4197564	1	-0.3330305	0.552546004	0.23640063
EndUseP_Com_Natural.Gas	-0.563909	-0.32045689	-0.32569916	0.39213196	-0.364916	-0.440154	-0.5523542	-0.4921837	0.044890133	-0.32282871	0.351512972	-0.041796119	-0.0605353	-0.09451291	-0.09395451	0.285821104	0.24870468	0.759166095	0.002055	0.57970174	-0.3330305	1	0.002432888	0.04144356
EndUseP_Com__Oil	0.0847316	0.10900402	0.20177611	-0.1155514	0.1563423	0.0169219	0.0408878	0.0403495	0.28282413	0.180335777	0.246322176	0.36204598	0.156754695	0.144603208	-0.00937904	0.602131322	0.629309356	-0.01146288	0.958438	-0.1080054	0.552546	0.00243289	1	0.46457714
ElecGen_Bio_Geo	0.3943641	0.38389314	0.27285781	-0.1260874	0.3140038	0.3274744	0.3983738	0.3357188	0.580377558	0.460984263	0.562872255	0.476603522	0.109701858	0.273441108	0.019754815	0.124973586	0.110080108	-0.14479768	0.363394	-0.0140879	0.23640063	0.04144356	0.464577137	1
ElecGen_NG	0.9676607	0.75867117	0.63865031	-0.0421884	0.6850162	0.858112	0.9274928	0.9285034	0.245937838	0.724617174	-0.13162134	0.346301646	0.203876834	0.383258438	0.124405181	-0.43448508	-0.385358033	-0.42795633	-0.06474	-0.3035533	0.10904443	-0.5775927	0.059979035	0.28511169
ElecGen_Oil	-0.311026	-0.27595517	-0.29085874	0.05601769	-0.383058	-0.182475	-0.2622437	-0.2515345	-0.25753222	-0.34547554	-0.21278452	-0.271054848	-0.16702472	-0.26956744	0.270787869	0.145547223	0.187696166	0.306137126	-0.12541	0.39894539	-0.4833154	0.24802505	-0.15323537	-0.186672
ElecGen_Solar	0.2076695	0.46377524	0.66499795	0.24231848	0.5818277	0.2285337	0.0102735	0.3163519	0.435768445	0.442534035	0.205690774	0.571482869	0.674411619	0.602883048	0.01705974	-0.091073699	-0.165557831	-0.17124234	0.245647	-0.0483035	-0.1959633	-0.2100012	0.206238548	0.02313751
ElecGen_Wind	0.3488432	0.57810885	0.53575386	0.24770082	0.5756888	0.3502218	0.2235667	0.4393642	0.641400951	0.582153157	0.173414467	0.412642897	0.46727026	0.652952984	0.267551403	-0.174515253	-0.193191305	-0.2476873	0.172221	-0.1506631	-0.1536724	-0.2430751	0.136452496	0.18218508
COP.Total	0.881437	0.48281246	0.26494751	-0.3136849	0.3650861	0.760363	0.9665503	0.7613037	0.016456349	0.452171427	-0.25803599	-0.037942494	-0.09902889	0.012303476	0.117677772	-0.382668888	-0.313696139	-0.40312647	-0.18471	-0.3562943	0.2093536	-0.5707979	-0.0424022	0.26343339
NGP.Total	0.800299	0.48399212	0.25869347	-0.3422974	0.3381609	0.7364417	0.8888095	0.7087768	0.179816204	0.488619497	-0.03654954	0.107013304	-0.0707882	0.04211306	0.005802738	-0.261051519	-0.24164062	-0.3427649	-0.06209	-0.217539	0.27385004	-0.3792916	0.089003461	0.5435427
Brent	-0.029718	0.00922674	-0.00681557	0.10004503	-0.034016	0.0656391	-0.0285667	-0.0038989	-0.02167133	0.036290166	0.084628401	0.053447598	0.026845642	-0.00734782	-0.0778359	0.706221407	0.701440683	0.164817059	0.566647	0.0773606	0.39048837	0.0399077	0.532121109	0.02472522
