Entry of the Electrolytic Ammonia Industry: Incentives and Effects

by

Carlo James Cunanan

A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Applied Science
in
Chemical Engineering

Waterloo, Ontario, Canada, 2024

Author’s Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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

Statement of Contributions

Chapter 3 of this thesis, titled, “Cost Benefit Analysis of Canadian Grid-Based Power-to-Ammonia Production across Provinces”, is adapted from part of a draft manuscript being prepared by myself and an undergraduate research assistant (Milind Jain). Milind Jain helped me with analyzing results and preparing the manuscript. XiaoYu Wu and Alain-Désiré Nimubona initiated the project and are providing guidance with the manuscript.

Chapter 4 of this thesis, titled, “Incentives and Effects of Green Ammonia Production” is adapted from part of a draft manuscript being prepared by myself under the guidance of XiaoYu Wu and Alain-Désiré Nimubona.

Abstract

Ammonia is an essential chemical to agriculture because of its tremendous positive impact on plant nitrogen uptake. Furthermore, due to its possible use as a hydrogen energy vector, ammonia is being considered as a method for green energy storage for the hydrogen economy. Ammonia production is traditionally a carbon-intensive process due to using natural gas as a feedstock. However, efforts are being made to reduce its carbon footprint through methods such as electrolysis, which uses water as the feedstock for hydrogen rather than natural gas. This thesis uses engineering and economics techniques to evaluate the viability and economics associated with producing and using electrolytic ammonia in Canada's food and energy sectors.

The first contribution concerns grid electrolytic power to ammonia systems in Canada across provinces. The objective of this research was to analyze the viability of grid-powered electrolytic ammonia in Canada. Using the concept of levelized cost of ammonia (LCOA), three processes were compared: The conventional process (P1), the conventional with CCS process (P2), and the grid electrolytic ammonia process (P3). The processes were compared across the ten provinces, and they were compared with different grid emissions, costs, and natural gas costs. These were also compared across two forecasted policies: Current Measures (CM) and Canada Net Zero (CNZ). The findings estimate that P3 costs 450-650 CAD more per tonne than conventional methods, while P2 costs about 200 CAD more. However, when considering the SCC, P3 can be competitive with P1, showing how adding environmental damages can change estimations. Each province has different production costs because of varying grid emissions and power prices, with P2 being the most cost-efficient way to cut down on carbon in Canadian ammonia production for most of the provinces. AB and SK are the best provinces for P2, while MB and QB are the best for P3. Lowering grid emissions and costs is essential to the viability of electrolytic grid-based ammonia. Future work to introduce learning curves, better costing methods, and other possible externalities should be performed.

The second contribution for this thesis is about the incentives and effects of green ammonia production. The model used in this chapter uses Cournot modeling of oligopolies and two firms as the baseline to model how green ammonia production may interact with a conventional industry already in place. The objective was to determine how social welfare can be maximized in the ammonia industry using policy instruments. The analysis reveals that the marginal costs of production in one industry have a notable impact on the output quantities of both industries. Furthermore, social welfare is affected by production costs, taxes, the social cost of carbon, demand changes, the number of firms, capacity limits, and subsidies. Taxes and subsidies can help shift quantities from more polluting firms to less polluting firms. This chapter found that the best tax was to have no tax for conventional ammonia for the industry. The no tax policy was optimal because the social cost was relatively low. Instead, subsidies should be in place to promote green ammonia. Future work should be done using other oligopoly models, more realistic costing and demand functions, and making the analysis time-dependent.

Reducing greenhouse gas emissions in the ammonia industry and increasing electrolytic ammonia uptake requires many conditions. Technological advancements must be made to reduce the production costs of electrolytic ammonia. The advancements include decreasing electricity costs and grid emission intensity, which affect social costs. Policies to increase conventional ammonia may work to make electrolytic ammonia more competitive. Carbon capture and storage (CCS) is the best option for ammonia production in most provinces due to low emissions and low costs. The government can help subsidize electrolytic ammonia production and plant building to alleviate the costs. Subsidies can allow easier entry for electrolytic ammonia firms. Taxes and subsidies can help shift markets from high emission intensity to low emissions intensities. With the numerical analysis, subsidy only is estimated to be the best policy for this industry without a carbon tax.

Acknowledgments

This thesis has been a journey; completing it would not have been possible without the support of many people.

First and foremost, I thank **Dr. XiaoYu Wu** and **Dr. Alain-Désiré Nimubona**, with whom I have had the honour and privilege of working with for the past two years. They have guided me in engineering and economics to perform this interdisciplinary research. I am grateful for their kindness, attention to detail, passion for the topics, and great encouragement, making this research work possible. I would also like to thank NSERC, the University of Waterloo Interdisciplinary Trailblazer Fund and Chemical Engineering Department, and the Queen Elizabeth II Scholarship in Science & Technology for their funding.

To my committee members, **Dr. Michael Fowler,** and **Dr. Mehrdad Pirnia**. They have helped me make my thesis the best it can be. Special thanks to Dr. Michael Fowler, who was my mentor and has provided me with great advice and opportunities to expand my education and knowledge.

To **Milind Jain,** who was a great help in my cost-benefit analysis section. He is creative and diligent in the field of energy and renewable systems, and I am excited to see what the future holds for him.

To my colleagues in **the Greener Production Group** – especially to **Jinhe, Daniel, Soukaina, Pengcheng, Aamer, Arda, Emily,** and **Joe**. The small Mandarin lessons, board game nights, meals, and laughs we have shared have been bright lights in the dark, gloomy periods that graduate research can sometimes be. I wish them all the best in their future endeavours.

To **Carlos, Mitchell,** and **Connor,** who were great and supportive lab mates and friends throughout my undergraduate and graduate studies. Our camaraderie for the past seven years is something memorable.

To **Migga, Saumay,** and **Andrew**, my fellow colleagues, for the plenty of grad house meals and conversations we have shared. Breaking bread and hanging out with you all was uplifting during my time in graduate school.

To **Kyle, Chris, Chris,** and **Nick,** who are my colleagues and friends. Besides being great friends, they have been fun trivia night partners and NYTimes Mini competitors. Their company was invaluable to me during my time in graduate school.

To **Yasmin,** for the many enriching and funny discussions as office mates. May your PhD go well and smoothly.

To my girlfriend, **Melissa**, who has been a constant beam of love, support, and encouragement throughout much of my undergrad and graduate school life. She has been a great comfort on tough days and an awesome celebrator to share in my successes. Her presence in my life brings me great joy each day.

To my sister, **Ciara**, and the many Starbucks trips and conversations we have had during the long days where we needed that extra caffeine boost. Your support does not go unnoticed.

To my grandmothers, **Trinidad** and **Erlinda,** who have also been supportive and encouraging throughout my research journey. They both raised me when I was young and have continued to be great comforts to me to this day.

To my wonderful parents, **Claro** and **Mary Ann,** who have supported this 7-year post-secondary journey from the start to the finish. I am always motivated by the hard work and perseverance you have displayed throughout your lives from the Philippines to Canada. Their love, support, and belief in me throughout my life have kept me fed and inspired me to continue this research.

Lastly, to **You** reading this. May this shed light, invoke curiosity, and provide knowledge. Or, if not any of those, at least some laughter.

Dedication

This is dedicated to all my teachers in the past and present.

Table of Contents

List of Figures

List of Tables

List of Acronyms

AB	Alberta
AEM	Anion Exchange Membrane
BC	British Columbia
CAD	Canadian Dollars
CAPEX	Capital Expenditures
CCS	Carbon capture and storage
CER	Canada Energy Regulator
CM	Current Measures
CNZ	Canada Net Zero
CRF	Capital Recovery Factor
CSX	Consumer Surplus from Fertilizer
CSZ	Consumer Surplus from Energy Storage
GDP	Global Domestic Product
GHG	Greenhouse gases
GWP	Global Warming Potential
HB	Haber-Bosch
IAM	Integrated Assessment Model
IPCC	Intergovernmental Panel on Climate Change
LCOA	Levelized Cost of Ammonia
MB	Manitoba
MC	Marginal Costs
MEA	Monoethanolamine
MR	Marginal Revenues
NA	Not applicable
NB	New Brunswick
NG	Natural Gas
NL	Newfoundland and Labrador
NS	Nova Scotia
ON	Ontario
OPEX	Operational Expenditures
P1	Process 1
P2	Process 2
P3	Process 3
PEM	Proton Exchange Membrane
ProfG	Profits from Green Ammonia Industry
ProfH	Profits from Conventional Industry
QB	Quebec
R&D	Research and Development

SC	Social Cost
SCC	Social Cost of Carbon
SK	Saskatchewan
SMR	Steam Methane Reforming
SSAS	Solid State Ammonia Synthesis
TR	Tax Revenues
TS	Total Subsidies
UN	United Nations
UP	Urea Production
US	United States
USD	United States Dollar
WGS	Water Gas Shift

List of Symbols

Chapter 3

i	Process type – 1,2, or 3
p	Province
s	Policy scenario – Current Measures or Canada Net Zero
t	Time (year) – 1,2… 25
m	Energy Source
$LCOA$	Levelized Cost of Ammonia (CAD 2022 per tonne of ammonia)
CRF	Capital Recovery Factor (year^{-1})
I	Initial capital investment in (CAD 2022)
CE	Total cost of natural gas and electricity that is used in a year (CAD 2022)
O	Operational expenditures within a year (CAD 2022)
X	Quantity of ammonia (Tonnes)
r	Discount rate
SC	Total social cost from the emissions (CAD)
N	Economic Lifetime (years)
EF	Emission Factor (Tonnes of CO_2e per unit)
$Q_{m,p,t,s}$	Energy capacity of a specific source, province, time, and scenario.

Chapter 4

H	One unit of conventional ammonia (Tonnes)
G	One unit of green ammonia (Tonnes)
G_X	One unit of green ammonia that is used for fertilizer (Tonnes)
Z	One unit of green ammonia that is used for energy storage (Tonnes)
X'	One unit of ammonia that is used for fertilizer (Tonnes)
$\alpha_{X'}$	Y-intercept of demand curve for fertilizer (CAD)
$\beta_{X'}$	Magnitude of the slope of demand curve for fertilizer (CAD/tonne of ammonia)
α_Z	Y-intercept of demand curve for energy storage (CAD)
β_Z	Magnitude of the slope of demand curve for energy storage (CAD/tonne of ammonia)
C_H	Marginal cost of conventional production of ammonia (CAD per tonne of ammonia)
C_G	Marginal cost of green production of ammonia (CAD per tonne of ammonia)
$p(X')$	Price of ammonia as a fertilizer (CAD)
$p(Z)$	Price of ammonia as energy storage (CAD)
τ	Tax rate (CAD/tonne of emissions)
τ^*	Optimal tax rate (CAD/tonne of emissions)
ξ_H	Emission factor of conventional ammonia (Tonne of emissions per tonne of ammonia)
v	Social cost of emissions (CAD/tonne of emissions)
π_H	Profits from conventional ammonia industry (CAD)
π_G	Profits from green ammonia industry (CAD)
$CS_{X'}$	Consumer surplus from fertilizer ammonia (CAD)

CS_Z	Consumer surplus from energy storage ammonia (CAD)
SC	Total social cost from the emissions (CAD)
TR	Total tax revenues (CAD)
W	Social Welfare (CAD)
M	Number of symmetrical conventional firms
N	Number of symmetrical green firms
S_b	Subsidy given to green firm per unit of ammonia (CAD/tonne of ammonia)
S_b^*	Optimal subsidy given to green firm per unit of ammonia (CAD/tonne of ammonia)
$\bar{G}$	Green ammonia capacity (Tonnes)

Quote

“Kung walang tiyaga, walang nilaga”

- Filipino Proverb

“If you don’t persevere, there is no reward.”

Chapter 1 Introduction

1.1 Overview and Motivation

Canada is making many recent efforts to meet net-zero carbon emissions by 2050, and there are many efforts to reduce the carbon footprint of certain industrial processes [1]. Ammonia production is one such industrial process, as it accounts for approximately 1.2% of the global anthropogenic CO_2 emissions [2]. The process presently deployed by many manufacturers uses fossil fuels as feedstock. Therefore, there is motivation to move ammonia production to greener production as the conventional method produces many greenhouse gas emissions.

Although there are other applications in refrigerants and chemical feedstocks, ammonia is mainly used as an essential component in agricultural applications [3]. Ammonia-based nitrogenous chemical fertilizers such as ammonium nitrate, urea, and ammonium sulphate serve to feed approximately 70% of the global population [4]. Nitrogen availability is key to crop productivity as it improves plant development [5]. Consequently, the usage of nitrogen fertilizers is massive despite the negative impacts the emissions can have on local ecosystems and human health [6]. The global production of ammonia is estimated at approximately 150 million metric tonnes and is estimated to increase as the population grows, and potential applications of ammonia may increase [7].

There is also great interest in ammonia as a future energy carrier for a clean hydrogen economy. This is because ammonia has better storage properties than storing hydrogen by itself. A significant problem of hydrogen is that it must either be heavily refrigerated or compressed to be transported easily. This hydrogen storage problem could be solved with ammonia as it carries approximately 17.6 weight percent of hydrogen, has a higher volumetric energy density than hydrogen, and can be used as a fuel directly or cracked back into hydrogen [3].

Presently in Canada, ammonia is conventionally produced carbon-intensively through its hydrogen production via steam-methane reforming (SMR) and the water gas shift reactions [3]. Canadian ammonia production uses natural gas and high-pressure steam as feedstock and produces carbon dioxide and hydrogen. The hydrogen is then further processed with nitrogen at high pressure and temperature within a reactor alongside a catalyst via the Haber-Bosch (HB) process to produce the ammonia [3]. Canada also uses carbon capture technology to recover some carbon from SMR, which can be further used in urea production by combining ammonia and carbon dioxide [8]. However, further carbon capture could be done and possibly used in parallel with carbon storage to prevent further carbon emissions. Unfortunately, urea applications re-release carbon once recovered from SMR [9].

Suppose Canada were to switch the hydrogen production method from SMR to one with greater carbon capture and storage (CCS) or one that uses electrolysis which takes water and electricity as the feedstock. In that case, one can significantly reduce ammonia production's greenhouse gas emissions. The reduction is only possible assuming the energy used in the CCS or electrolysis is significantly less carbon-intensive. The problem is that carbon capture, electrolyzers, and green electricity often come at a higher cost, and an analysis of the techno-economic feasibility of “greener” ammonia in Canada should be performed to provide the most considerable benefit. One must find a way to balance the benefits of emission reductions with the costs that those emission reductions may require.

1.2 Research Objectives

This thesis aims to predict the effect that the entry of an electrolytic ammonia industry would have alongside a present conventional ammonia industry on Canada's fertilizer and energy sectors. An analysis of the emission reductions, the costs, benefits, and economic incentives is also performed.

The first part of the research is a cost-benefit analysis that seeks to analyze Canada’s best course of action regarding electrolytic ammonia production in each province. This part considers the social cost of carbon (SCC), the forecasted costs of electricity and fossil fuels, the emission intensity of each provincial grid, and the production costs of various ammonia technologies. The cost-benefit analysis uses the concept of LCOA and indicates which ammonia production technology is expected to be more suitable for each province.

The second part of the research is a broad economic analysis that uses Cournot modeling and equilibrium analyses to see the incentives and effects various policies, costs, and emissions will have on ammonia production regarding the fertilizer and energy markets. This research aims to analyze how taxation and subsidies, lowering and raising production costs, the rising demands for ammonia, and other circumstances may affect Canadian ammonia production. The concept of social welfare and the way to optimize it with government incentives is the primary focus of this research.

1.3 Thesis outline

The subsequent sections of the thesis are structured as follows: Chapter 2 provides a literature review and the background information for the ammonia economics research, such as the supply-demand concepts, the social cost of carbon, and the various ammonia production technologies. Chapter 3 describes the first part of this research, which pertains to the cost-benefit analysis of grid-based electrolytic ammonia production across the various provinces in Canada. Chapter 4 covers the second part of the research, which is about the economic Cournot analysis that was used to investigate how the government can help achieve the greatest social welfare in the ammonia market. Lastly, Chapter 5 presents the conclusions and overall recommendations of my thesis.

Chapter 2 Introduction

2.1 Fundamentals

2.1.1 Hydrogen

Hydrogen is an elemental gas that naturally occurs diatomically with the chemical formula H_2 [10], [11]. It is the most abundant element in the universe [10]. It is combustible, explosive, and is often stored under pressure. Hydrogen has been seen as a promising energy storage alternative to fossil fuels as it does not release greenhouse gas emissions when used for energy and contains the highest gravimetric energy density of all known substances which is around 120 kJ/g [11]. For comparison, a fuel such as gasoline has around 42-46 kJ/g energy density [12]. However, the disadvantage is that the volumetric energy density is often much lower due to the amount of space hydrogen often takes up [13].

2.1.2 Ammonia

Ammonia is a compound with the chemical formula NH_3 and is a gas at ambient conditions [14]. It is a colorless, poisonous gas with a distinct and pungent odour [14]. Some properties include its boiling point of -33.3 degrees Celsius and its molar mass of 17.03 g/mol. It is often a gas or liquid that is contained under pressure. Ammonia can also cause skin and eye damage and is toxic to both human life and aquatic life.

Most of the ammonia is used presently for fertilizer and agricultural applications. However, since it contains hydrogen and it is easier to store than hydrogen, it has been seen as an excellent potential hydrogen energy vector for the future [15]. However, much research is still required and limitations regarding its safety and efficiency in cracking back into hydrogen must be addressed [16], [17].

2.2 Ammonia Applications

2.2.1 Ammonia as a Fertilizer

Around 70% of the ammonia produced worldwide is used for agricultural applications [18]. Ammonia-based nitrogenous chemical fertilizers such as ammonium nitrate, urea, and ammonium sulphate serve to feed approximately 70% of the global population [4]. Nitrogen is one of the most essential plant nutrients, and ammonia helps bind the nitrogen to plant uptake. Nitrogen availability is a key element in crop productivity as it improves plant development [5]. Consequently, the usage of nitrogen fertilizers is massive despite the negative impacts the emissions can have on local ecosystems and human health [6].

2.2.2 Ammonia in non-fertilizer applications

Ammonia has excellent potential to be a hydrogen energy vector for the transition to a less carbon-intensive economy. Ammonia's potential is because it may have better storage properties that are preferential to storing hydrogen. A difficulty with storing hydrogen is that it must either be heavily refrigerated or compressed to be transported easily. The difficulty in storing hydrogen could be resolved with ammonia as it contains around 17.6 weight percent of hydrogen, has a higher volumetric energy density than hydrogen, and can be used as a fuel directly or cracked back into hydrogen [3]. Some governments, such as Canada, Germany, Korea, and Japan, have already made intentions to include green ammonia as a part of the energy economy in the future [19], [20].

Some limitations include possible pollution and leakage and the safety guidelines that must be addressed with ammonia being an energy carrier as it is toxic [21]. An ongoing debate exists on ammonia's hydrogen carrier potential due to low energy efficiency and safety regarding toxicity [16], [17]. However, since ammonia has had a history of being handled and stored for over 100 years, there is already precedence that it can be handled safely [22].

Other applications for ammonia presently are as a refrigerant gas in air conditioning equipment [21]. Ammonia is also a building block in manufacturing explosives, plastics, fabrics, cleaning products, and other applications [21].

2.3 Ammonia Production Methods

2.3.1 Conventional

The conventional process of producing ammonia can often be split into two steps: hydrogen generation and ammonia synthesis. Hydrogen generation is often the most carbon-intensive step [2]. Conventional hydrogen generation uses fossil fuels such as oil, coal, or natural gas. In Canada, only hydrogen produced from natural gas is used in ammonia production [23], using a conventional way through the steam methane reforming (SMR) of natural gas. This process takes steam at a high temperature and pressure with methane and produces carbon monoxide and hydrogen in the presence of a catalyst [24]. The SMR reaction is depicted in Equation (1).

$$CH_4 + H_2O \rightarrow CO + 3H_2 \tag{1}$$

A subsequent water gas shift (WGS) reaction then occurs with carbon monoxide, which produces carbon dioxide and hydrogen in the presence of a catalyst [24]. The WGS reaction is shown in Equation (2). The WGS reaction is the primary reaction that produces carbon dioxide.

$$CO + H_2O \rightarrow CO_2 + H_2 \tag{2}$$

The ammonia synthesis occurs downstream of the hydrogen production process when nitrogen gas and hydrogen gas react at a high temperature and pressure to produce ammonia. Ammonia synthesis is done in a reactor and in the presence of a catalyst, often composed of iron oxide or ruthenium nowadays [3]. The overall reaction is depicted below in Equation (3).

$$N_2 + 3H_2 \rightarrow 2NH_3 \tag{3}$$

A highly optimized methane-fed process emits around 1.5 to 1.6 tons of CO_2 per tonne of ammonia while the actual global average is around 2.4 tons of CO_2 per tonne of ammonia production due to the significant use of coal [2], [18]. In Canada, part of the carbon dioxide emissions is captured for downstream urea production, so on average, less CO_2 per tonne of ammonia is produced, with some estimates indicating around 0.91 to 1.11 metric tonnes of CO_2 emissions per tonne of ammonia produced [23]. CO_2 is utilized in tandem with ammonia to form urea, which reduces the amount of CO_2 emitted. Urea production (UP) often consumes a significant proportion of the ammonia produced within a factory. Figure 2.1 is a flowsheet of a typical conventional ammonia production process alongside urea production. However, other downstream products can be made with ammonia that are not present in this flowsheet such as ammonium nitrate and ammonium sulphate.

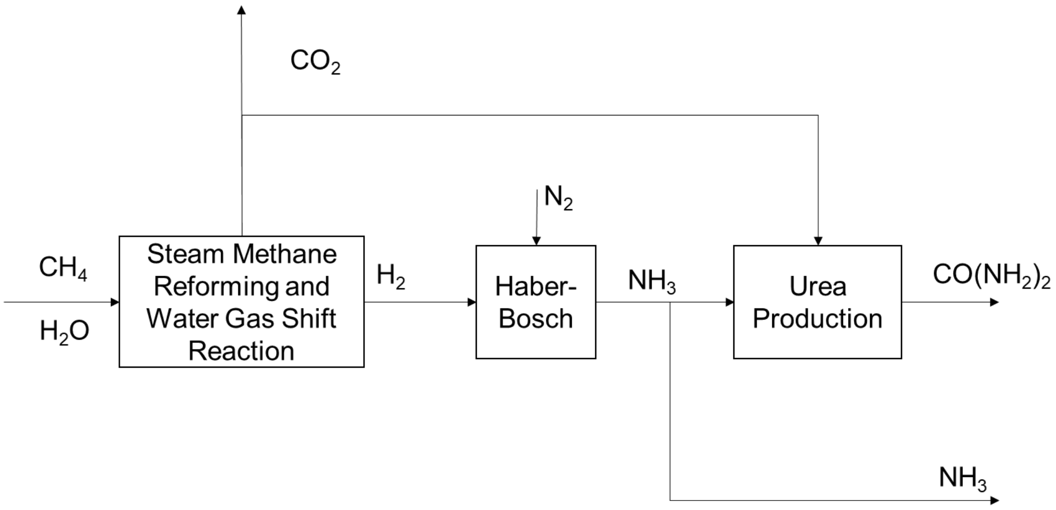


Figure 2.1 Flowsheet of a typical ammonia production facility with urea production

2.3.2 Electrolysis

One of the greener processes proposed to produce ammonia involves generating hydrogen through electrolysis. Electrolysis is a process by which water is consumed with an electricity input to produce hydrogen and oxygen as an output [25]. The overall reaction is depicted in Equation (4).

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2 \tag{4}$$

With this method, the ammonia will still be produced using the traditional HB reactor through Equation (3), but with hydrogen produced using electrolysis. This type of ammonia is often known as green ammonia as it has the potential to be zero emissions if the hydrogen and electricity are made in a carbon-free way.

Electrolysis can occur through various systems such as proton exchange membranes (PEM) or anion exchange membranes (AEMs), which differ in the materials and conditions but have the same overall reactions [25]. Electrolyzer development has been seen as a critical step in the evolution of the hydrogen economy [26]. Finding an alternative route to produce hydrogen has been seen at the forefront of many green ammonia proposals since hydrogen is the most carbon-intensive step.

The energy from electricity required from green ammonia is predicted to be around 37.4 GJ/ tonne of ammonia [3]. However, other studies suggest that the number could be higher, such as 41.76 GJ/tonne [27] or 50 GJ/tonne [28]. There is room for improvement, and it depends on the assumptions and methods used to develop the process. For the production to be completely zero-emission, the electricity taken must be from zero-emission sources such as wind, hydro, or solar, which must be manufactured or constructed in a zero-emission way. Zero-emission ammonia is presently not technically available in any provincial grid, so dedicated renewables must be created for entirely zero-emission ammonia production.

2.3.3 Blue hydrogen and ammonia

Blue ammonia is produced using fossil fuel sources as a feedstock with a carbon capture and utilization or storage component to recover the carbon produced [29]. The term “blue” is often ambiguous as there is no standard for how much carbon must be recovered to receive the name “blue.” Technically, all of Canada’s ammonia production facilities use carbon capture technology and utilizes the carbon in urea production - except for one facility in Joffre, which does not make its hydrogen [8]. Canada’s ammonia production could be attributed to being “blue” ammonia as the facilities recover and utilize the carbon in urea. The amount recovered from process emissions is around 61% [8]. Unfortunately, the urea often breaks down and releases carbon dioxide into the atmosphere when applied to the farmland [9]. Hence, even though carbon is recovered, it merely delays the time some of it is released into the atmosphere. Blue hydrogen and ammonia are often considered a transitional solution between conventional and green hydrogen and ammonia production [30]. Blue ammonia is considered a transition solution is because it reduces greenhouse gas emissions without significantly changing fossil fuel usage and the resulting supply chains.

2.3.4 Other methods of producing ammonia

Other ways can be utilized to produce ammonia.

Firstly, some methods merely change the hydrogen production method and make it less carbon intensive while still using the HB process described in previous sections. The electrolytic method that is analyzed in this thesis is precisely that. Instead of using SMR to produce hydrogen, which is often carbon-intensive, electrolysis is used to produce the hydrogen. There are also biochemical, thermochemical, and photonic methods of producing hydrogen that can be used [7]. There are also ways to recover hydrogen from other industrial processes, such as using it for the hydrogen economy instead of directly producing it for ammonia. These are outside the scope of this report.

Secondly, another method is to use alternatives to the Haber-Bosch process and change the ammonia production completely. Due to the extreme conditions that Haber-Bosch requires, there are often notions that there are ways to directly produce ammonia from nitrogen in the air and water in the presence of a catalyst and electricity. An example overall reaction [31] is presented below:

$$N_2 + 3H_2O \rightarrow 2NH_3 + \frac{3}{2}O_2 \tag{5}$$

This equation represents Solid State Ammonia Synthesis (SSAS), where steam and nitrogen use a solid-state proton conducting cell to produce ammonia and oxygen and can be operated at temperatures below 400 ºC [31]. However, there are difficulties in the electrochemical approach as it often has low catalytic activity at the cathodic electrode and low protonic conductivity of the cell [31]. Most of the electrochemical ammonia synthesis routes for green ammonia are in the early stages of research and development [32] and, therefore, are outside of the scope.

2.4 Ammonia Supply and Demand

2.4.1 Global supply and demand

At the time of writing, the global production of ammonia is estimated at approximately 235 million metric tonnes and is estimated to increase significantly as the population grows and potential applications of ammonia may increase [7]. The demand for ammonia may significantly grow, with the potential of double or triple the total amount of ammonia in 2050, due to the hydrogen economy as the world transitions to reduce greenhouse gases (GHG) [18]. China is presently the top ammonia producer at around 42 million metric tonnes annually [33]. Russia, the United States, and India are the next most significant ammonia producers [33].

2.4.2 Canada Supply

From 2015 to 2022, Canada produced around 4.690 million tonnes of ammonia on average across nine different facilities [34]. Canadian production is around 80-90% of the predicted capacity of around 5.5 million tonnes of ammonia [35]. Six of the facilities can be found in Alberta. The other three are in Saskatchewan, Manitoba, and Ontario, respectively. Figure 2.2 shows the proportion of ammonia production each province has relative to each other in Canada. Figure 2.3 shows the locations and companies that run the nine facilities and their estimated capacities [35]. Please note that in Figure 2.3, Nutrien's Redwater and Fort Saskatchewan plants are so close together that Fort Saskatchewan’s facility is not seen.

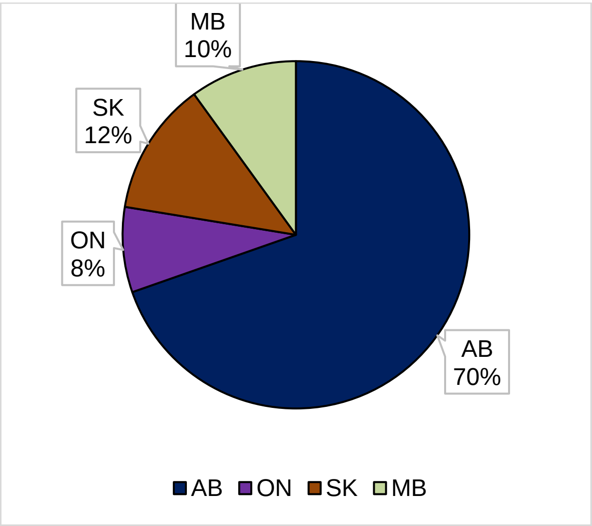


Figure 2.2 Ammonia Production Capacity Proportions by Province in 2022 [35]

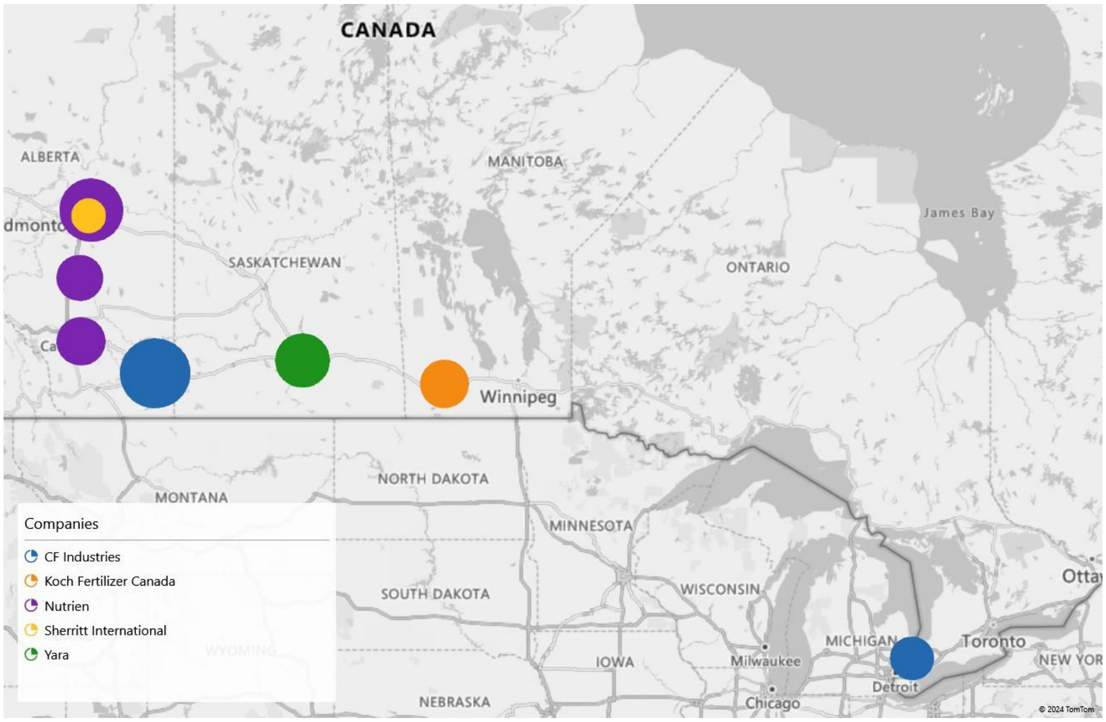


Figure 2.3 Map of the locations and relative capacities of the Ammonia Plants in Canada [35]

Canadian facilities mainly use SMR as the production method, which would require around 2.627 million kg of methane and 5.903 million tonnes of water, assuming a 65% SMR efficiency to produce the basis amount of ammonia [30]. This is true except for the Nutrien Joffre facility, which uses a neighboring industrial facility and buys hydrogen from them [36]. The ammonia facilities would result in around 7.671 million tonnes of carbon dioxide using a mass balance. However, in Canada, some of the CO_2 is used by urea production, so around 5.953 million kg of CO_2 is emitted to the atmosphere. The carbon dioxide emission calculations result in a carbon dioxide to ammonia mass ratio of around 1.27. The ratio is similar to what is reported in the Greenhouse Gas Reporting Program (GHGRP), which averaged around 1.33 between 2015-2022 [37]. A 2004 Benchmarking report that uses 2000-2002 data by the Canadian Fertilizer Institute stated that the ratio was around 1.07 [23], while a similar 2023 study states that the average net emissions was around 1.2 [8]. For comparison, this ratio is around 30% lower than what is presented in the United States (US) and 52% less than China using gas as a feedstock [8].

2.4.3 Canadian Demand

Ammonia produced in Canada mainly goes into two places: fertilizers and exports to the US. In 2019, over 70% of the ammonia produced in Canada acted as feedstock for making more fertilizers [34]. These ammonia-based fertilizers enter the Canadian agricultural market and are exported from Canada. Around 20% of the ammonia produced went into anhydrous ammonia exports to other countries (only the United States) [38]. An average of around 1 million tonnes were exported between 2015 to 2022 from Canada to the United States [39]. The remaining ammonia is used directly as ammonia in the fertilizer market.

Canada imports around 1 million tonnes of nitrogen fertilizers on a per-nutrient basis of nitrogen [40]. On a per-nutrient basis, Canada exports around 1.7 million tonnes of nitrogen fertilizers [40]. However, the Western and Eastern parts of Canada regionally paint different pictures. Western Canada is a net exporter of nitrogen-based fertilizers, while Eastern Canada is a net importer of nitrogen-based fertilizers [40].

There has been an increase in demand for ammonia – specifically green ammonia - from Canada as an export. For example, Germany signed an agreement with Canada that Canada would send renewable ammonia from Nova Scotia at a rate of over 500,000 tonnes per year starting in early 2025 [19]. The renewable ammonia will mainly be powered by onshore wind and a green grid. There are also specific changes in demand that can be realized if the hydrogen economy becomes more prevalent in the energy and transportation sectors.

Figure 2.4 shows a Sankey diagram of the inputs and outputs of ammonia and sums up all the data from the supply and demand. An SMR efficiency of 65% [41] and an HB process of 97% overall conversion was assumed [3]. Furthermore, the data was compiled from Statistics Canada from Fertilizer Shipment surveys observing the years from 2015 to 2022 [34], [39].

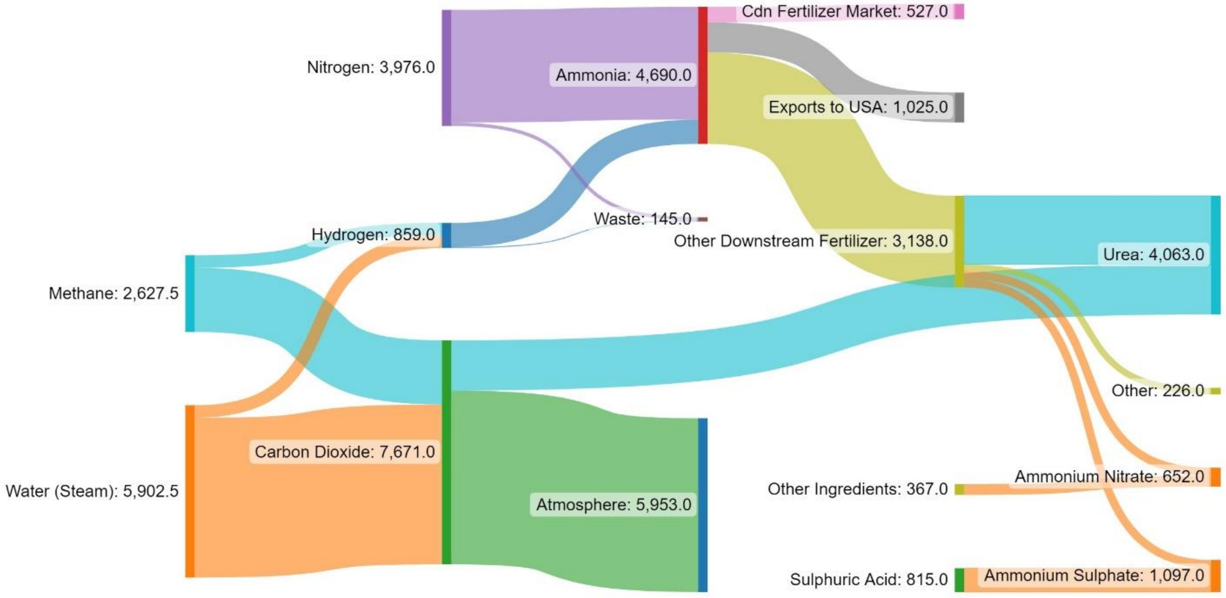


Figure 2.4 Average Canadian Ammonia Industry Input and Output Quantities from 2015 to 2022 [3], [34], [39], [41]

2.5 Greenhouse Gas Emissions and Climate Change

2.5.1 Greenhouse Gases and the Greenhouse Effect

Greenhouse gases are gases found in the atmosphere, such as carbon dioxide, methane, ozone, nitrous oxide, chlorofluorocarbons, and water vapor, contributing to the Earth’s greenhouse effect. The greenhouse effect is a process by which energy can be trapped near the Earth’s surface through these gases. The gases are relatively inefficient at absorbing solar radiation, allowing solar energy to reach the Earth’s surface. However, they absorb the infrared radiation emitted from the Earth’s surface and reradiate it back to the surface to produce additional global warming [42]. These gases contribute to global warming differently, as they have different lifetimes and capabilities in absorbing and reflecting the energy [42]. A standard measure to analyze each gas's effect on global warming is the global warming potential (GWP) [43]. The basis unit is often one unit of CO_2. For example, Methane is estimated to have a GWP of 27-30, which would be 27-30 times the global warming potential of CO_2 [43]. This means that atmospheric emissions per unit of methane would contribute to global warming significantly more than CO_2 per unit. In this report, GWP is used to convert other emissions such as methane and nitrous oxides to carbon dioxide equivalents using their GWPs. Table 2.1 below shows the global warming potentials used by Canada and the Intergovernmental Panel on Climate Change (IPCC) for various greenhouse gases in the fifth assessment report released in 2013. [44].

Table 2.1 Global Warming Potentials for Greenhouse Gases from the IPCC's Fifth Assessment Report 2013 [44]

Greenhouse Gas	Formula	GWP in CO_2e
Carbon dioxide	CO_2	1
Methane	CH_4	28
Nitrous oxide	N_2O	265
Sulphur hexafluoride	SF_6	23 500
Nitrogen trifluoride	NF_3	16 100

2.5.2 Climate Change and the Social Cost of Carbon

The 13th United Nations Sustainable Development Goal is to combat climate change and its impacts [45]. According to the IPCC, human activities through the emission of greenhouse gases have unequivocally caused global warming [46]. There is a great push to reduce greenhouse emissions to help slow down the rate of global warming. The long-term shifts in temperature attributed to global warming can affect weather patterns and are estimated to have negative impacts on the Earth via increased magnitude and frequency of natural disasters, decreased crop productivity, and decreased biodiversity [47].

The social cost of carbon (SCC) is a concept that describes the economic cost caused by an emission of one tonne of carbon [48]. This is highly important for policymakers as it can help quantify the costs of emission abatement with the benefits that can be achieved. In Canada, the SCC has been used since 2010 to play a role in cost-benefit analysis in policy creation [49]. For Canadian policymakers, Figure 2.5 shows the estimates of the SCC from the years from 2020 to 2080 with 2021 Canadian dollars. In the figure, one can see that the SCC is increasing as time goes on. The estimates of SCC increase because there are larger incremental damages from future emissions due to the stress that both physical and economic systems will already have from greater climate change and because global income is estimated to increase over time which means that future impacts will affect more wealth [49]. The social cost of carbon at the time of writing this in Canada is around $266 (2021CAD) and in 2080 it is predicted to be around $520 (2021 CAD). There is also variance in the values of SCC depending on the discount rate that is chosen as seen in Figure 2.5 with higher discount rates valuing carbon less than ones with lower discount rates.