CanLightSweet	-0.032141	0.00917869	-0.00666367	0.10631337	-0.033691	0.0562205	-0.0307631	-0.003808	-0.02392531	0.033863919	0.089759877	0.054067396	0.012127775	-0.00661495	-0.08454373	0.685818575	0.689801043	0.171221645	0.548653	0.1163643	0.36973035	0.06240979	0.517270852	0.02081205
HenryHub	-0.061857	0.00410728	-0.00448163	0.18610032	0.0008971	0.0056367	-0.0671365	-0.0117549	-0.03968822	-0.02321759	0.142890881	0.030913481	0.070316423	-0.01404597	-0.12552307	0.168653951	0.169686176	0.302146585	-0.03979	0.7094941	-0.0638418	0.31661899	-0.06940202	-0.070822
NovaInventoryTransfer	-0.064336	0.00073226	-0.00674289	0.191944	-0.002123	0.0112607	-0.0701163	-0.0131134	-0.05791268	-0.02322998	0.145175225	0.028510511	0.056873284	-0.01893295	-0.13085041	0.165285447	0.161450741	0.319442317	-0.05582	0.70770305	-0.0719495	0.32226689	-0.08597606	-0.0666077
WTI	-0.040278	0.00837283	-0.00774288	0.12800546	-0.032776	0.0561783	-0.039721	-0.0065775	-0.03196918	0.028338326	0.110721098	0.05399102	0.026051425	-0.00941226	-0.10051242	0.664281329	0.663389572	0.209878658	0.502212	0.2121177	0.33770289	0.10104268	0.469098121	0.0094169
WesternCanSelect	-0.038096	0.00575554	-0.00905926	0.11814195	-0.0365	0.0541953	-0.0369739	-0.007674	-0.04243799	0.03054241	0.108067366	0.054290132	0.008437782	-0.00918492	-0.09475412	0.621023246	0.619586618	0.192180749	0.480446	0.14260364	0.32340282	0.07644625	0.45421131	0.00720126
EleCap_Pfuel_NG	0.8042832	0.87471513	0.93124306	0.2126072	0.9127059	0.7256488	0.6276318	0.8583606	0.51165791	0.843050099	0.09943247	0.70585975	0.597418812	0.740179516	0.157600116	-0.337050449	-0.358807636	-0.39064303	0.110647	-0.1768199	-0.0381172	-0.4744904	0.163862781	0.2374949
EleCap_Pfuel_Oil	-0.375791	-0.23677478	-0.32878507	0.27084623	-0.371643	-0.214871	-0.3357981	-0.2589119	-0.22318553	-0.30164269	-0.01007756	-0.288352907	-0.10544768	-0.16390921	-0.02434678	0.077460577	0.20980351	0.143292518	-0.09928	0.2552376	-0.5442183	0.25567032	-0.20862593	-0.2356763
GHG.emissions_O.G_Inventory	0.9097943	0.55044741	0.33456715	-0.2975359	0.4276972	0.8207699	0.9791378	0.8091091	0.08410672	0.5357556	-0.18905919	0.057544445	-0.04151061	0.078100645	0.011258769	-0.376033909	-0.326382002	-0.40846912	-0.14392	-0.3188902	0.25779272	-0.5426757	0.0065188	0.35424787
GHG.emissions_PRI_Inventory	0.6424402	0.86813691	0.79694771	0.56712439	0.8112755	0.66578	0.475858	0.7933097	0.496165894	0.807985756	0.123880547	0.58545223	0.523414508	0.783914594	0.232808077	-0.282809167	-0.242633957	-0.24080178	-0.02517	0.11636761	-0.3183992	-0.2477016	-0.04584526	0.10102317
GHG.emissions_OGE_Inventory	0.9020759	0.53320401	0.30447371	-0.2905532	0.3935987	0.8121722	0.9833354	0.793295	0.093362263	0.51137043	-0.17573965	0.038724191	-0.06394141	0.057768719	0.092660202	-0.370772874	-0.309387426	-0.37317481	-0.13839	-0.3167133	0.22351284	-0.5147073	0.013642964	0.3805561

	ElecGen_NG	ElecGen_Oil	ElecGen_Solar	ElecGen_Wind	COP.Total	NGP.Total	Brent	CanLight Sweet	HenryHub	NovaInventoryTransfer	WTI	Western CanSelect	EleCap_Pfuel_NG	EleCap_Pfuel_Oil	GHG.emissions_O.G_Inventory	GHG.emissions_PRI_Inventory	GHG.emissions_OGE_Inventory
PED_NG	0.9676607	-0.311026	0.2076695	0.3488432	0.881437	0.800299	-0.029718	-0.032141	-0.061857	-0.064336	-0.040278	-0.038096	0.804283182	-0.3757911	0.90979426	0.642440175	0.90207588
PED_RPP	0.7586712	-0.275955	0.4637752	0.5781089	0.4828125	0.4839921	0.0092267	0.0091787	0.0041073	0.0007323	0.0083728	0.0057555	0.874715131	-0.23677478	0.55044741	0.868136906	0.533204007
End_Use_Res_NG	0.6386503	-0.290859	0.6649979	0.5357539	0.2649475	0.2586935	-0.006816	-0.006664	-0.004482	-0.006743	-0.007743	-0.009059	0.931243063	-0.32878507	0.334567155	0.796947706	0.304473714
End_Use_Res_RPP	-0.042188	0.0560177	0.2423185	0.2477008	-0.313685	-0.342297	0.100045	0.1063134	0.1861003	0.191944	0.1280055	0.118142	0.212607196	0.270846234	-0.297535889	0.567124393	-0.290553247
End_Use_Com_NG	0.6850162	-0.383058	0.5818277	0.5756888	0.3650861	0.3381609	-0.034016	-0.033691	0.0008971	-0.002123	-0.032776	-0.0365	0.912705906	-0.371643	0.427697181	0.811275527	0.393598702
End_Use_Com_RPP	0.858112	-0.182475	0.2285337	0.3502218	0.760363	0.7364417	0.0656391	0.0562205	0.0056367	0.0112607	0.0561783	0.0541953	0.725648813	-0.21487141	0.820769854	0.665779965	0.812172238
End_Use_Ind_NG	0.9274928	-0.262244	0.0102735	0.2235667	0.9665503	0.8888095	-0.028567	-0.030763	-0.067136	-0.070116	-0.039721	-0.036974	0.627631834	-0.33579806	0.979137756	0.475857966	0.983335438
End_Use_Ind_RPP	0.9285034	-0.251534	0.3163519	0.4393642	0.7613037	0.7087768	-0.003899	-0.003808	-0.011755	-0.013113	-0.006577	-0.007674	0.858360615	-0.25891187	0.809109096	0.79330966	0.793294984
End_Use_Tran_AviFuel	0.2459378	-0.257532	0.4357684	0.641401	0.0164563	0.1798162	-0.021671	-0.023925	-0.039688	-0.057913	-0.031969	-0.042438	0.511657911	-0.22318553	0.08410672	0.496165894	0.093362263
End_Use_Tran_Diesel	0.7246172	-0.345476	0.442534	0.5821532	0.4521714	0.4886195	0.0362902	0.0338639	-0.023218	-0.02323	0.0283383	0.0305424	0.843050099	-0.30164269	0.5357556	0.807985756	0.51137043
End_Use_Tran_HeavyFuelO	-0.131621	-0.212785	0.2056908	0.1734145	-0.258036	-0.03655	0.0846284	0.0897599	0.1428909	0.1451752	0.1107211	0.1080674	0.09943247	-0.01007756	-0.189059191	0.123880547	-0.175739651
End_Use_Tran_LPG	0.3463016	-0.271055	0.5714829	0.4126429	-0.037942	0.1070133	0.0534476	0.0540674	0.0309135	0.0285105	0.053991	0.0542901	0.70585975	-0.28835291	0.057544445	0.58545223	0.038724191