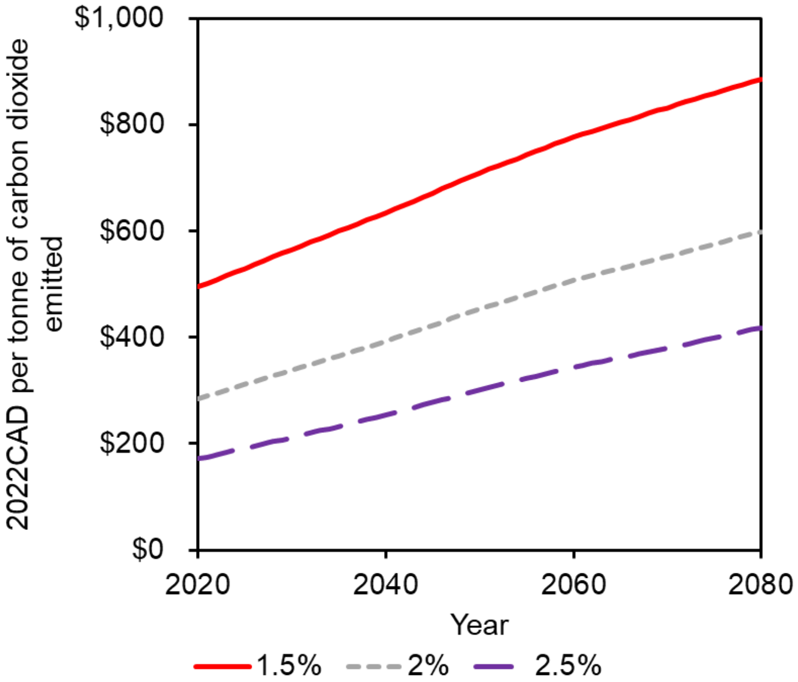


Figure 2.5 Social Cost of One Tonne of Carbon Dioxide at Varying Discount Rates

According to the government of Canada, the SCC is estimated using integrated assessment models (IAMs). These IAMs integrate aspects from various domains to form a climate-economy model. There are four modules that are part of the IAM: socioeconomics, climate, damage, and discounting.

Firstly, the socioeconomic module uses projected distributions of economic activity, population growth, and emissions in the future. The climate module uses an Earth system model that captures the relationship between the emissions of CO_2 with sea level rise and global temperature change. The damage model integrates the global temperature change and sea level rise with economic damages. These damages may include the cost of building dykes to stop flooding due to rising sea levels, crop failures, morbidities, The discounting module is the process by which the costs and benefits spread over current and future years [50]. With the four modules, the model is then run twice, once with the baseline and once with additional emissions. The expected damages and economic costs for both scenarios are then compared to get an evaluation of the SCC [49].

2.6 Externalities

In an economic sense, externalities are defined as a cost or benefit to an uninvolved third party that is caused by another party's activity. According to Kolstad [51], an externality exists when one person or firm's consumption or production choices enter another entity's utility or production function without that entity's permission or compensation. An example includes the building of hydroelectric dams for electricity in a city. The cost of building the dam and the benefit of selling electricity afterward is often incurred by the company or government that supplies the dam. However, an externality that can arise from the example is the disruption of fish migration and local ecosystems, which may incur costs for local fishermen and farmers. In the context of ammonia production, an externality that arises is the emission of greenhouse gases and other pollutants attributed to climate change or local air quality that can cause health and environmental damage [52].

Two primary regulatory instruments can be used in dealing with externalities described by Kolstad [51]: prescriptive regulations and economic incentives. Prescriptive regulations are a command-and-control strategy that requires the government to command a polluter to take physical steps to achieve a certain level of pollution reduction. Prescriptive regulations can be performed using technological or performance standards. It has the advantage that it is easy to enforce, and there is a greater certainty of how much pollution will result from the regulations. However, this doesn't give producers the flexibility to choose or not to pollute, and it is often quite costly to administer the regulatory system. For this reason, prescriptive regulations are not further discussed in this report. The second regulatory instrument is economic incentives, a large portion of Chapter 4 in this thesis.

Two economic incentives are described in this report, often used hand in hand in the real world, and are often given to deal with externalities: taxes and subsidies.

2.6.1 Taxes

An economic instrument that can be used to deal with the externality of climate change is taxes. Taxes are a method that forces polluters to pay a price for the pollution that they incur. In order to attain equilibrium, the tax must be priced equal to the damage incurred by the pollution [51]. This type of tax is often called a Pigouvian tax. In the case of carbon dioxide in many countries nowadays, this is known as a carbon tax. By setting a price for carbon emissions, one can internalize a product's cost to its environment.

Canada presently has a carbon tax in all its provinces and territories [53]. Canada has said that putting a price on carbon pollution is the most efficient means to drive innovation and energy efficiency to reduce greenhouse gas emissions. At the time of writing, the minimum carbon pollution price set in place was $80 per tonne of carbon dioxide but is intended to increase as time passes [54]. The minimum carbon pollution price in 2030 is around $170 per tonne of carbon dioxide. Table 2.2 shows the carbon price schedule as assigned by the government of Canada [54].

Table 2.2 Canadian Carbon Pollution Price Schedule from 2024-2030 [54]

Year	2024	2025	2026	2027	2028	2029	2030
Minimum Carbon Pollution Price (CAD/tonne CO_2e)	80	95	110	125	140	155	170

The implementation of the minimum carbon pollution price can be adjusted depending on the province to meet local needs. The implementation can take place across Canada [55]. Examples include a pure levy on fuels, or it can take place as a cap and trade system with a government that sets a cap to emissions, hands out emission credits to companies, and allows for trading between high-emitting and low-emitting companies [56].

2.6.2 Subsidies

A subsidy is another economic instrument that can deal with an externality. Subsidies give money to consumers or producers of less polluting products (which often have higher costs) to make them more competitive with traditional, more polluting products [57]. Subsidies can shift the supply-demand equilibrium by allowing more people to buy the greener product at a similar or cheaper price to the polluting product.

An example of a Canadian subsidy includes the Clean Hydrogen Investment tax credit [58]. According to the fall 2023 economic statement, there would be a 15 percent credit rate – subject to certain conditions – supporting clean ammonia production. The support of clean ammonia production includes equipment such as compressors, reactors, and storage for ammonia [58]. The subsidy allows green ammonia to be produced at a lower marginal cost for the producer, which may allow consumers to buy it at a more competitive cost and allow producers to compete with conventional producers.

2.7 Economic Analyses

The economic analyses presented in this report include Cost-Benefit Analysis, which is found in Chapter 3, and Cournot Modeling, which is found in Chapter 4. This section provides a small overview of the two types of analyses here.

2.7.1 Cost Benefit Analyses

The economic analysis used in Chapter 3 is a cost-benefit analysis. The decision-making variable used is the levelized cost of ammonia (LCOA). The three processes of conventional, blue, and electrolytic ammonia are analyzed across different provinces and policy scenarios.

The LCOA is the average net cost of one ammonia unit, assuming a particular process, province, and policy scenario. The LCOA is calculated by taking the whole lifecycle cost of an ammonia plant, which includes the operational and capital expenditures, and dividing it by the total amount of ammonia generated by the ammonia plant [59]. The goal for electrolytic ammonia is to have an LCOA that can be competitive with conventional technologies. A comparison of the LCOAs can help with deciding between various processes, as one should opt for the one with the lowest costs.

2.7.2 Cournot Modelling

Another part of the research that is used in economics is oligopoly modeling using Cournot. Oligopolistic markets are markets dominated by only a small number of suppliers relative to the number of buyers and they can be found in many different sectors [60], [61]. Oligopolies can arise when there are high entry barriers, either due to product differentiation, economies of scale, or demand [57]. A fundamental property of oligopolies is that actions and reactions done by each oligopoly can affect the outcome of another firm's actions due to the significant share that the firms will have in the market [57]. Five companies run the ammonia production industry in Canada at nine different facilities and can, therefore, represent an oligopoly [8]. Conventional ammonia production has often been performed in large factories due to the extreme conditions that optimize for economies of scale. In Canada, the range of factories can produce around 280 to over 1100 kilotonnes of ammonia each year [35]. Cournot modeling is the type of oligopoly competition and modelling present in this report. However, other oligopolistic competition models, such as the Bertrand model, exist.

Cournot modeling describes oligopolies where each producing firm simultaneously and independently sets a production quantity and brings it into the market, with the market price being determined where the total supply equals the total demand [62]. On the other hand, the Bertrand model is a method where firms simultaneously and independently name prices, and then the demand is allocated to the lowest price firm until a capacity is reached, and then it will be given further to the second lowest price firm, and so on [62]. A weakness of the Bertrand model is that it can fall under the Bertrand paradox if there are constant marginal costs and no product differentiation [63]. The Bertrand paradox would result from firms undercutting the price and yielding an equilibrium price setting where the marginal cost equals the price. Under the assumption that ammonia is the same product between conventional and green ammonia and the fact that there are different marginal costs between conventional and green ammonia, Cournot modeling was chosen for the economic analyses. Cournotmodeling is done to avoid the Bertrand paradox and provide a more realistic view of what entry of the electrolytic industry could have in the industry.

Chapter 3 Cost Benefit Analysis of Canadian Grid-Based Power-to-Ammonia Production across Provinces

3.1 Introduction

Ammonia is a versatile chemical used in various industries and is mainly used as a fertilizer for agricultural purposes [64]. In 2022, ammonia's annual global production rate was nearing 240 million metric tonnes. Furthermore, global production is expected to reach nearly 290 million metric tons by 2030 alone, which could increase over 20% in 8 years [65]. In 2022, Canada produced 3.8 million metric tons of ammonia, making it the 10th largest producer worldwide [33]. Nearly all Canadian ammonia plants are in Western Canada, with the majority in Alberta [23].

Most of the ammonia and all current Canadian ammonia production is produced via the Haber-Bosch process [8]. However, the Haber-Bosch process is currently environmentally unsustainable due to the carbon dioxide emissions associated with making the required hydrogen gas via steam methane reforming and downstream with the water gas shift reaction [66].

The emissions from fossil-fuel-based Haber-Bosch processes are estimated to be responsible for 1.8% of total annual global carbon dioxide emissions [67]. In Canada, ammonia production is estimated to represent a GHG emission of 8.8 million tonnes of CO_2e [8]. Proportionally, Canadian ammonia production has lower emissions because all the facilities incorporate some form of CO_2 recovery, mainly to produce urea, another chemical fertilizer that uses carbon dioxide as a feedstock [8]. This results in Canadian ammonia having an average GHG impact from ammonia production that is at least 30% less than that of the United States or Russia, which are other top global producers of ammonia [8].

Several opportunities exist to decrease the total GHG emissions from Canadian ammonia production further. When carbon capture and storage (CCS) is incorporated as part of the ammonia production process, it is referred to as blue ammonia, where the hydrogen (also referred to as blue hydrogen) is sourced from natural gas (NG) as a feedstock and some or all the portion of the carbon dioxide emissions being captured and stored [68]. Furthermore, there is also the potential to use water electrolysis to produce hydrogen gas for the feedstock required as part of the Haber-Bosch process, and this is the most widely adopted method to produce sustainable hydrogen gas [7]. When the hydrogen for the ammonia production process is produced using this method and renewables, it is referred to as green hydrogen, and the subsequently produced ammonia is referred to as green ammonia [67]. If electrolysis is performed using one's grid, it can often be described using yellow hydrogen and yellow ammonia [29].

However, the color-coding system for ammonia production does not fully account for the nuances associated with ammonia production. Most ammonia production facilities in Canada have a carbon capture unit to recover some carbon and produce urea [8]. For blue ammonia, it should be noted that no certified or industry-accepted percentage of CCS is required to certify ammonia as blue [69]. In addition, it should be noted that using urea as a carbon utilization method is a temporary storage method, as the application of urea as a fertilizer results in the carbon stored being released as emissions once applied to soil [70]. The ambiguous blue ammonia label is part of why "blue" is controversial in the industry [69]. Green ammonia describes ammonia produced by 100% renewables with zero emissions [71]. However, if one uses a country's electrical grid as the primary or backup power source, it may not be entirely zero emissions as the electrical grid is often not composed of entirely renewable or zero-emission sources. Hence, it would be called yellow hydrogen. The power grid in most countries, including Canada, is not entirely low-carbon, and over 40% of worldwide emissions come from burning fossil fuels for electricity [72]. Canada has committed to a federal net-zero target of 2050, with an intermediate goal of a net-zero electricity sector by 2035 [73]. However, it should be noted that some provinces, particularly Alberta and Saskatchewan, have firmly refused to meet this target [74], [75]. These are also some of the provinces with the most carbon-intensive electric grids in the country [76]. Alberta is, by far, Canada's highest producer of ammonia. As such, the development of electrolytic ammonia may be worse in terms of environmental impact than conventional ammonia production itself if one were to build it using the grid. Hence, there is a motivation to see which provinces may be more optimal to produce ammonia via electrolysis. The terms used here will be specific to the process and not use the colour coding system.

The research questions addressed in this chapter are, "How do the costs of grid-based electrolytic and blue ammonia compare to conventional ammonia in the context of Canada?" and "What provinces may be more suitable for these alternatives to ammonia production?" This chapter provides a cost-benefit analysis of grid-based power-to-ammonia (P2A) production alongside conventional and CCS methods in Canada. The expected costs of production of electrolytic and conventional Canadian ammonia were calculated considering capital expenditures (CAPEX) and operational expenditures (OPEX), as well as the social cost of carbon (SCC) alongside the carbon intensity of the grid. Also, this chapter provides a recommendation for the direction that each province's ammonia strategy should take.

The chapter is organized as follows: Section 3.2 contains the literature review that summarizes articles related to electrolytic ammonia and greener production in this chapter. Section 3.3 provides the scope and methodology for the various processes and scenarios. In section 3.4, the results and discussion are shown, which includes an analysis of the emissions, the levelized cost of ammonia (LCOA), and the sensitivities of different processes. Finally, Section 3.5 conveys the conclusions and recommendations relevant to policymakers and industry.

3.2 Literature Review

No literature discusses a cost-benefit analysis of low-carbon ammonia using the SCC within Canada. However, there is a 2023 report written by Fertilizer Canada [8] and a 2008 report written by National Resources Canada [23] benchmark ammonia production GHG emissions from existing Canadian ammonia facilities, which comes close. The greenhouse gas emissions and the processes where most greenhouse gases are emitted were reported [8]. Canadian ammonia facilities' emission rates and efficiency are reported in [23]. These reports show that Canadian ammonia facilities are among the most efficient and least carbon-intensive compared with other facilities worldwide. Emissions result from the SMR process for hydrogen production, combustion of NG for heat, and venting of process gases. In addition, indirect emissions from electricity used for operations and heat processing from a neighboring facility or non-ammonia section of the plant must also be considered. Process and combustion emissions are the top two carbon-intense emissions categories, accounting for over 80% of emissions at typical fossil fuel-based ammonia production facilities in Canada [8]. However, all facilities recovered part of the carbon during the process that would have otherwise been emitted into the atmosphere, for it was found that 8.8 million tonnes of CO_2e was emitted directly and indirectly during the study period, resulting in an average of 2 tonnes of CO_2 per tonne of ammonia generated, 0.76 tonnes of CO_2 per tonne of ammonia recovered, and 1.2 tonnes of CO_2 per tonne of ammonia emitted from Canadian ammonia facilities. Canadian ammonia production carbon emissions are 30-31% less than the United States or the Russian Federation and 52% - 63% less than that from China [8]. However, guidance regarding the social cost of carbon of the greenhouse gases that are emitted and what other alternatives may cost were not provided.

Furthermore, there is also literature regarding general techno-economic analyses of various ammonia production methods. Saygin et al. [59] studied grey, blue, and green ammonia production and how the increasing demand for these processes would impact the global NG market. The study estimates the production costs of the various processes across different regions in the world, the environmental impacts, and the required policies to facilitate market deployment for this. They also provide the basis for this cost-benefit analysis and many of the data values in this chapter. Mersch et al. [77] analyzed the techno economics of blue, green, and hybrid ammonia production in the United States and showed that all the alternatives could reduce emissions. Their model concludes that blue ammonia remains the most economical due to tax credits under the Inflation Reduction Act, making it less expensive than conventional ammonia. They found that electrolytic ammonia heavily depends on the price of reliable low-carbon electricity, which must be around 35 USD/MWh or lower. Arnaiz del Pozo et al. [78] found that the levelized cost of blue and green ammonia in 2022 can reach competitive levels compared to conventional ammonia plants with NG costs at 6.5 €/GJ and electricity costs at 60 €/MWh. However, they also found that green ammonia continues to be significantly more expensive in the long term than blue ammonia across global markets. Campion et al. [79] compared the methods of ammonia production and found that between purely grid-based and purely islanded dedicated renewable P2A processes, a semi-islanded approach was optimal in terms of economics because of reduced curtailment. Lee et al. [80] analyzed various pathways for ammonia production, including nuclear and renewable-powered ammonia, compared to conventional NG ammonia production. They found that carbon capture in conjunction with NG-based ammonia can reduce greenhouse gas emissions by 55-70% when compared to conventional NG-based grey ammonia production. Furthermore, they found that the levelized costs of renewable and nuclear-based P2A production were approximately four times that of conventional grey ammonia. Nayak-Luke et al. [81] reviewed the potential of using dedicated islanded renewables for green ammonia production to minimize the levelized cost. It was found that a levelized cost of ammonia (LCOA) of 473 USD/tonne was achievable, with the significant cost components coming from the electrolyzers' capital costs as well as operating expenses. It was also found that the LCOA could reach below 310 USD/tonne by 2030, with many locations below 350 USD/tonne.

There has been literature related to the economic cost of carbon abatement in other industries. Kajaste et al. [82] found that the cost of avoiding emissions in the cement industry varies from 4-448 USD per tonne of CO_2, varying based on locational and technological factors. Strategies to reduce carbon emission would be to replace clinker with mineral components, reduce thermal energy and electricity usage, use carbon capture technology, and use MgO and geopolymer cement. Gillingham and Stock [83] found that the cost of intervention (i.e., CO_2 reduction) measures varies widely for CO_2 reduction, from less than 10 USD per tonne to over 1000 USD per tonne of CO_2. Most costs are relatively expensive, as they exceed 46 USD/tonne, which is what the social cost of carbon was calculated to be. Finke et al. [84] reviewed various industrial chemical process pathways that produce hydrogen as a by-product to produce hydrogen more cleanly. They found enough industrial chemical process reactions to have the combined potential to make over 150% of the world's industrial hydrogen needs under present-day, average US economic conditions while reducing cost and reducing or eliminating CO_2 emissions. This study found that the technologies that may already exist in the market reduce costs and potentially CO_2 emissions.

There is a gap in the literature regarding the techno-economics of less carbon-intensive ammonia production methods, specifically in Canada. Furthermore, literature has yet to consider the SCC alongside the production costs. This report aims to fill the literature gap and provide information regarding what provinces may be suitable in Canada for electrolytic ammonia production on small and large scales, considering production costs, SCC, NG, and electricity costs.

3.3 Methodology

3.3.1 Scope

This paper analyzes three different processes of producing ammonia in the context of Canada. The three types of processes that are discussed are the baseline process (Process 1 – P1), the carbon capture process (Process 2 - P2), and the electrolytic ammonia process (Process 3 -P3). The paper also analyzes two different policy scenarios: Current Measures (CM) and Canada Net Zero (CNZ) measures. The CM and CNZ scenarios are two different trajectories that Canada can use policy-wise, and they impact the expected electricity and NG costs and future grid intensities [85]. The CM scenario assumes limited action to reduce GHG emissions beyond the measures in place today. Only climate regulations that are implemented as of 2023 are included. On the other hand, in the CNZ scenario, Canada achieves net-zero emissions by 2050, with the rest of the world moving slowly to reduce GHG emissions [85]. Some policies include greater electricity regulations, oil and gas emissions caps, considerable reductions in methane emissions, and various tax credits for clean hydrogen [85].

The analysis uses the basis of building a new factory that produces 1000 tonnes of ammonia daily, which is a reasonable production capacity of ammonia as ammonia production often works based on economies of scale [86], [87]. The average Canadian ammonia factory can produce over 600 tonnes of ammonia daily across the nine facilities, ranging from around 300 to 1100 tonnes of ammonia [35].

The scope for emissions considers only the emissions released during the process indicated by each of the schematics and the emissions from using the power generation required from the grid. Upstream emissions before natural gas enters the plant are not considered. For example, the emissions released from oil extraction are not included. However, in the case of using the electrical grid power generation, if fossil fuels are used, there is a consideration of the upstream emissions associated to fuels when used for electricity [88]. The upstream emissions are included in the electrical grid because the government of Canada estimates the greenhouse gas intensity of each provincial grid in that way, and the statistics are provided using that method [88]. The upstream emissions are not included for the NG feedstock for P1 and P2 out of simplicity and due to the significant variance in emissions that can occur from different transportation distances. The defined scope also means that emissions after the ammonia is applied to soil, in the form of urea, are not considered. For example, when applied to the ground for agricultural purposes, urea releases carbon dioxide into the atmosphere [70].

The P1 baseline process is ammonia production using NG through SMR without CCS. Figure 3.1 shows the schematic of the primary units within the scope in P1. For P1, the primary units include the SMR unit, the nitrogen production, and the ammonia synthesis portion. There are emissions from the SMR unit and electricity usage from the grid that powers the processing unit. The green outline indicates that it is taking electricity from the grid to power some of the systems within the unit. Some of the natural gas in the P1 baseline process is used for the gas boiler, which turns water into steam, which then meets feedstock natural gas used for the SMR reaction.

The emissions counted are only from electricity usage and the combustion and process emissions of the SMR unit, which account for more than 97% of the emissions in a traditional Canadian plant [8]. In Canada, there is a level of carbon recovery from the process emissions, which happens downstream from the ammonia synthesis in the majority of the existing plants due to the production of urea [8]. There are also significant variations in the emissions for each plant [8]. However, when modeling the P1 process, urea production is not considered. Emissions from ammonia facilities are likely higher when the entire lifecycle of ammonia and urea is considered. This is because carbon stored in urea is released into the atmosphere once it is applied for agricultural purposes [70].

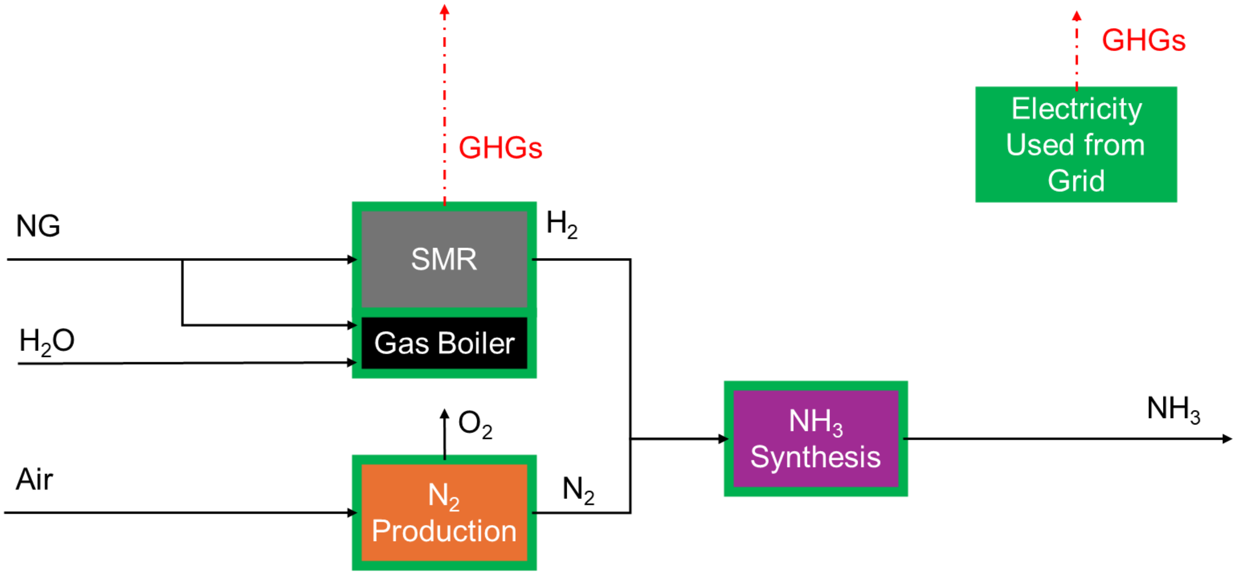


Figure 3.1 P1 Schematic

The P2 process is similar to P1's process. However, it includes a CCS unit, which captures 90% of the CO_2 that exits the hydrogen production unit and the flue gas from combustion [59]. The cost of CCS in this specific process is relatively expensive since it is post-combustion CCS. The CCS process unit will be located after the SMR and gas boiler to capture both the process emissions and the flue gas emissions. The flue gas stream has a lower concentration of CO_2, which makes it more difficult to capture than the process emissions stream of CO_2 [89]. The P2 process contains the exact same process units as P1 but with the additional CCS unit. The P2 schematic is shown in Figure 3.2. This CCS unit requires more electricity and heat than the P1 counterpart but would result in less carbon overall. Chemical absorption via monoethanolamine (MEA) is the method of carbon capture [90]. However, the actual design and flowrates of the MEA carbon capture was beyond the scope. CCS costs are expected to vary based on the availability of CCS options in the province. This may result in the cost of carbon capture in certain regions being more expensive than others, potentially due to the limited options or due to the transportation requirements of the CO_2. These factors have not been included in the consideration for this paper, and it was assumed that the transport and storage costs were the same across the provinces. An additional 14.71 CAD per tonne of CO_2 was added to all the CCS analyses to consider the transport and storage costs based on research by Saygin et al. [59], [90].

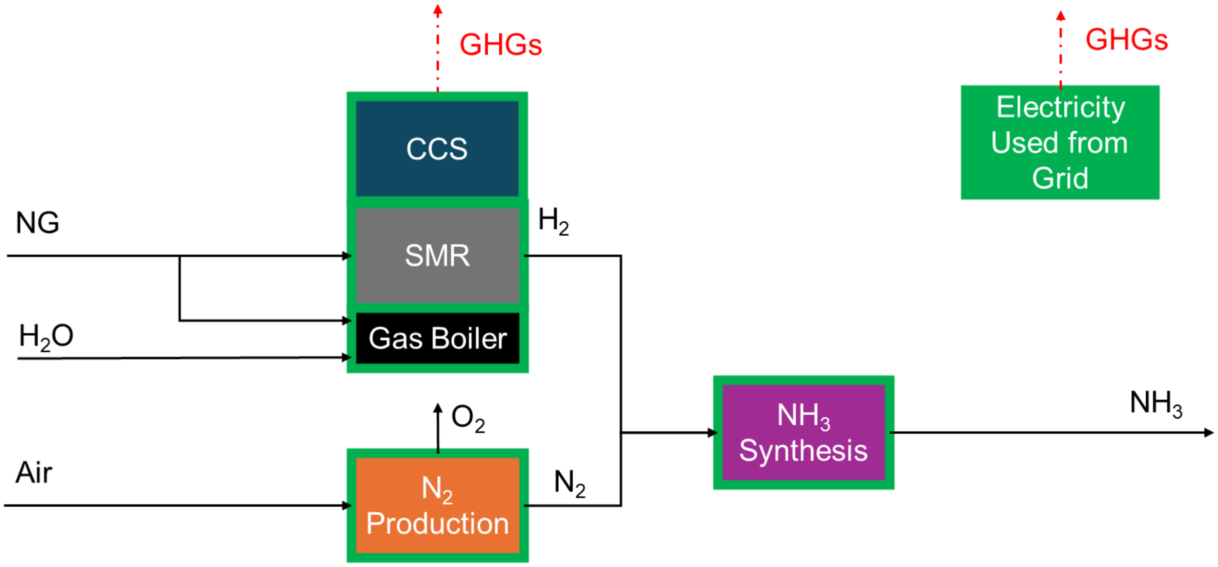


Figure 3.2 P2 Schematic

Lastly, the P3 process is the electrolysis method process of producing ammonia. Figure 3.3 shows the schematic. The figure shows that the ammonia synthesis and the nitrogen production remain the same as P1 and P2; however, the hydrogen production in P3 differs. Hydrogen production is now performed using an alkaline electrolyzer powered by electricity supplied by the grid, which takes water as its feedstock. In this case, the only GHGs emitted are from grid usage.

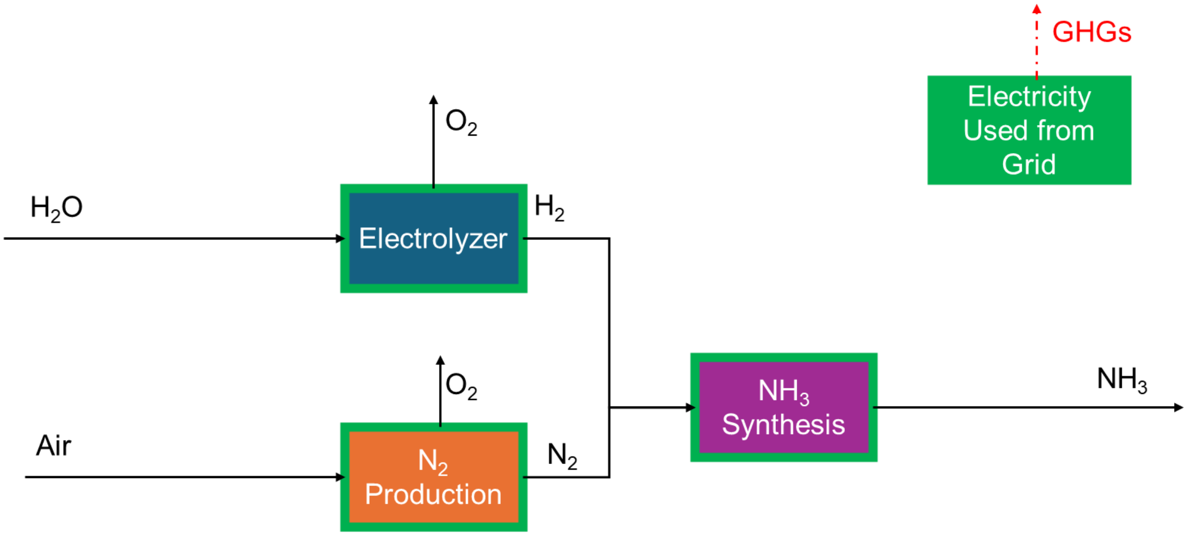


Figure 3.3 P3 Schematic

A conventional ammonia production facility ranges from 200-500 tonnes per day to as large as 4500 tonnes per day [91]. If a 1000 tonne/day P2A plant were then processed for one year, this would require energy in the range of 3-4 TWh [3], which could account for 2-40% of the grid electrical production of various provinces [92]. As such, it should be noted that these findings may not necessarily be directly applicable to the installation of a green ammonia facility but may provide direction in terms of policy as well as optimal areas for production. Further, this may indicate that purpose-built electricity production facilities may be required for P2A production to ensure that the power is low carbon and has sufficient capacity to produce the required ammonia.

3.3.2 Levelized Cost of Ammonia (LCOA)

The economic concept of levelized cost of ammonia (LCOA) is used to analyze the costs and benefits of the various methods of producing ammonia in each province. LCOA is a concept that takes all the average annual costs incurred throughout its lifetime and divides it by the amount of ammonia produced in a year. Equation (6), which forms the basis of our calculations, shows the LCOA equation used in this analysis [59].

$$LCOA_{i,p,s} = \frac{(CRF) \times I_i + (CE)_{i,p,s} + O_i + (SC)_{i,p,s}}{X} \tag{6}$$

$$CRF = \frac{r(1+r)^N}{(1+r)^N - 1} \quad (7)$$

$LCOA_{i,p,s}$ (CAD 2022/tonne of ammonia) is the levelized cost of ammonia of a given process i, province p, and scenario s. CRF (year^{-1}) refers to the capital recovery factor given by Equation (**7**) which refers to the ratio of the annual payment of the annualized initial capital investment and the total initial investment's present value, I_i (CAD 2022). $(CE)_{i,p,s}$ (CAD 2022/year) then refers to the average total cost of natural gas and electricity that is used in the year, which varies by province p and process i, which can be 1, 2, or 3. $(CE)_{i,p,s}$ also varies by the policy scenario s analyzed. O_i (CAD 2022/year) refers to the fixed operational expenditures of process i that do not include the natural gas or electricity used. $(SC)_{i,p,s}$ refers to the annual social cost of the emissions incurred by the plant and the grid usage (CAD 2022/year). X (tonnes of ammonia) refers to the amount of ammonia that is produced in a year from the plant. In Equation (2), the r represents the discount rate and the N (years) refers to the economic lifetime which is given as 25 years.

There is plenty of debate on how to discount the future, such as whether the rate should be higher or lower or even a constant [93]. In this report, a constant discount rate for both the costs and the benefits is used with uncertainty considered by testing out different values for the discount rate. The constant discount rate is to keep the model simple, but it could be a limitation regarding the analyses.

The economic lifetime of this project is based on a 25-year lifetime from 2026-2050 and assumes a three-year construction period beginning in 2023 and ending in 2025 [59], [94]. This timeline is performed in this way to be synchronous with Canada's 2050 net zero carbon target with available data only projected to 2050. All currency displayed in this report is in 2022 Canadian Dollars and the Chemical Engineering Plant Cost Index was used to convert from one year to another [95] when needed. A currency exchange rate of 0.75:1 USD:CAD ratio was used to convert to the Canadian currency. Revenue is not included in the LCOA analyses as it was assumed that all processes would have the same marginal revenues.

Each province has different electrical grid usage costs, natural gas costs, and grid intensities. The differences would result in some provinces incurring higher costs than others. This chapter aims to find which process is more suitable for each province using these variables. One can then calculate each LCOA for every province for each process. These LCOAs are then compared using the concept of ΔLCOA which subtracts the alternative process's LCOA from the baseline (b) which is given by Equation (8).

$$\Delta LCOA_{i,p,s} = LCOA_{b,p,s} - LCOA_{i,p,s} \quad (8)$$

$\Delta LCOA_{i,p,s}$ (CAD 2022/tonne of ammonia) represents the change in LCOA. In the above equation, i can represent P2 and P3 and b represents P1, with i being the process that we want to calculate the ΔLCOA for and b being the baseline. P1 is not i because the change for all the combinations would be trivially zero. The subscript p, and s represent the province and policy scenario the LCOA was calculated for, respectively. The different subscripts shows the difference between the LCOAs calculated for each process in each province. P1 was taken to be the baseline for the analyses (except for some of the sensitivity analyses, where P2 is taken to be the baseline). P2 and P3 were then subtracted from P1, which indicated which choice should be made. A positive ΔLCOA means one should choose the alternative (P2 or P3) since the baseline scenario will incur a higher cost. A negative ΔLCOA means that one should choose the baseline process (P1) since the cost will be less for the baseline.

The analysis for ammonia production in each province does not include the impact of transportation in terms of the social cost of emissions, the cost of logistics, or whether there is a suitable domestic market for the sale of ammonia within the province. This chapter also does not analyze how differences in ammonia demand across provinces may affect ammonia prices and influence other factors, such as logistics. For example, there is great interest in green ammonia in the maritime provinces due to key interests in Europe, which may make it easier to access than Manitoba or Saskatchewan [96]. However, this is not taken into consideration in the chapter.

3.3.3 Input Data

3.3.3.1 Social Cost of Carbon (SCC)

The SCC was determined based on the estimates from Environment and Climate Change Canada's 2% Near-term Ramsey discount rate Social Cost of Greenhouse Gases guidance [49]. 2% was chosen as the average between the 1.5% and 2.5% discount rates shown in the SCC article. The 1.5% and 2.5% discount rates are analyzed in the sensitivity analyses. There is debate on the value of discount rates, especially regarding climate change policies [97], [98]. 2% was chosen as it was used for the SCC numbers provided by the Government of Canada [49].

The annual values of the SCC for each year in this guidance are meant to represent, for policy decisions, the value of the incremental damage from the release of each tonne of CO_2, CH_4, and N_2O. Each of the gases' incremental damage was converted to be relative to the GWP of carbon dioxide. These numbers are listed in 2021 Canadian dollars and show values from 2020-2080. These values were considerations appropriate for weighing decisions that would affect the amount of GHG emissions on a federal level [49]. Figure 3.4 shows how the SCC is estimated to increase over time and at varying discount rates. The SCC is directly related to time but is inversely related to the discount rate.

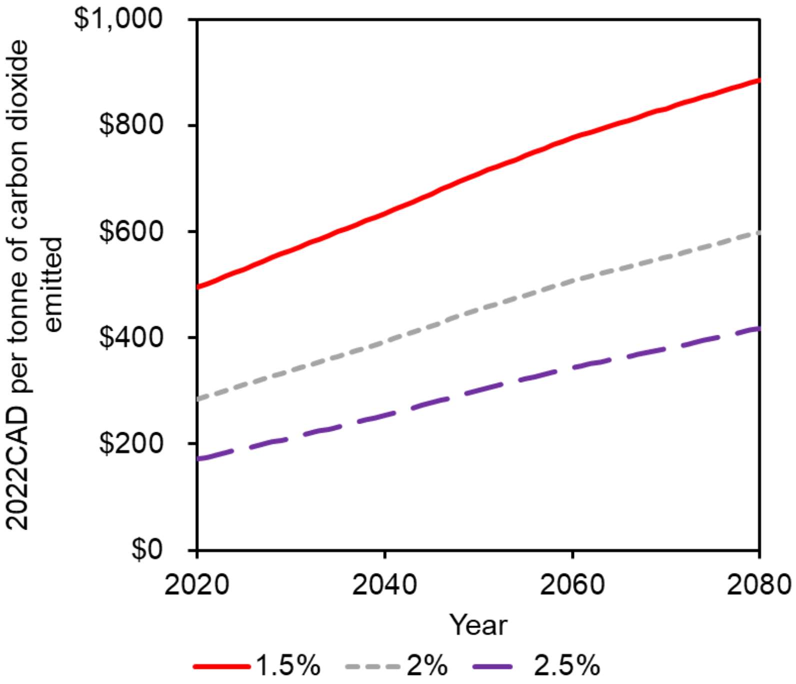


Figure 3.4 Social Cost of One Tonne of Carbon Dioxide at Varying Discount Rates [49]

The SCC estimate includes predicted damage from various potential effects, such as from loss of agricultural productivity and human health effects [49]. The cost of emissions increases year over year based on the assumption that future systems would continue to become more stressed by the accumulation of greenhouse gases (and thus, additional GHG emissions cause more impact in the future). It is also based on the assumption that income would continue to grow over time and, as such, there would be an increased willingness to pay to avoid additional damages for an increased amount of property. The SCC is estimated on a global scale rather than on a domestic level [49]. Although Canada would also suffer the effects of climate change, it is impossible to directly correlate what percentage of the overall social cost of carbon would directly impact the well-being of Canadians.

Conventional ammonia production also significantly affects other local pollutants in an area [6], but this was not considered in the social cost analysis for this chapter. Only carbon emissions were considered for the cost-benefit analysis associated with this chapter. Since local pollution damages are not included in the social costs, the damages from ammonia production could have a higher total social cost than what is used in this chapter. Other types of emissions, such as ammonia and particulate matter, are important and of interest [6] but are not included in the scope.

To find the variable annual social cost $(SC)_{i,p,s}$ In the LCOA equations, the SCC was used and is given by Equation (9).

$$(SC)_{i,p,s} = (SCC)_{avg,r}(EF)_{avg,i,p,s}X \tag{9}$$

$(SCC)_{avg,r}$ (CAD 2022/tonne of carbon dioxide) is the average SCC across the 25 years at a specific discount rate r. $(EF)_{avg,i,p,s}$ (Tonnes of carbon dioxide per tonne of ammonia) represents the average carbon emission factor across the 25 years from producing one tonne of ammonia in each province p with a given process i, where i could be 1, 2, or 3. This emission factor is also dependent on what type of policy scenario s is chosen. This emission factor considers the NG emissions from feedstock and the electrical grid usages in the production of ammonia across all processes P1, P2, and P3. X (tonnes of ammonia) represents the amount of ammonia that is produced each year which is assumed to be 365,000 tonnes per year.

3.3.3.2 Emissions, Electricity, and Natural Gas Costs

The electrical grid mix, NG costs, and electricity costs for each province were estimated using Canada’s Energy Future annual report series from the Canada Energy Regulator (CER) which explores the expected variations in the electric grid over the long term in the Canadian provinces and territories [85]. As part of this report series, data tables on how the grid mix, electricity costs, and natural gas costs are expected to vary based on two policy scenarios: Current Measures (CM) and

Canada Net-Zero (CNZ). These data tables convey data until 2050 and show how each province's energy sources and costs could vary across time [85].

Regarding the grid mix, each province's electricity sources are split into categories, including Hydro/Wave/Tidal, Wind, Biomass/Geothermal, Solar, Uranium, Coal & Coke, Natural Gas, and Oil. The data shows how much of each energy source contributes to the grid in each province. It was assumed that each province’s grid's intensity was uniform. These scenarios are created based on CER’s consultations with government bodies, industry, and academic organizations and internal economic and energy model analysis [85]. The electrical grid emissions were calculated using Equation (10). In a nutshell, this equation represents the total grid emissions that a 1000-tonne ammonia production capacity plant would have in a year. The emission factor is calculated by multiplying the amount of energy used by an ammonia plant that uses a particular process and the average grid emissions per unit of energy.

$$(EF)_{Grid,i,p,t,s} = X\left(E_{grid,i}\right)\frac{\sum_{m}^{M} Q_{m,p,t,s}(EF)_m}{\sum_{m}^{M} Q_{m,p,t,s}} \tag{10}$$

$(EF)_{Grid,i,p,t,s}$ (Tonnes of carbon dioxide) represents the total carbon emissions emitted for a given process i, province p, year t, and policy scenario s. X (tonnes of ammonia) is the total ammonia in tonnes that is produced by the plant. $E_{grid,i}$ (GJ/tonne of ammonia) is the total energy that is used up by the plant from the grid per tonne of ammonia for a given process i. $Q_{m,p,t,s}$ (GJ) is the capacity of a province p’s energy source m at a year t for a policy scenario s. These values are obtained from the CER. M represents the final energy source in the index, which would be 8. $(EF)_m$ (tonnes of carbon dioxide per GJ) represents the emission factor of a given energy source m and are given by Table 3.1 Emission Factors of Various Energy Sources. Values for most of the emission factors were taken from an Integrated Lifecycle Assessment of Electricity Sources report from the United Nations Economic Commission for Europe [99]. Since the categories Biomass/ Geothermal are lumped into one as per the Canada Energy Futures report, the lower value of 38 g CO_2e/kWh for Geothermal was not included in this analysis for a conservative result.