End_Use_Tran_Lubricants	0.2038768	-0.167025	0.6744116	0.4672703	-0.099029	-0.070788	0.0268456	0.0121278	0.0703164	0.0588733	0.0260514	0.0084378	0.597418812	-0.10544768	-0.04151061	0.523414508	-0.063941406
End_Use_Tran_Gasoline	0.3832584	-0.269567	0.602883	0.652953	0.0123035	0.0421131	-0.007348	-0.006615	-0.014046	-0.018933	-0.009412	-0.009185	0.740179516	-0.16390921	0.078100645	0.783914594	0.057768719
End_Use_Tran_NG	0.1244052	0.2707879	0.0170597	0.2675514	0.1176778	0.0058027	-0.077836	-0.084544	-0.125523	-0.13085	-0.100512	-0.094754	0.157600116	-0.02434678	0.011258769	0.232808077	0.092660202
EndUseP_Trans_Gasoline	-0.434485	0.1455472	-0.091074	-0.174515	-0.382669	-0.261052	0.7062214	0.6858186	0.168654	0.1652854	0.6642813	0.6210232	-0.33705045	0.077460577	-0.376033909	-0.282809167	-0.370772874
EndUseP_Trans_Diesel	-0.385358	0.1876962	-0.165558	-0.193191	-0.313696	-0.241641	0.7014407	0.689801	0.1696862	0.1614507	0.6633896	0.6195866	-0.35880764	0.20980351	-0.326382002	-0.242633957	-0.309387426
EndUseP_Resi_Natural.Gas	-0.427956	0.3061371	-0.171242	-0.247687	-0.403126	-0.342765	0.1648171	0.1712216	0.3021466	0.3194423	0.2098787	0.1921807	-0.39064303	0.143292518	-0.40846912	-0.240801776	-0.373174807
EndUseP_Resi_Oil	-0.064737	-0.125411	0.2456473	0.1722206	-0.184713	-0.062093	0.5666469	0.5486525	-0.039791	-0.055822	0.5022118	0.4804463	0.110646937	-0.09927523	-0.14391552	-0.025174591	-0.138390113
EndUseP_Ind_NG	-0.303553	0.3989454	-0.048304	-0.150663	-0.356294	-0.217539	0.0773161	0.1163634	0.7094941	0.707703	0.2121118	0.1426036	-0.1768199	0.255237597	-0.3188902	0.116367613	-0.316713274
EndUseP_Ind_Oil	0.1090444	-0.483315	-0.195963	-0.153672	0.2093536	0.27385	0.3904884	0.3697303	-0.063842	-0.071949	0.3377029	0.3234028	-0.03811724	-0.54421827	0.257792717	-0.318399151	0.223512841
EndUseP_Com_Natural.Gas	-0.577593	0.2480251	-0.210001	-0.243075	-0.570798	-0.379292	0.0399077	0.0624098	0.316619	0.3222669	0.1010427	0.0764463	-0.47449043	0.25567032	-0.542675723	-0.247701583	-0.514707324
EndUseP_Com__Oil	0.059979	-0.153235	0.2062385	0.1364525	-0.042402	0.0890035	0.5321211	0.5172709	-0.069402	-0.085976	0.4690981	0.4542113	0.163862781	-0.20862593	0.0065188	-0.045845265	0.013642964
ElecGen_Bio_Geo	0.2851117	-0.186672	0.0231375	0.1821851	0.2634334	0.5435427	0.0247252	0.0208121	-0.070822	-0.066608	0.0094169	0.0072013	0.237494901	-0.23567628	0.354247871	0.101023172	0.380556103
ElecGen_NG	1	-0.253612	0.1921629	0.2883534	0.8702406	0.733796	-0.029761	-0.035978	-0.103248	-0.102853	-0.050299	-0.044195	0.802511123	-0.3124396	0.881326945	0.649898682	0.874710019
ElecGen_Oil	-0.253612	1	-0.079925	-0.171502	-0.196781	-0.214133	0.0500513	0.061884	0.2110667	0.2179245	0.0905593	0.0717463	-0.28212283	0.664893425	-0.233858118	-0.011970957	-0.201523968