Table 3.1 Emission Factors of Various Energy Sources

m	CER Grid Category	Source Emission Factor Category	$(EF)_m$ (tonnes of CO_2e/GJ)	Source

1	Oil	Petroleum	0.3000	[100]
2	Coal & Coke	Coal	0.2278	[99]
3	Natural Gas	Natural Gas	0.1361	[99]
4	Biomass/Geothermal	Biomass	0.0639	[99]
5	Solar	Solar Utility	0.0133	[99]
6	Uranium	Nuclear	0.0033	[99]
7	Hydro/Wave/Tidal	Hydro	0.0031	[99]
8	Wind	Onshore Wind	0.0031	[99]

To retrieve the emissions from the processing and combustion of NG through the process of SMR, emission factors from Saygin et al. [59] were used. These emission factors were often based on the energy usage of NG and had to be converted to be based on one tonne of ammonia. P1 and P2 used the SMR process, and these emission factors benefitted this.

Electricity production facilities for the grid in Canada vary in emissions, efficiency, and other components that would affect their performance and, thus, overall carbon footprint. However, it was assumed that the lifecycle carbon impact for each electricity production plant within a province would be identical and that the carbon intensity values provided in Table 3.1 would be acceptable to use as a meaningful input to the model for policy analysis.

Once emission factors for SMR and the grid in each year (t) were retrieved, one could then sum up the emission factors for SMR and the grid and find the average emission factor rate for a given province p and process i. This is given by Equation (11). The $(EF)_{avg,i,p,s}$ can then multiplied by the quantity of ammonia, the SCC, to obtain the total social cost ($(SC)_{i,p,s}$) incurred by the amount of ammonia produced.

$$(EF)_{avg,i,p,s} = \frac{\sum_{t=1}^{N=25}\left((EF)_{SMR,i,p,t,s} + (EF)_{Grid,i,p,t,s}\right)}{25} \tag{11}$$

Equation (12) , analogous to the emission factors equation, is used to determine the average total cost of natural gas and electricity of a given province and process for producing one tonne of ammonia. The NG and electrical grid costs were found in a parallel and similar way as the emission factors were found in the Canada Energy Futures 2023 and were found in the Data Appendices of the End-Use prices for the Industrial Sector and analyzed for the Canada Net-Zero and Current Measures policies [76]. The electricity cost was important for P1, P2, and P3, while the NG costs were used to determine the production costs in P1 and P2.

$$(CE)_{i,p,s} = \frac{\sum_{i=1}^{N=25}\left((CE)_{NG,i,p,t,s} + (CE)_{Grid,i,p,t,s}\right)}{25} \tag{12}$$

3.3.3.3 Production Costs

The other components of the costs in the LCOA are the initial investment I_i and fixed annual operational expenditures O_i. With the basis of 1000 tonnes of ammonia, these components were all costed using Saygin et al.'s [59] numbers, shown in Table 3.2. I_i mainly is composed of the CAPEX components while O_i is composed of the OPEX components. The fourth column describes which process it is used in.

Table 3.2 CAPEX, OPEX, and Other Miscellaneous Items [59]

Item	Units	Value	Used in Process	Notes
Hydrogen Production				
CAPEX: SMR	USD/kW	910	P1, P2	
CAPEX: Electrolyzer	USD/kW	750	P3	
CAPEX: CCS	USD/t CO_2/year	300	P2	Includes transport and storage. A systematic addition of 10 € per tonne of CO_2 was added to account for this [90].

CAPEX: Gas boiler	USD/kW	500	P1, P2	This considers a 90% capacity factor and 90% efficiency.
OPEX: SMR	% of CAPEX	4.7	P1, P2	
OPEX: Electrolyzer	% of CAPEX	2.5	P3	
OPEX: CCS	% of CAPEX	7	P2	
Gas boiler OPEX	% of CAPEX	3	P1, P2	
Capacity factor: SMR	%	90	P1,P2	
Capacity factor: CCS	%	90	P2	
SMR Gas input: Feedstock	GJ/t H_2	140.7	P1, P2	
SMR Gas input: Fuel	GJ/t H_2	15.4	P1, P2	
Electrolyzer Energy Demand	kWh/kg H_2	55	P3	This considers an efficiency of 65% and a capacity factor of 50%.
Electrolyzer water demand	l/kg H_2	15	P3	
CCS steam	GJ/t CO_2 captured	2.5	P2	
CCS electricity	GJ/t CO_2 captured	0.4	P2	
CCS capture rate	%	90	P2	This is 90% of the capture rate from the flue and process emissions combined.
Emission factor of natural gas	tons CO_2/GJ	0.056	P1, P2	
Average methane emissions from natural gas	t CO_2-eq/GJ	0.015	P1, P2	
Nitrogen Production				
CAPEX: cryogenic air separation	USD/t N_2/h	1,500,000	P1, P2, P3	
OPEX: cryogenic air separation	% of CAPEX	2	P1, P2, P3	

Electricity	kWh/t N_2	265	P1, P2, P3	
Capacity factor	%	90	P1, P2, P3	
Ammonia Synthesis				
CAPEX: ammonia synthesis	USD/t NH_3/h	3,450,000	P1, P2, P3	
OPEX: ammonia synthesis	% of CAPEX	2	P1, P2, P3	
Electricity for synthesis	kWh/kg NH_3	0.65	P1, P2, P3	
Note: All costs listed as 2019 USD				

From Table 3.2, one can obtain Table 3.3 by using 1000 tonnes of ammonia per day as a basis and summing up the quantity required for each process. Unit conversions from USD to CAD were done using a 0.75:1 USD to CAD ratio. Table 3.3 shows that the most significant initial investment and fixed operational costs come from P2. On the other hand, P3 has the lowest values in both categories.

Table 3.3 Resulting initial investment and operational costs (approximate values, rounded to the nearest million)

Process	$\boldsymbol{I_i}$ (millions CAD 2022)	$\boldsymbol{O_i}$ (millions CAD 2022/year)
P1	1048	46
P2	1560	81
P3	964	24

3.4 Results and Discussion

3.4.1 Emissions

Figure 3.5 shows the emissions mass ratio of the ammonia across the three processes and two policies. The emission comparisons show that CNZ policies are estimated to reduce emissions in many provincial grids. The CNZ policies result in fewer emissions if one chooses P3. However, the emission comparisons show that if one were to choose P3, it does not necessarily mean that there will be fewer greenhouse gas emissions than P1.

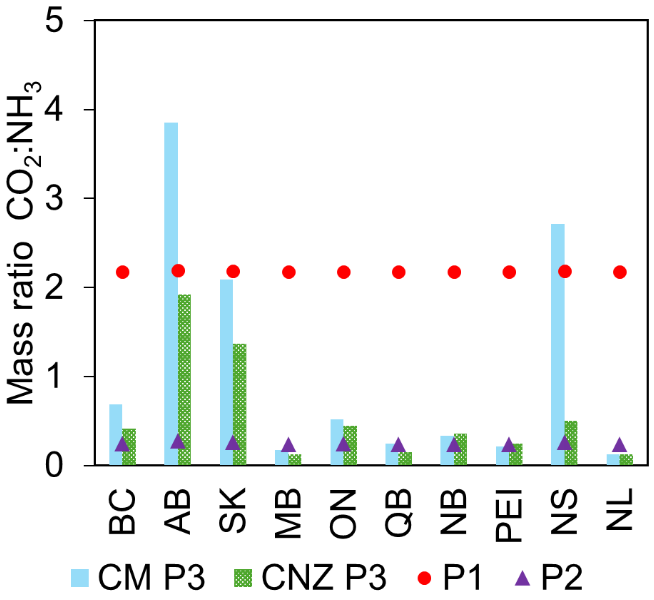


Figure 3.5 Emissions mass ratio between carbon dioxide and ammonia produced from various processes across two policies and averaged over 2026-2050. Note: P1 and P2 are the averages between the two policies because the values are very similar across the two policies.

Using Canadian averages, P1 production has an emission mass ratio of 2.18. P2 has an emissions ratio of 0.25. Lastly, P3 production in the CNZ and CM policies have emission ratios of 0.56 and 0.94, respectively.

Alberta and Saskatchewan have substantial grid emissions per mass of ammonia, and if one were to choose P3 in those provinces, it is estimated to produce similar or even greater emissions than P1. Most other provinces are estimated to produce fewer emissions with P3 than with P1.

The emission comparisons show that out of the three scenarios if P2 were chosen, it would have the most significant overall difference in emissions when it comes to greenhouse gases from ammonia production. P2 assumes a 90% capture recovery, which is less than most provincial P3 emissions from the grid.

3.4.2 National Levelized Cost of Ammonia

Figure 3.6 shows the estimated production costs of producing ammonia in Canada across the two policy scenarios and the three different processes. This figure also shows the breakdown of the different components of the production costs which convey the contributions to costs in each scenario and process. P1 costs around 700 – 900 CAD per tonne of ammonia. P2 costs around 900 – 1100 CAD per tonne of ammonia. Lastly, P3 is estimated to cost around 1300 CAD per tonne.

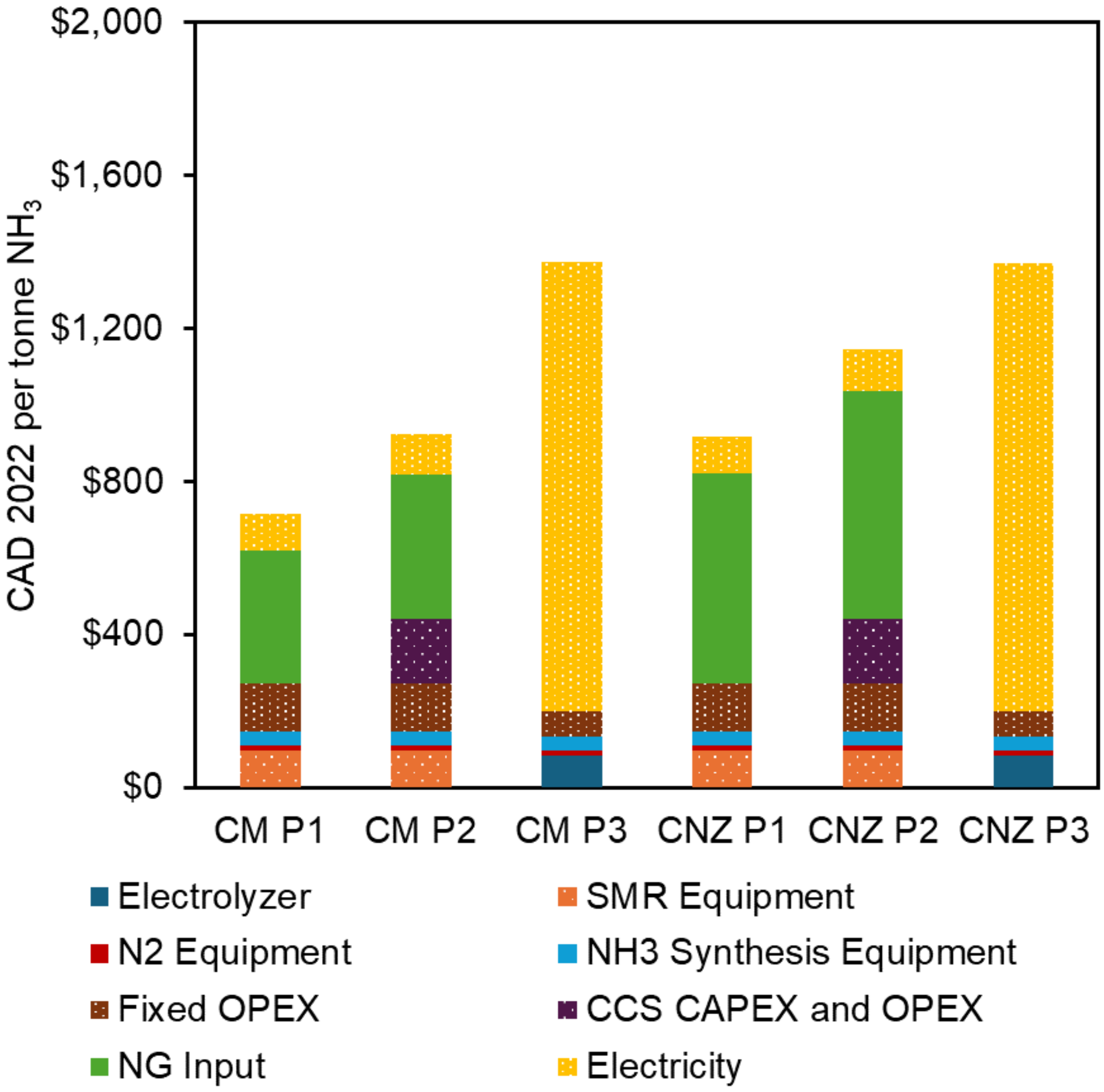


Figure 3.6 Canadian Average Production Cost Breakdown of producing one tonne of ammonia with both Current Measures and Canada Net Zero Policies

Firstly, when looking at the policy differences, the major difference is that the CNZ policies do not significantly affect the production cost of P3. However, the CNZ policies affect the costs of both P1 and P2. The difference in CNZ policy effects is because the electricity costs are predicted to be similar in both the CM and the CNZ policies [76]. P1 and P2 in the CNZ policies become around 200

CAD more expensive than with the CM policies. The increase in cost from CM policies to CNZ policies is due to the strengthened climate policies in place for CNZ, which would result in higher NG costs. The remaining components of P1 and P2 stay around the same across the policies.

Secondly, when comparing the processes, P2 is estimated to add around 200 CAD per tonne of ammonia to the cost of P1 in both policy scenarios. The additional cost is due to the CCS unit's cost, which recovers carbon that would otherwise be emitted, and the extra NG and electricity required to run the system. Even though they get more expensive across the policy scenarios, P3 is still significantly greater in production cost than P1 and P2. On average, P3 is estimated to be around 450 – 650 CAD, which is more expensive than P1, and 200-400 CAD, which is more expensive than P2. This is mainly due to the cost of electricity, which accounts for the bulk of the production cost. The energy and electricity from the grid are expensive and account for around 70% of the production cost.

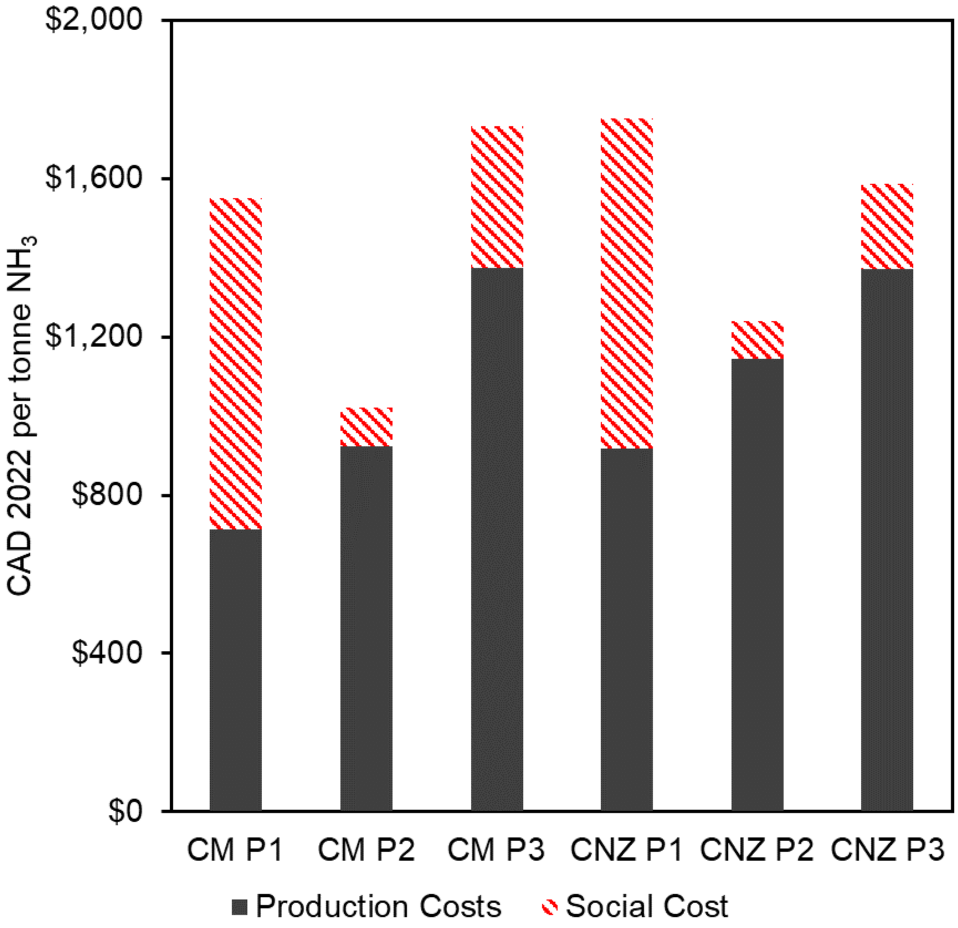


Figure 3.7 Canadian Average Levelized Cost of Ammonia Breakdown with both Current Measures and Canada Net Zero Policies with Social Cost of Carbon

Figure 3.7 shows the same graph as Figure 3.6 but with the social cost of carbon considered. With CM policies, one can see that when one considers the social cost, P2 has the lowest levelized cost of ammonia in Canada on average. One can see that P3 also starts to become competitive with P1 when social cost is considered. When the CNZ policies are in place and social costs are considered, the average levelized cost of ammonia shows a lower cost for P3 than P1. The lower cost in P3 than P1 is realized because the social cost from electrolytic ammonia is lesser than that of conventional ammonia due to the lesser average emissions. Also, there is an estimated increase in NG cost that increases the total production cost of P1 when CNZ policies are in place. However, the electricity costs for P3 remain relatively the same across the CM and CNZ policies.

This section's levelized cost is based on the Canadian average values. In the next section, I will present the variance across provinces that may show another interesting story.

3.4.3 Comparison across Provinces

The two policies compared in Figure 3.8 are the CNZ and CM Policies. The ΔLCOA criteria were judged between P1, P2, and P3, with P1 being the baseline.

From Figure 3.8, one can see that P2 is estimated to have a positive ΔLCOA in all the provinces. P2 having the positive ΔLCOA across all the provinces means that if one were to build an ammonia plant, a plant that uses SMR but with carbon capture should be the way to go across all the provinces if P1 and P2 are the only options.

Secondly, one can also see that P3 has a positive ΔLCOA in seven out of the ten provinces if the CNZ policies are in place. Only five out of the ten provinces would be positive if the CM policies were in place. The fact that there is an increase in provinces that have positive ΔLCOAs with the CNZ policies compared with the CM policies means that for most provinces, the CNZ policies will make using P3 to produce ammonia more beneficial. The increase in competitiveness in P3 ammonia is due to the estimated increased NG prices due to strengthened climate policies, which would increase the cost of both P1 and P2 ammonia. The provinces with the most negative ΔLCOAs for P3 are AB and SK because they have high costs of electricity and high grid intensities. On the other hand, the provinces with the most positive ΔLCOAs for P3 come from the provinces of MB and QB, which have low electricity costs and low grid intensities. NB, BC, and PEI are also comparable to MB And QB but have slightly lower ΔLCOAs.

Figure 3.8 also shows the ΔLCOA between P3 and P1 is higher in CNZ policies than in CM policies for all provinces but NL. The increase in ΔLCOA means CNZ policies make it more viable for most provinces to choose P3, except for NL. CNZ policies make it less viable for P3 in NL because of the projected decreased costs of NG prices in NL, which is unusual and do not occur in the other provinces [76]. The decrease in NG prices in NL are possibly because of the substantial NG reserves in NL, estimated to contain 12.6 trillion cubic feet of NG [101]. Furthermore, the projected NG prices in NL are significantly lower than those of all the other provinces. The averaged forecasted NG price in NL between 2026 and 2050 is 4.65 CAD (2022) per GJ, while the average for the rest of Canada is 11.96 CAD (2022) per GJ [76]. The low NG prices presently and forecasted in NL mean that creating a conventional ammonia plant with carbon capture may be more beneficial for that specific province.

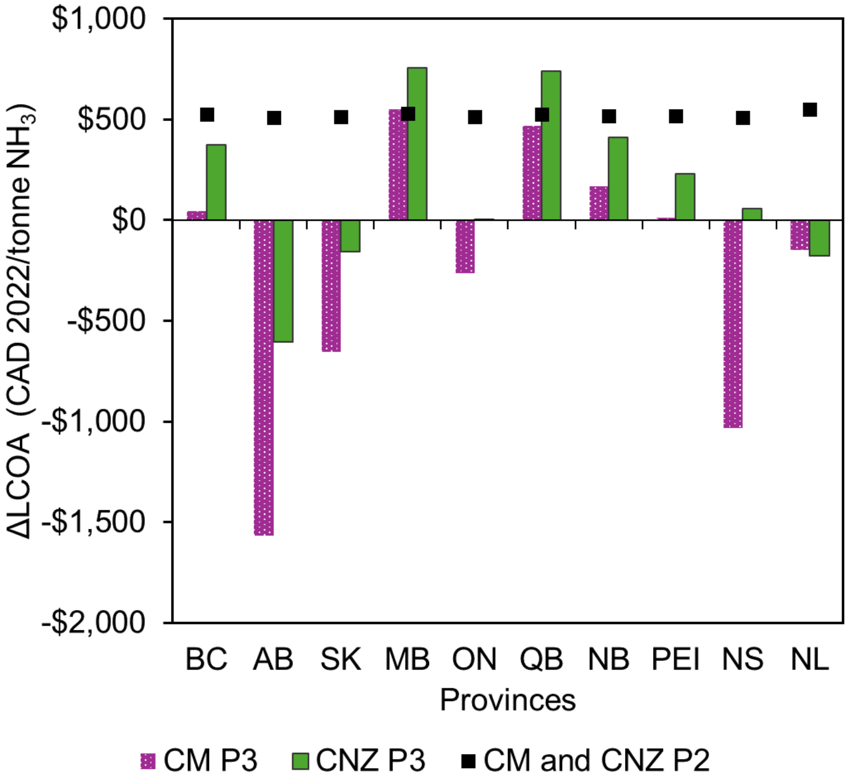


Figure 3.8 ΔLCOA across the CM and CNZ policies

3.4.4 Sensitivity Analysis

Figure 3.9 shows the Canada average case sensitivity analyses under CNZ policies. This figure shows the effect of changing each variable's value by 25% on the ΔLCOA.

The ΔLCOA is most sensitive to changes in the discount rate in both P2 and P3. An increase in the discount rate would result in significantly lesser social costs and an increase in initial investment costs, electricity and natural gas costs, and operational costs. An increased discount rate makes it less viable for P2 and P3 due to the cost increases.

For P3, electricity costs are another factor that leads to significant changes. The extensive changes from electricity costs is because of the large proportion of the LCOA of P3 made up by electrical grid costs. An increase in electricity cost, like an increase in the discount rate, reduces the benefits of the P3. For P2, an increase in electricity costs do reduce the ΔLCOA, but not as significantly because it does not make up a large component of the total costs.

Increases in grid intensity, electrolyzer costs, and CCS costs are estimated to reduce the benefits derived when choosing P2 and P3 rather than P1. The reduction in benefits is because of the increase in costs of P2 and P3 that result from those sensitivity changes. On the other hand, increases in SCC and SMR production costs increase the benefits of choosing the P2 and P3. The increase in benefits is because the costs of P1 are estimated to increase, which makes it more beneficial to choose the P2 and P3.

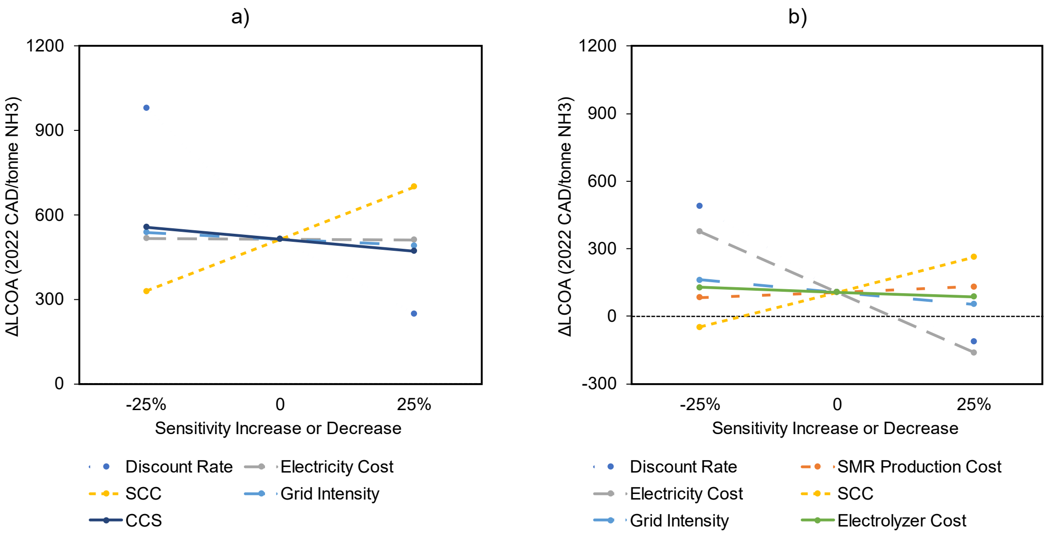


Figure 3.9 Canada Average Sensitivity Analyses of the ΔLCOA of the a) P2 and b) P3 processes when CNZ policies are in place with P1 as the baseline.

Figure 3.10 shows how changing the discount rate, SMR production cost, electricity cost, electrolyzer cost, and grid intensity will affect the overall $\Delta LCOA_3$ between P2 and P3 across provinces. In the figure, P2 is the baseline. CNZ is the policy. All provinces with negative ΔLCOAs imply that the best plant to make is to use the P2 process, which is through CCS. On the other hand, provinces with positive ΔLCOAs imply that the best plant to make would be one using the P3 process, which is through electrolysis powered by the grid.

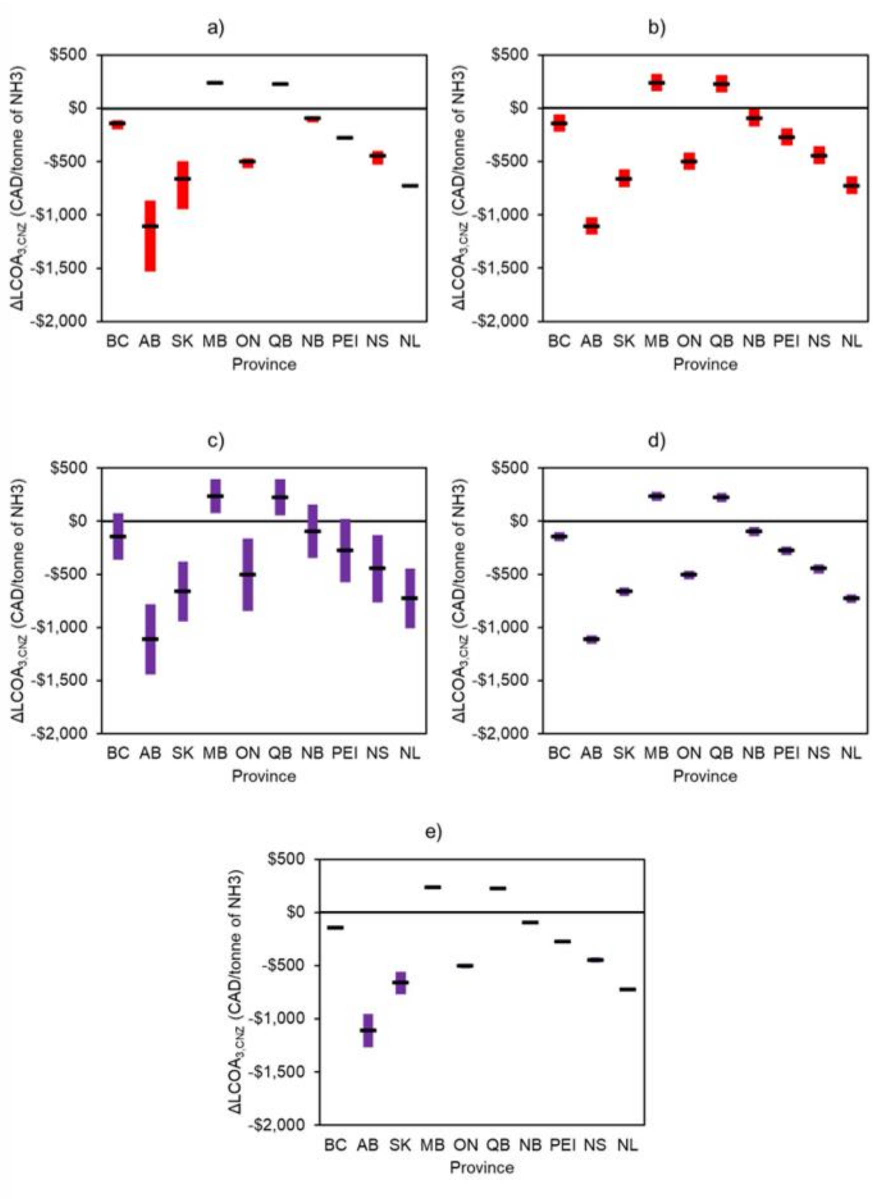


Figure 3.10 Sensitivity Analyses (+/- 25%) (2022 CAD per tonne of ammonia) between P2 and P3 across changes of specific parameters: a) Discount rate; b) SMR production cost; c) Electricity cost; d) Electrolyzer cost; e) Grid intensity. The y-axis is the ΔLCOA between P2 and P3. The red indicates a direct relationship between the discount rate and the ΔLCOA, while the purple indicates an inverse relationship. When y-axis values are positive, then P3 is the optimal choice for the province. When y-axis values are negative, then P2 is the optimal choice for the province.

Firstly, increasing the discount rate and increasing SMR production cost by 25% resulted in P2 being more costly than before and less advantageous overall. However, P2 is still often the better choice compared to P3. On the other hand, increasing electricity costs, electrolyzer costs, and grid intensities make P3 more costly, making P2 more advantageous. Specifically, electricity costs have the most significant effect on sensitivity, corroborating the previous section. P3 uses a significant amount of electricity, and changes in electricity costs significantly change P3's costs. Discount rate and grid intensity are also significant, but mainly in the provinces of AB and SK.

Secondly, it is shown in the figure that P2 is the optimal choice for most provinces except for QB and MB. QB and MB have low electricity costs and grid intensities and, according to this analysis, provide good places to produce P3 plants.

3.5 Conclusions and Recommendations

This chapter shows that the CNZ policies enhance the viability of grid-based electrolytic ammonia production (P3). The increase in viability for electrolytic ammonia is because of the increasing NG costs that make electrolytic ammonia more competitive. However, more advancements are still necessary for the P3 method to achieve cost competitiveness with both conventional ammonia production (P1) and conventional ammonia production coupled with CCS (P2). The model used in this chapter estimates that P3 ammonia production incurs costs of between 450 CAD and 650 CAD per tonne higher than conventional ammonia production processes. The P2 process is estimated to cost around 200 CAD per tonne of ammonia, which is more expensive than conventional.

However, when the SCC is considered in the cost-analysis, the P2 process becomes the most advantageous, and the P3 process becomes relatively cost-competitive with P1. This finding underlines the importance of accounting for social costs in cost assessments to represent the costs accurately.

Currently, CCS integrated with conventional ammonia production appears to offer the most significant benefits across most scenarios in Canada. The cost-effectiveness of electrolytic ammonia production varies significantly by province due to differences in grid emissions intensities and electricity costs. For instance, in provinces such as Alberta and Saskatchewan, using the electrical grid for electrolytic ammonia production results in higher costs and emissions than conventional methods, primarily due to the high emissions intensity and high grid electricity costs. Conversely, Quebec and Manitoba are more favorable candidates for grid-based P2A production due to their lower electricity costs and lower emissions intensities. The expense of electricity currently drives high production costs for P2A. Therefore, strategies to lower electricity costs, reduce grid emissions intensities, and increase the costs of SMR could allow for broader adoption of electrolytic ammonia. However, overall, CCS remains Canada's most cost-effective approach for decarbonizing ammonia production.

Future research should help enhance the accuracy and comprehensiveness of economic cost and benefit analysis, which can be achieved by integrating a range of factors such as learning curves, the efficiency, and costs of carbon capture equipment, logistics, the social costs of other pollutants, and detailed considerations of revenue and demand within the country. Different time scales, learning curves, and more sophisticated costing methods may result in more accurate forecasts and decision-making capabilities. Exploring alternative ammonia production technologies, such as those based on direct renewables or electrochemical processes, may also be helpful for their potential contributions in the green ammonia transition.

The conclusions and recommendations in this chapter provide a more comprehensive understanding of the techno-economics influencing the transition to greener ammonia production methods and grid-based electrolytic ammonia production. This chapter may help develop policies and strategies that effectively balance economic feasibility with environmental sustainability. Such research is vital for optimizing our ammonia production methods today and encouraging innovative solutions that can enhance the sustainability and economic viability of greener ammonia production in the context of Canada’s climate change goals.

Chapter 4 Incentives and Effects of Green Ammonia Production

4.1 Introduction

Efforts are being made in industries around the world to reduce greenhouse emissions in various sectors as they have “unequivocally” caused global warming, according to the Intergovernmental Panel on Climate Change (IPCC) [46]. The significant efforts are due to the risks of climate change, which can devastate the environment and human populations [47], [102]. Greenhouse gas emissions are often externalities from the production of valuable things such as energy for electricity, transportation, and manufacturing of products [84], [103], [104], [105]. Finding ways to reduce that externality in industries such as ammonia production is essential as ammonia manufacturing contributes to around 1.8% of global greenhouse gas emissions [67]. Understanding the economics and incentives that can transition ammonia production from one that is carbon-intensive to one that is not carbon-intensive can prove helpful to the world as motivation to reduce greenhouse gas emissions increases.

The ammonia fertilizer market and the energy market in the world is presently run by oligopolies [106]. An oligopoly is when a few firms run the market, often when there are very high barriers to entry [60]. Ammonia production often requires large process units, making it more suitable for large-scale manufacturing [107]. Large-scale manufacturing often results in considerable barriers to entry due to the significant initial investment costs. Examples may include oil companies, pharmaceutical companies, and the automotive industry. Oligopolies are often attractive to study as they lie between the two types of markets studied in economics, i.e., markets that fall under monopoly and those that fall under perfect competition.

In Canada, nine facilities and five companies produce around 4-5 million tonnes of ammonia per year in the conventional natural gas way [8], [108]. With the rise of new demands for ammonia in the field of energy storage as well as the increasing demand for low-carbon fertilizer, green ammonia firms could enter the market [96], [109]. This chapter analytically and numerically models what markets would look like if green production firms entered.

This research aims to figure out ways governments can optimize social welfare using instruments such as emission taxes in the context of the ammonia production industry when there are differences in emissions. The research question aimed to be answered is “How can social welfare be maximized in the ammonia industry using government instruments?" This question is framed within the context of taxes, subsidies, numbers of firms, and capacity constraints in green firms.

It is observed in this chapter that taxes can work better at higher social costs. However, because the social costs are relatively low compared to the benefits, using subsidies may be more beneficial. Generally, it is observed that increasing the number of firms brings greater welfare as it increases competition within the industry, lowering the price for consumers. However, increasing the number of green firms can increase the amount of conventional ammonia produced in some cases where conventional production costs are low. Lastly, it is observed that capacity constraints in the green firms result in an allocation issue that reduces social welfare relative to one without capacity constraints. Since there may be higher demands and profits from ammonia used as a fertilizer rather than energy storage, incentives may be required for the green ammonia to be sold to energy storage if there is a capacity constraint issue.

Presently, some literature theoretically analyzes how the presence of emission taxes and subsidies can incentivize the emergence of green technologies. Fu et al. [110] studied how two competing production firms under Cournot fashion with different sets of emissions would fair with opportunities to make green technology investments fair under a carbon tax. They found that the carbon tax does not necessarily induce the adoption of green technology and that the carbon-inefficient firm is more likely to benefit from the green technology. Buccella et al. [111] analyze a Cournot polluting duopoly where two firms produce homogenous goods with the choice to abate under three policies: an emissions tax, an abatement subsidy, and a policy mix. They find that a subsidy, alone or coupled with a tax, always increases abatement. Furthermore, taxes can lower production, negatively impacting profits and consumer surplus. At a particular environmental damage per unit good, reducing production and increased tax revenues offset the negative impact of reduced profits and consumer surplus due to output contraction. Krass et al. [112] examined the role that environmental taxation can play in reducing environmental pollution for one profit-maximizing firm that has the choice to invest in greener technology. They find that high levels of taxes may induce dirtier rather than cleaner technology and that high levels of emissions may react similarly to high levels of taxes. In that case, the firm would choose to produce less with less abatement due to the high costs. They also find that supplementing environmental taxation with subsidies and consumer rebates may help the choosing of greener technology. Guo et al. [113] examine the effects of a carbon tax and a subsidy if the government could only choose one policy. They show that as marginal environmental damage of the high carbon product increases, the control instrument should change from a subsidy to a carbon tax policy. Yi et al. [114] investigate the impact of green subsidies and emission taxes for a supply chain consisting of a manufacturer and a retailer, considering consumer preferences and green investment options from the manufacturers. They found that if the marginal cost of green technology is low or the marginal damage cost of pollution is high, the government seeking to maximize social welfare should choose a green subsidy policy; otherwise, it should apply an emission tax. Vidal-Melia et al. [115] explore how market size asymmetry influences government environmental policies in bilateral trade. They find that governments should shift from emission taxes to production subsidies as market size asymmetry grows. They suggest effective policies should regulate these subsidies and improve practices to mitigate pollution.

There has also been literature that analyzes the impacts of carbon taxes on green technology adoption and the economy from a more numerical and empirical perspective. Hu et al. [116] proposed an oligopoly game theoretical model with competition occurring in a Cournot fashion to analyze green and ordinary manufacturing sectors. They investigate how cost efficiency, innovative design, Pigouvian taxes, and subsidies can affect market competition. Their model is slightly more optimistic for green products than real market statistics from Corolla/Prius and Incandescent/Fluorescent comparisons. Norouzi et al. [117] performed a carbon tax simulation for the Iranian economy using game theory and modeled it with three actors: the government, energy intermediaries, and a final product firm to find an optimal tax rate and subsidy. They found that a 9% tax rate on the Iranian Gross Domestic Product, an 18% tax on fossil fuel energy prices, and a 53% and 47% reallocation of the tax revenues back into investment into renewables and to households, respectively, is the optimal way forward for the government. Liu et al. [118] conducted a case study using a computable general equilibrium model for the province of Saskatchewan and analyzed the socio-economic impacts of a carbon tax throughout the province. They found that a carbon tax will reduce GHG emissions while contracting the economy and possibly reducing the GDP. They suggest that clean coal and petroleum technologies are critical issues in simultaneously achieving economic growth and GHG reduction.

This chapter aims to provide better insight into how zero-emission firms will interact with high-emissions firms within the same market under various policies and market characteristics. The literature reviewed above is not specific to ammonia, and this chapter fills that research gap in the economic literature of green transition specific to green ammonia and reducing carbon emissions related to ammonia. The research in this chapter aims to also incorporate the fact that green ammonia may be demanded not just from the consumers of fertilizer but for the consumers for green energy storage.

The next sections are as follows: Section 4.2 conveys the baseline model and framework, Section 4.3 describes how various changes to the system will change the welfare, Section 4.4 then summarizes the report and provides policy implications and conclusions from the results.

4.2 Model

4.2.1 Framework

Let us consider one conventional firm and one green firm that produces ammonia. Thus, we have a Cournot model in which the two firms compete in quantities. The conventional firm produces a quantity of H while the green firm produces a quantity of G. The conventional firm produces each unit of ammonia at a marginal cost of production given by $C_H + \tau\xi_H$. The first term is the base cost of producing one unit of ammonia, while the second term is the tax per unit of pollution multiplied by the units of pollution per unit of ammonia. The green firm produces each unit of ammonia at a marginal cost of C_G. For simplicity, the marginal cost is not influenced by the quantity of product in this chapter. The green firm does not have a second term as it produces zero emissions while the conventional firm would. We assume that $C_G > C_H$ for the most part to represent the greater cost that often occurs for producing greener ammonia. Also, another assumption is that the capital and the operational costs over the lifetime can be analyzed by one base cost per unit ammonia which can be attributed to a levelized cost of ammonia [59].