ElecGen_Solar	0.1921629	-0.079925	1	0.703403	-0.111401	-0.154325	-0.11324	-0.119821	-0.1794	-0.18763	-0.140891	-0.137152	0.672289779	-0.0757029	-0.089684918	0.367355266	-0.102352333
ElecGen_Wind	0.2883534	-0.171502	0.703403	1	0.0977702	0.0434898	-0.248505	-0.257318	-0.361713	-0.377804	-0.300431	-0.282987	0.59450856	-0.15947345	0.099775876	0.387764491	0.110347225
COP.Total	0.8702406	-0.196781	-0.111401	0.0977702	1	0.8592709	-0.049514	-0.052679	-0.075134	-0.079403	-0.061012	-0.05887	0.488696113	-0.28733665	0.971982816	0.3340922	0.982672695
NGP.Total	0.733796	-0.214133	-0.154325	0.0434898	0.8592709	1	-0.017008	-0.016306	0.0156811	0.0144243	-0.01336	-0.016707	0.382768001	-0.33736376	0.912581833	0.229820017	0.919592233
Brent	-0.029761	0.0500513	-0.11324	-0.248505	-0.049514	-0.017008	1	0.9852574	0.3051909	0.3310128	0.9745038	0.9595972	-0.04519333	0.021243912	0.000859916	0.055128316	-0.022698121
CanLightSweet	-0.035978	0.061884	-0.119821	-0.257318	-0.052679	-0.016306	0.9852574	1	0.3646746	0.3837934	0.9844981	0.9781877	-0.04912469	0.025637009	0.000374762	0.058460171	-0.024570354
HenryHub	-0.103248	0.2110667	-0.1794	-0.361713	-0.075134	0.0156811	0.3051909	0.3646746	1	0.9884192	0.4732017	0.3752591	-0.11546274	0.082935681	-0.020916028	0.104256614	-0.054599584
NovaInventoryTransfer	-0.102853	0.2179245	-0.18763	-0.377804	-0.079403	0.0144243	0.3310128	0.3837934	0.9884192	1	0.4932057	0.4012311	-0.11762523	0.08384401	-0.022042419	0.10874951	-0.056662882
WTI	-0.050299	0.0905593	-0.140891	-0.300431	-0.061012	-0.01336	0.9745038	0.9844981	0.4732017	0.4932057	1	0.9759624	-0.06404688	0.037922211	-0.00330755	0.071043768	-0.031598333
WesternCanSelect	-0.044195	0.0717463	-0.137152	-0.282987	-0.05887	-0.016707	0.9595972	0.9781877	0.3752591	0.4012311	0.9759624	1	-0.05468533	0.034447766	-0.002767792	0.065469923	-0.028637991
EleCap_Pfuel_NG	0.8025111	-0.282123	0.6722898	0.5945086	0.4886961	0.382768	-0.045193	-0.049125	-0.115463	-0.117625	-0.064047	-0.054685	1	-0.3224859	0.522844213	0.767881631	0.503473869
EleCap_Pfuel_Oil	-0.31244	0.6648934	-0.075703	-0.159473	-0.287337	-0.337364	0.0212439	0.025637	0.0829357	0.083844	0.0379222	0.0344478	-0.3224859	1	-0.327874801	0.115515243	-0.295028058
GHG.emissions_O.G_Inventory	0.8813269	-0.233858	-0.089685	0.0997759	0.9719828	0.9125818	0.0008599	0.0003748	-0.020916	-0.022042	-0.003308	-0.002768	0.522844213	-0.3278748	1	0.376702156	0.986241321
GHG.emissions_PRI_Inventory	0.6498987	-0.011971	0.3673553	0.3877645	0.3340922	0.22982	0.0551283	0.0584602	0.1042566	0.1087495	0.0710438	0.0654699	0.767881631	0.115515243	0.376702156	1	0.351148835
GHG.emissions_OGE_Inventory	0.87471	-0.201524	-0.102352	0.1103472	0.9826727	0.9195922	-0.022698	-0.02457	-0.0546	-0.056663	-0.031598	-0.028638	0.503473869	-0.29502806	0.986241321	0.351148835	1