The conventional firm would only produce for one sector of buyers, the fertilizer sector, while the green firm could produce for two sectors: the fertilizer sector and the energy storage sector. This is the case as Canada's ammonia demand for energy storage is only for low-carbon ammonia [96]. In this case, for simplicity, it is only for zero-emission ammonia, representative of the green firms. Furthermore, the assumption is made that all the ammonia that is supplied to each of those sectors is bought and that the ammonia for fertilizer is not further processed into urea. Another assumption here is that conventional firms cannot choose to abate their emissions. The demand curves are all assumed to be linear inverse and are assumed only to be influenced by the price. The demand curve for fertilizer ammonia is given by $p(X') = \alpha_{X'} - \beta_{X'}(X')$. X' represents the sum of the quantity of conventional ammonia that is produced, given by H, and the quantity of green ammonia that is produced, given by $G_X : X' = H + G_X$. It is assumed that buyers of the fertilizer ammonia only have one price to choose from and would only buy the least expensive ammonia available to them. The demand curve for energy storage ammonia is given by $p(Z) = \alpha_Z - \beta_Z(Z)$. Z represents the amount of ammonia produced for the energy storage sector by the green firm.

Lastly, in this framework, there is also the government. This government can impose an emission tax, represented by τ which is the unit of tax per unit of pollution. Each unit of pollution would have a unit damage cost of v. The emissions assumed in this chapter will only be for greenhouse gases and climate change. In this chapter, the optimal tax will be analytically calculated so that a benevolent government can administer the tax that will optimize for the highest welfare. This government is assumed to be able to accurately predict the profits, consumer surpluses, and emissions to estimate a social welfare function.

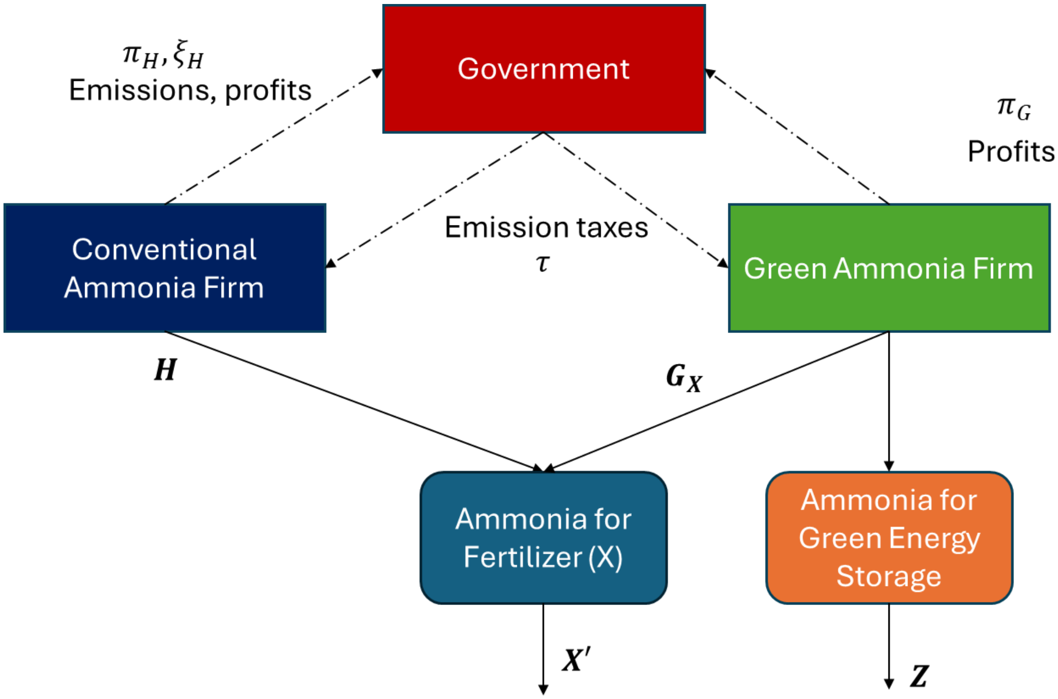


Figure 4.1 Schematic of the Framework for the baseline 2 firm Cournot Model

Figure 4.1 shows the overall schematic of the baseline Cournot model. The dotted lines represent some of the information flows, where each firm will share its profits and emissions while the government will impose the tax. The solid lines represent the unit product flows – in this case, it would be either ammonia for fertilizer or green energy storage.

4.2.2 Profit Optimization and Equilibrium Quantities

Given the costs and demand curves, each firm will optimize the quantity of their production via Cournot competition. Simultaneously, they will choose their quantities by optimizing their profits. The profit of the conventional firm is given by

$$\pi_H = p(X')(H) - (C_H + \tau\xi_H)(H) \tag{13}$$

However, since the price of ammonia changes based on the quantity of X' which is the sum of H and G_X the equation changes to:

$$\pi_H = \left(\alpha_{X'} - \beta_{X'}(H + G_X)\right)(H) - (C_H + \tau\xi_H)(H) \tag{14}$$

Now to maximize the profit, one can derive the first-order condition by taking the derivative of the profit function with respect to H and setting it equal to 0. The derivative will result in the equation that states that the marginal revenue equals the marginal cost.

$$\alpha_{X'} - 2\beta_{X'}(H) - \beta_{X'}(G_X) = C_H + \tau\xi_H \tag{15}$$

A profit equation can be generated with the green industry for the two products it generated, which is given by:

$$\pi_G = \left(\alpha_{X'} - \beta_{X'}(H + G_X)\right)(G_X) - (C_G)(G_X) + \left(\alpha_Z - \beta_Z(Z)\right)(Z) - C_G(Z) \tag{16}$$

By deriving the first-order condition in a similar way as the conventional firm, another equation can be made for the green firm for the fertilizer industry, but with respect to G_X and that is given by:

$$\alpha_{X'} - \beta_{X'}(H) - 2\beta_{X'}(G_X) = C_G \tag{17}$$

However, since the green firms produce two products, the profit function can be optimized in two different ways and that is with respect to G_X or Z. Therefore, the profit maximization first-order condition with respect to Z is given by.

$$\alpha_Z - 2\beta_Z Z = C_G \tag{18}$$

With equations (15), (17), and (18), we can now calculate the equilibrium quantities by solving for H, G_X, and Z. Equations (**19**), (**20**), and (21) show the quantities respectively.

$$H = \frac{C_G - 2\,C_H + \alpha_{X'} - 2\,\tau\,\xi_H}{3\,\beta_{X'}} \tag{19}$$

$$G_X = \frac{C_H - 2\,C_G + \alpha_{X'} + \tau\,\xi_H}{3\,\beta_{X'}} \tag{20}$$

$$Z = \frac{\alpha_Z - C_G}{2\,\beta_Z} \tag{21}$$

An interesting corollary result is that if the marginal cost of the conventional firm $(C_H + \tau\xi_H)$ is equal to the marginal cost of production of the green firm (C_G), then $H = G_X$. The corollary indicates that the quantity the conventional firm produces will equal the green firm. This corollary is highly dependent on the capacity constraints of both firms, but in the baseline model, there are no capacity constraints, so each of the firms is free to produce as much as necessary. Conventional ammonia production has a much larger capacity than green ammonia production, which is still in the early stages [7]. The other point is that whichever firm has a higher (lower) marginal cost will produce less (more).

4.2.3 Equilibrium Price

Now given the quantities, one can obtain the price of the fertilizer and the energy storage ammonia by substituting equations (19), (20), (21) into their respective demand curves. Equations (22) and (23) are then obtained.

$$p(X') = \frac{C_G}{3} + \frac{C_H}{3} + \frac{\alpha_{X'}}{3} + \frac{\tau\,\xi_H}{3} \tag{22}$$

$$p(Z) = \frac{C_G}{2} + \frac{\alpha_Z}{2} \tag{23}$$

One can see here that the demand for ammonia influences the fertilizer sector's ammonia price, the costs of production of both firms' ammonia, and a tax and emission factor. On the other hand, the price for green energy storage ammonia is only influenced by the cost of producing green ammonia and the demand for green ammonia energy storage. In general, when production costs increase, the ammonia price will increase. Also, when the demand, emissions, and taxes increase, the price of ammonia will increase.

4.2.4 Equilibrium Profits

Now, with the prices and the quantities, one can determine the profits of the two firms. The conventional firm's profit equation is shown in equation (24), while the green firm's profit equation is shown in equation (25).

$$\pi_H = \frac{(C_G - 2\,C_H + \alpha_{X'} - 2\,\tau\,\xi_H)^2}{9\,\beta_{X'}} \tag{24}$$

$$\pi_G = \frac{\left(\frac{C_G}{3} + \frac{C_H}{3} + \frac{\alpha_{X'}}{3} + \frac{\tau\,\xi_H}{3}\right)(C_H - 2\,C_G + \alpha_{X'} + \tau\,\xi_H)}{3\,\beta_{X'}} - \frac{{C_G}^2 - {\alpha_Z}^2}{4\,\beta_Z} - \frac{C_G\,(2\,C_H\,\beta_Z - 4\,C_G\,\beta_Z - 3\,C_G\,\beta_{X'} + 2\,\alpha_{X'}\,\beta_Z + 3\,\alpha_Z\,\beta_{X'} + 2\,\beta_Z\,\tau\,\xi_H)}{6\,\beta_{X'}\,\beta_Z} \tag{25}$$

The profit equation for the conventional firm is more straightforward than that of the green firm because the conventional firm only sells one product while the green firm sells two. Overall, the cost of production of a firm negatively impacts their own firm's production and profit while positively impacting the other firm's production and profit. The demand increases both of their profits.

4.2.5 Consumer Surplus

The consumer surplus is obtained similarly to the profits by substituting the prices and quantities for the consumer surplus function for both X' and Z . The consumer surplus for fertilizer is obtained by taking the integral of the demand function from 0 to X' and subtracting the amount consumers pay. Below is the initial equation for X'.

$$CS_{X'} = \int_0^{X'} \{\alpha_{X'} - \beta_{X'}(X')\} dX' - p(X')X' \tag{26}$$

When finding the integral with respect to X' and substituting the X' quantity - which is the sum of H and G_X - the $CS_{X'}$ can now be obtained analytically. The resulting equations for the consumer surpluses of X' and Z are now shown in Equations (27) and (28):

$$CS_{X'} = \frac{1}{18\,\beta_{X'}}(C_G + C_H - 2\,\alpha_{X'} + \tau\,\xi_H)^2 \tag{27}$$

$$CS_Z = \frac{1}{8\,\beta_Z}(\alpha_Z - C_G)^{\,2} \tag{28}$$

4.2.6 Social Cost and Tax Revenue

The social cost and tax revenue are dependent on finding the emissions. The emissions are determined by multiplying the quantities with an emission factor. In this case, since this model only has an emission factor for conventional industry (ξ_H) the emissions can be determined. The social cost and the tax revenue is then a scalar multiple of the emissions, which are now determined and is obtained by multiplying the given tax or social cost with the total emissions. Below are the resulting social costs and tax revenue.

$$SC = \frac{\nu\,\xi_H\,(C_G - 2\,C_H + \alpha_{X'} - 2\,\tau\,\xi_H)}{3\,\beta_{X'}} \tag{29}$$

$$TR = \frac{\tau\,\xi_H\,(C_G - 2\,C_H + \alpha_{X'} - 2\,\tau\,\xi_H)}{3\,\beta_{X'}} \tag{30}$$

As one can see, the social cost and the tax revenues are just scalar multiples of the quantity of H. It is easy to see that if the unit social cost ν is equal to the unit pollution tax τ then the total social cost and the tax revenue expressions are equal.

4.2.7 Welfare

In this work, the welfare equation is given by the equation:

$$W = \pi_H + \pi_G + CS_X + CS_Z + TR - SC \tag{31}$$

Equation (31) represents welfare and is the sum of the profits of the conventional and the green firms, the consumer surpluses of the fertilizer and energy storage sectors, the tax revenue from the pollution tax, and the negative of the social cost from emissions. From the analytical solutions to each of the quantities, one can substitute each of the welfare components (profits, consumer surpluses, tax revenues, and social costs) from the previous equations and find that the analytical solution to welfare is given below:

$$\begin{aligned} W = -\frac{1}{72\,\beta_{X'}\,\beta_Z}\big(&56\,C_G\,C_H\,\beta_Z - 44\,C_G{}^2\,\beta_Z - 44\,C_H{}^2\,\beta_Z - 32\,\alpha_{X'}{}^2\,\beta_Z - 27\,\alpha_Z{}^2\,\beta_{X'} \\ &- 27\,C_G{}^2\,\beta_{X'} + 32\,C_G\,\alpha_{X'}\,\beta_Z + 54\,C_G\,\alpha_Z\,\beta_{X'} + 32\,C_H\,\alpha_{X'}\,\beta_Z + 4\,\beta_Z\,\tau^2\,\xi_H{}^2 \\ &+ 8\,\alpha_{X'}\,\beta_Z\,\tau\,\xi_H + 24\,\alpha_{X'}\,\beta_Z\,v\,\xi_H - 48\,\beta_Z\,\tau\,v\,\xi_H{}^2 + 32\,C_G\,\beta_Z\,\tau\,\xi_H \\ &- 40\,C_H\,\beta_Z\,\tau\,\xi_H + 24\,C_G\,\beta_Z\,v\,\xi_H - 48\,C_H\,\beta_Z\,v\,\xi_H\big) \end{aligned} \tag{32}$$

4.2.8 Optimal Tax

The optimal tax for the model can now be obtained from an analytical solution to welfare. The tax is obtained by taking the derivative of the welfare function with respect to τ, setting the derivative to be equal to 0, and then isolating for τ. The result for the specific model is found below:

$$\tau^* = -\frac{4\,C_G - 5\,C_H + \alpha_{X'}}{\xi_H} + 6\,v \tag{33}$$

The optimal tax (τ^*) must be greater than 0 and not yield a negative H quantity. Therefore, the lower limit to τ^* is 0, while the upper limit to τ^* is $\frac{C_G+\alpha_{X'}-2C_H}{2\xi_H}$, which would yield H of 0.

Since the first term is most likely negative due to the demand parameter, an increase in the emissions rate would increase the optimal tax, while a decrease in the emission rate would decrease the optimal tax. The direct relationship between emissions and optimal tax is relatively intuitive. If the conventional firm decides to decrease its emission rate by committing to some pollution or carbon abatement, the government could also reduce the tax rate.

This equation shows that the unit social cost and the optimal tax are unequal. Contrary to a traditional Pigouvian Tax, which states that the social cost should be equal to the tax if a social cost can be gauged, this chapter's model shows that the optimal tax could be equal to, less than or more than the social cost [119]. Furthermore, it shows that an increase in social and conventional production costs increases the optimal tax. On the other hand, an increase in the production cost of green ammonia and an increase in demand for fertilizers decreases the optimal tax.

An interesting thing to note here is that increasing the production cost of green ammonia decreases the tax. In other words, the tax should be decreased if the green ammonia costs more. The opposite holds with conventional ammonia. When the cost of conventional ammonia increases, so should the tax. The relationship is counterintuitive as higher green ammonia costs should require more significant taxes on the conventional to switch to green. However, since the welfare function does not prefer green or conventional, it would tax to optimize only for what maximizes the welfare function. If marginal green ammonia costs more, the tax would be lower to incentivize people to use conventional. This is most likely due to the desire to shift the markets to the most efficient cost-wise. Simpson et al. [120] and Carlsson et al. [121] observed similar trends when finding the optimal tax for a Cournot duopoly with varying costs. They found that the optimal tax may be lesser or greater than the social cost as the tax can be an effective instrument to allocate production due to cost efficiency and the nature of imperfect competition.

In this analysis, the optimal tax considers the difference in pollution. If the green ammonia firm incurs much more costs to produce one unit of ammonia, then the tax should shift the market towards one unit of conventional ammonia, which costs less and can be incentivized by lowering the taxes. If the conventional ammonia firm incurs more costs to produce the same amount of ammonia than the green ammonia firm, then the tax should shift the market towards the green ammonia firm, which is done by raising the taxes.

4.3 Welfare Analyses

4.3.1 Baseline Parameters

Due to some of the model analyses having very complicated analytical equations, a numerical analysis was performed for the model to confirm and check the robustness of our explicit results. Number values to the variables relevant to the demand functions, marginal costs, and social costs equations were retrieved. These variables were obtained through previous analyses in Chapter 3 or from the literature. These parameters are displayed in the table below; some information regarding the derivation of each of the parameters can be obtained from the appendix.

Table 4.1 Numerical Analyses parameters

Parameters	Symbol	Value	Units	Source
Baseline				

Fertilizer demand parameter y-intercept	$\alpha_{X'}$	4360.9	CAD	[108], [122], [123] Use urea prices as proxy (more info in Appendix)
Fertilizer demand parameter slope	$\beta_{X'}$	0.0008449	CAD/tonne of NH_3	[108], [122], [123] Use urea prices as proxy (More information in Appendix)
Energy storage demand parameter y-intercept	α_Z	1923	CAD	[3], [96], [124], [125] Use hydrogen price elasticity as proxy. (More information in Appendix)
Energy storage demand parameter slope	β_Z	0.00125	CAD per tonne of NH_3	[3], [96], [124], [125] Use hydrogen price elasticity as proxy. (More information in Appendix)
Marginal production cost of green ammonia	C_G	1300	CAD	Chapter 3
Marginal production cost of conventional ammonia	C_H	800	CAD	Chapter 3
Emissions from conventional ammonia	ξ_H	2	Tonnes of CO_2 per tonne of ammonia	[8]
Social cost of Carbon	v	266	CAD per tonne of CO_2	[49] Use 2024 estimate.
Baseline tax	τ	80	CAD per tonne of CO_2	[54] Use 2024 Canadian Carbon tax.
Other parameters for Effects				
Subsidy	S_b	160	CAD per tonne of NH_3	Equal in value to the tax per tonne of NH_3
Green ammonia firm capacity	$\bar{G}$	600000	Tonnes of NH_3	[96] Assume 20% more than the 500,000 tonnes from Uniper agreement

4.3.2 Baseline Scenario

4.3.2.1 Resulting values

With the parameters from 4.3.1, the equilibrium results for the model's baseline scenario described in section 4.2 was generated. The quantities and prices are displayed in Table 4.2.

Table 4.2 Equilibrium Quantities and Prices for Baseline Scenario

Variable	Values	Units
H	1,475,900	Tonnes of NH_3
G_X	1,073,500	Tonnes of NH_3
Z	249,200	Tonnes of NH_3
X'	2,549,300	Tonnes of NH_3
$p(X')$	2,207	CAD per tonne of NH_3
$p(Z)$	1,612	CAD per tonne of NH_3
Total Emissions	2,951,800	Tonnes of CO_2

Table 4.2 shows that the quantity of conventional ammonia is larger than green ammonia for fertilizer. The difference in quantity is due to the lesser marginal cost of conventional ammonia. Energy storage ammonia quantity is also significantly less than fertilizer ammonia. Emissions are two times the quantity of conventional ammonia due to the emission factor. The price of ammonia for fertilizer is estimated to be much higher than what is found presently because there is only one firm in each industry, and they will exhibit monopolistic behavior. As of July 12, 2024, the price of ammonia was estimated to be around 1047 CAD per tonne of NH_3 using a conversion rate of 1.37 CAD:USD [123]. The price of ammonia presently is significantly less than the 2207 CAD per tonne of NH_3 estimated in this analysis. However, there were times in 2022 when ammonia prices reached high levels of over 2200 CAD per tonne of NH_3 [126].

The results for the welfare components are provided, showing the respective values in the form of a bar chart in Figure 4.2 obtained for the baseline scenario. Appendix B shows the exact values.

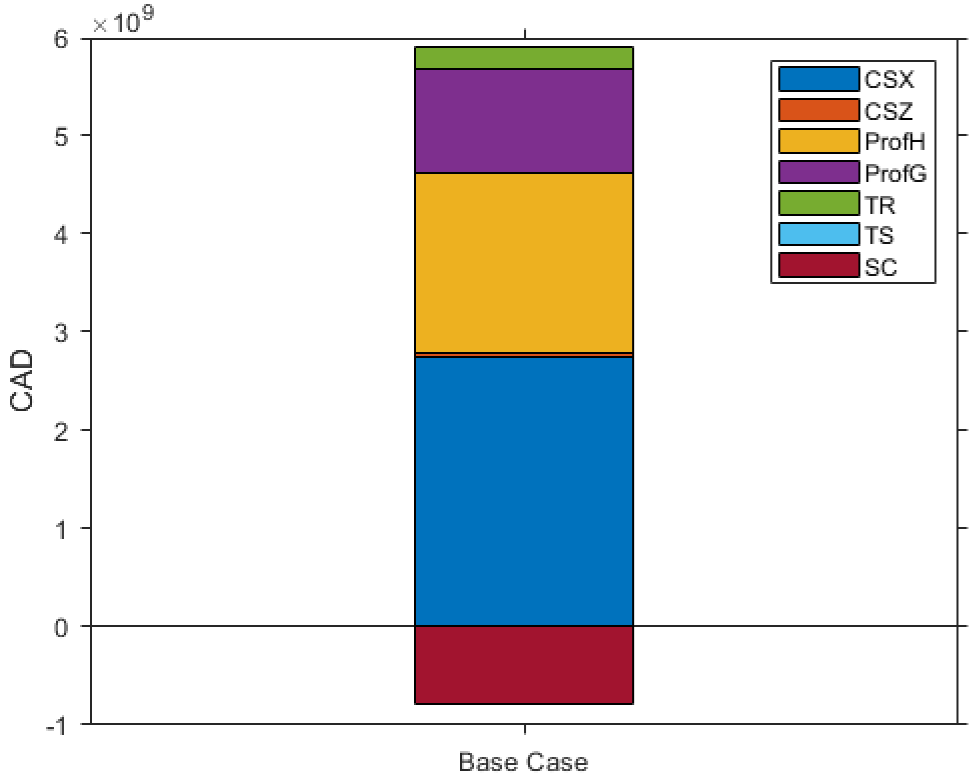


Figure 4.2 Welfare components for baseline scenario

The values show that the two largest components that influence welfare are the consumer surplus associated with the use of ammonia as a fertilizer and the profits of the conventional firm represented by *CSX* and *ProfH,* respectively, with the profits of the electrolytic firm (*ProfG*) following soon after. The social cost (*SC*) also contributes significantly to the overall cost. The consumer surplus from energy storage (*CSZ*) does not provide a large share of the overall components of welfare.

The optimal tax with the baseline scenario was determined to be zero. An optimal zero tax means that welfare is at maximum when there is no carbon tax in this industry. Using the optimal zero tax, the highest welfare retrieved was 5.17 billion dollars, more significant than the 5.12 billion dollars with the baseline tax of 80 CAD per tonne of carbon dioxide. An optimal tax of zero means that the optimal tax is less than the social cost of carbon dioxide on society. The optimal tax being less than the social cost is most likely due to the desire to shift markets to more efficient methods of production (conventional) and the desire to lower prices for greater consumer surplus and quantities, which are part of the welfare components.

4.3.2.2 Sensitivity Analyses on Baseline Scenario

The sensitivity analyses in Figure 4.3 analyzed the sensitivity of the welfare and emissions to a change in the parameters by adding and subtracting 25% to the baseline scenario parameters while holding the other parameters constant.

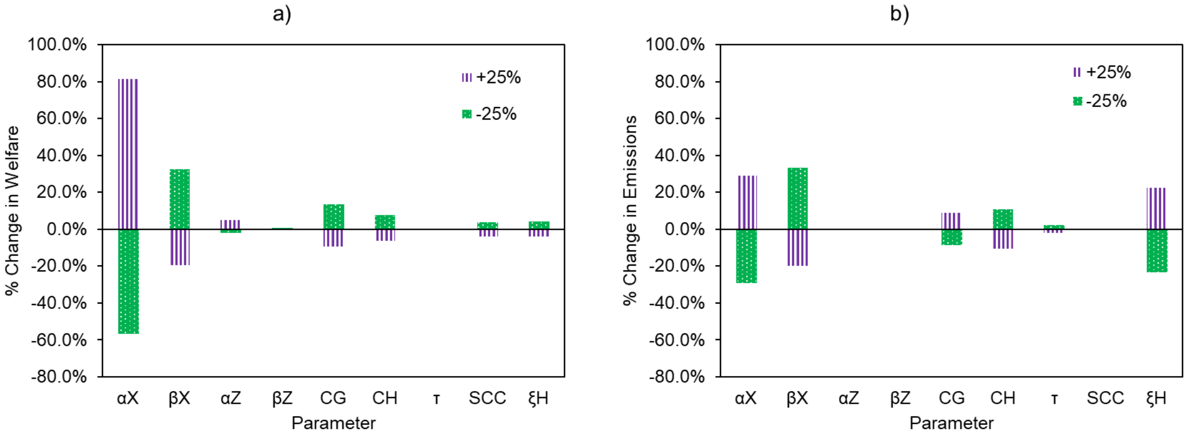


Figure 4.3 Sensitivity analyses of the parameters with respect to the change in a) Welfare and b) Emissions

Figure 4.3 shows that the parameters that resulted in the largest of changes in both welfare and emissions were the demand parameters for the fertilizer ($\alpha_{X'}$ and $\beta_{X'}$). $\alpha_{X'}$ has a direct relationship to the welfare and emissions while $\beta_{X'}$ has an inverse relationship to welfare and emissions. Increasing demand for fertilizer increases overall societal welfare, as there would be more consumer surplus and profits while decreasing demand does the opposite. These can have effects that change the welfare by 40-60% and the emissions by around 20-30%, with a 25% change in the demand parameters. The demand parameters for energy storage do not affect the welfare or emissions very greatly, and this is because of the lesser quantity demanded.

In addition, marginal costs can play a significant role in sensitivity. Increasing the marginal cost of green ammonia decreases welfare and increases emissions. However, increasing the cost of conventional ammonia decreases welfare, and increases emissions. The marginal cost parameter changes have effects of around 5-15% of the welfare and emissions.

The optimal tax does not change in all the sensitivities with a 25% change, and it is still recommended to be zero. However, the optimal tax can change with the greater social costs of carbon and emissions past the 25% change. A social cost of carbon of around \$463 or an emissions ratio of around 3.49 while holding everything else constant will result in a positive optimal tax for this industry. An optimal tax would be zero for this industry, but the optimal tax could change with higher emissions or higher emissions costs.

4.3.3 Effects of Increasing Number of Firms

The assumption of symmetry within their type of firms is made to analyze the effects of increasing the number of conventional or green firms. The assumption of symmetry means that each conventional firm would be identical to each other, and each green firm would be identical. The assumption is made out of simplicity and is a limitation of this study. In Canada, ammonia firms are asymmetrical, with some firms producing larger amounts than others [8], [35]. We consider the number of conventional firms as M and the number of green firms as N. Then we do the same analyses as above where each firm will produce via Cournot oligopoly. The resulting quantities and prices are displayed below in Table 4.3.

Table 4.3 Analytical solutions to the Quantities and Prices considering number of Firms

Product	$M = 1, N = 1$	Any $M\ and\ N$
H	$\frac{C_G - 2\,C_H + \alpha_{X'} - 2\,\tau\,\xi_H}{3\,\beta_{X'}}$	$\frac{M\,(\alpha_{X'} - C_H - \tau\,\xi_H + N(C_G - C_H - \tau\xi_H))}{\beta_{X'}\,(M + N + 1)}$
G_X	$\frac{C_H - 2\,C_G + \alpha_{X'} + \tau\,\xi_H}{3\,\beta_{X'}}$	$\frac{N\left(\alpha_{X'} - C_G + M(C_H + \tau\xi_H - C_G)\right)}{\beta_{X'}\,(M + N + 1)}$
Z	$\frac{\alpha_Z - C_G}{2\,\beta_Z}$	$\frac{N\,(\alpha_Z - C_G)}{\beta_Z\,(N + 1)}$
$p(X')$	$\frac{C_G}{3} + \frac{C_H}{3} + \frac{\alpha_{X'}}{3} + \frac{\tau\,\xi_H}{3}$	$\frac{\alpha_{X'} + C_H\,M + C_G\,N + M\,\tau\,\xi_H}{M + N + 1}$
$p(Z)$	$\frac{C_G}{2} + \frac{\alpha_Z}{2}$	$\frac{\alpha_Z + C_G\,N}{N + 1}$

For H, both increasing M and N can result in larger quantities of H. The increase in H is because M is multiplied by a net positive set of parameters in the numerator and multiplied by N, which is itself multiplied by positive terms within the bracket. The increase in H assumes that $C_G - C_H - \tau\xi_H > 0$.

Since the numerator is constrained to positivity, as we assume no negative quantities, then we can see that any increases to M will undoubtedly result in increases to H. However, the increases in H may not be the case when increasing N. If $C_G - C_H - \tau\xi_H < 0$, then increasing the N firms may result in decreases to H. The decrease in H is because N will then be multiplied by a negative term. The negative term would be the case if green firms became significantly more cost-efficient than conventional firms. More competitive green firms may result in less H being bought as fertilizer.

As an analog to H, for G_X, increasing N will result in strictly increasing the total G_X. However, increasing the number of M firms may result in decreases to G_X because it is multiplied by a most likely negative expression $(C_H + \tau\xi_H - C_G)$. However, if the production cost of green ammonia decreases (or the production cost of conventional ammonia increases), then increasing M may make it more positive.

Why would increasing N (M) increase the H (G_X) ammonia being produced? There are two interesting cases to consider from the equilibrium quantities related to fertilizer ammonia. Firstly, this occurs to H at high green ammonia costs and low conventional costs when increasing the number of green ammonia firms. Secondly, this occurs to G_X at high conventional ammonia costs and low green ammonia costs when increasing the number of conventional firms. These are analogous to one another as each quantity benefits from the inefficiencies of the other industry. An increase in N strictly increases, G_X, which will then lower $p(X')$. For the first case, lowering the price of ammonia will result in conventional firms having to produce more conventional ammonia to obtain more profit. Conventional firms will decide to produce more since they have a significantly lower marginal cost than green ammonia. In the second case, the same thing occurs, but with the green ammonia firms deciding to produce more due to the higher efficiencies and increased competition. One can see that increasing the number of firms in one industry may not lower the other industry's quantity. The market will shift to what is most cost-efficient as well.

For Z, increasing N will result in increases to the Z. The increase to Z is proven as N is multiplied by $\alpha_Z - C_G$ which is a positive expression and would be larger than the denominator's scalar term β_Z. In general, in Cournot oligopolies, increasing the number of firms will result in increased quantities and reduced prices [127].

Regarding prices $p(X')$ and $p(Z)$, increasing M and N in this model will always decrease the price of the fertilizer ammonia. Increasing N will also decrease the price of energy storage ammonia. The decrease in price due to increased output is a common economic occurrence as competition increases within a market [127].

With how the quantities and prices will interact with M and N, one can see then it is possible to find the results regarding how the welfare components can be affected. Overall, the consumer surpluses are increased when there are greater numbers of firms. The increase in consumer surplus is due to the higher quantities, which reduce the prices, which results in a more significant consumer surplus for each product. However, industry profits, on the other hand, will take a hit as they must sell greater quantities at lower costs. Social costs and tax revenues will depend on which quantities increase or decrease. If H increases, there will be greater social costs, and if H decreases, then this will result in lesser social costs. Welfare and optimal tax were also analytically calculated but resulted in very complicated equations and, therefore, were omitted. A numerical analysis was done in place of the analytical expressions.

4.3.3.1 Numerical Analysis of the Increase of the Number of Firms

A numerical analysis was conducted with the baseline parameters with respect to M and N up to 10 firms. The equilibrium quantities for H, G_X, and Z are shown graphically in Figure 4.4.

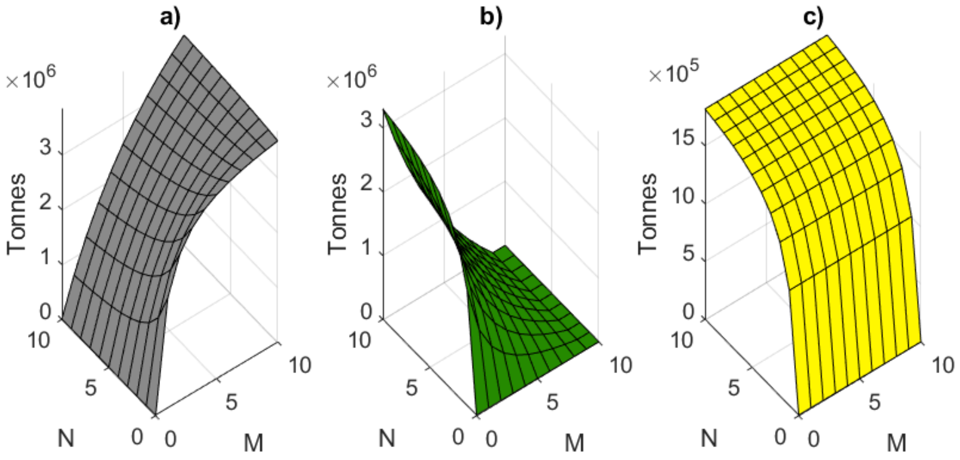


Figure 4.4 Equilibrium Quantities of a) H b) G_X and c) Z with respect to M and N

Figure 4.4 shows the direct relationship between the quantity of the good sold and the number of firms available to sell it. When M increases, so does H and when N increases, so does G_X. The amount of green ammonia for green energy storage is independent of the number of conventional firms. The possible trend observed in the analytical solutions where increasing the number of green firms (N) increases the amount of conventional ammonia being produced is shown. This is seen at around eight conventional firms. This indicates a difference in cost-efficiencies between the green and conventional firms. Markets want to shift the market to the more cost-efficient firms, which in this case, would be the conventional ammonia since they have lower marginal costs than green ammonia. Also, note that the amount of green ammonia produced at around nine conventional firms becomes zero. Green ammonia firms becoming zero is because the conventional firms are now more competitive and have significantly lower marginal costs than green ammonia.

There would also be lower prices in the market at an increased number of firms, as shown in Figure 4.5. An increase in any number of firms would result in lower prices.

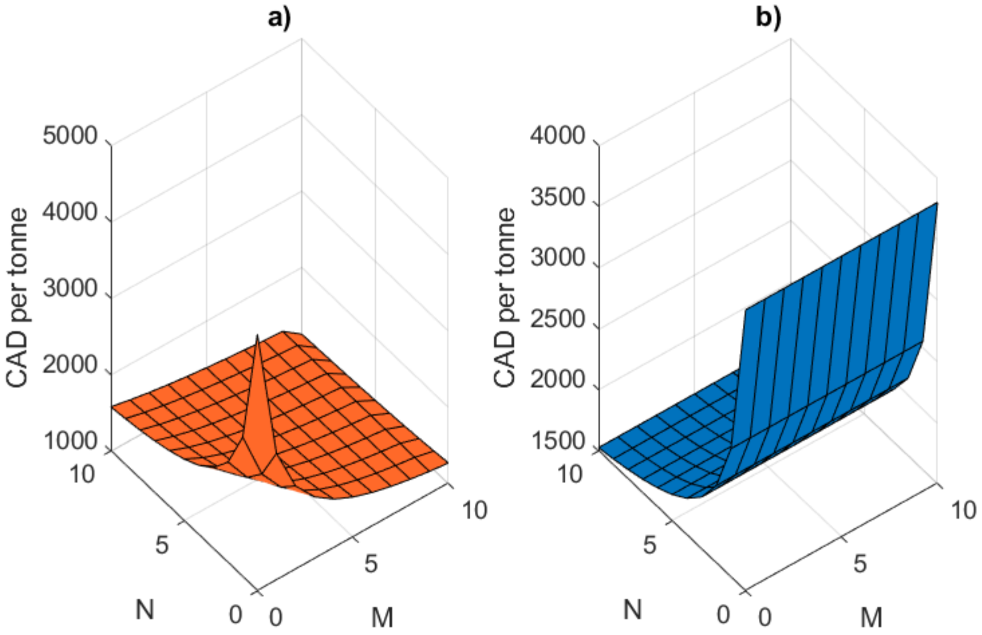


Figure 4.5 Prices for ammonia as a) fertilizer or b) energy storage with respect to M and N firms

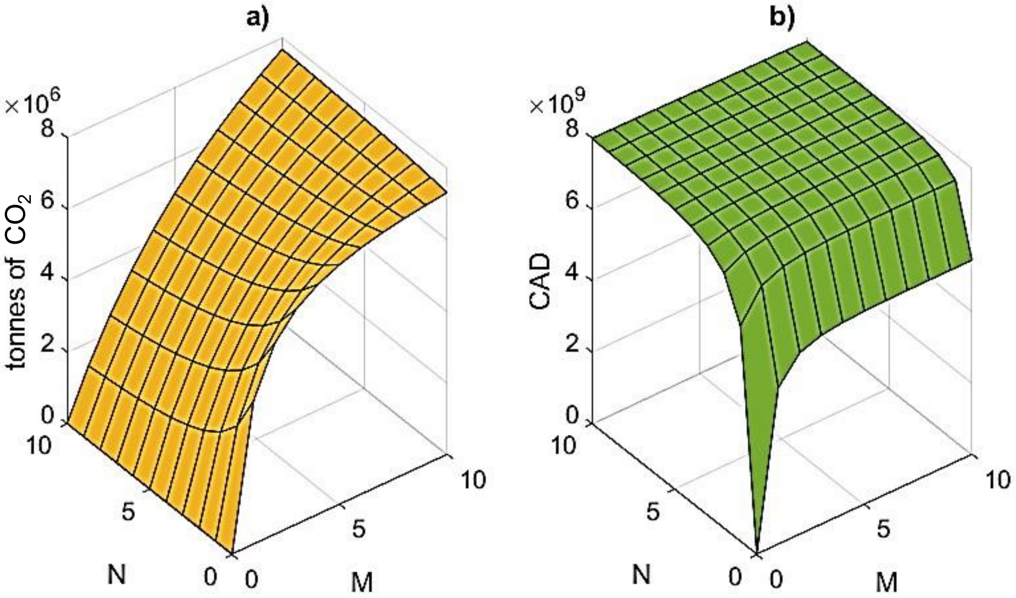


Figure 4.6 Total a) Emissions and b) Welfare with respect to M and N

Figure 4.6 shows the resulting emissions from an increase in conventional and green firms. In general, an increase in conventional firms raises the total emissions. The increase in emissions is because of the greater quantity of H that is produced generates more emissions. On the other hand, an increase in the number of green firms can decrease emissions at the beginning but is relatively independent of total emissions if conventional ammonia is being produced. The decrease in emissions is only the case if the number of conventional firms is less than seven or eight. An increase in green ammonia firms increases emissions at that number of conventional firms.

Secondly, an increase in both conventional and green firms will increase welfare. The increase in welfare is because of the more significant consumer surplus that occurs with the lower ammonia prices and greater quantities. However, it plateaus as welfare does not increase much when one increase the number of firms past 3.

All this numerical analysis uses a baseline tax of 80 CAD per tonne of carbon dioxide. However, the optimal tax at each combination of the number of firms was estimated. The optimal tax is obtained by taking the long analytical solutions and setting the bounds that do not result in negative equilibrium quantities.

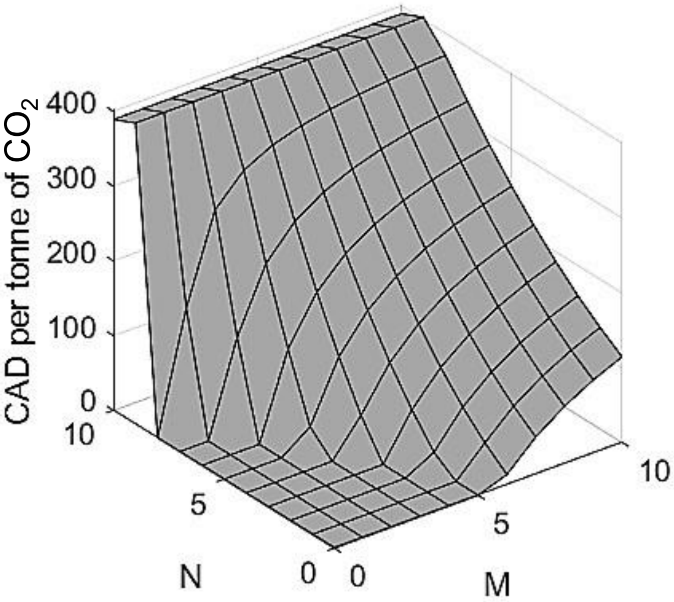


Figure 4.7 Optimal Tax with respect to M and N

The optimal tax increases as one increases both conventional and green firms. However, it is more strongly related to the number of green firms. As the number of green firms increases, the optimal tax also increases. The direct relationship between optimal tax and the number of green firms is because of increased competition among green firms, which leads to higher production and lower prices and encourages market demand to shift towards green firms. To support this shift, raising the tax becomes necessary. The optimal tax increases as one increases the number of conventional firms much more slowly but still does, as emission control becomes more necessary at greater quantities of conventional firms that would produce more conventional ammonia. Another special note is that for many scenarios with low numbers of total firms, the optimal tax is zero. The optimal tax being zero is most likely due to the high price of ammonia that results from few amounts of firms, which reduces consumer surplus due to the more monopolistic behavior observed in low numbers of firms.

The policy implications from this numerical analysis are that high numbers of firms (greater competition) result in the highest welfare for this industry. However, if the preference is for lesser emissions, simply increasing the number of green firms may result in greater emissions, not less.

4.3.4 Effects of Taxes and Subsidies

Another standard government instrument that can incentivize and influence markets is subsidies. These are government expenditures that can be used to reduce a particular product's production costs or increase consumers' buying power for that product [57]. Subsidies are particularly useful in environmental economics, where the cost of greener products is often more expensive and has a cost premium. For example, in this case, for green ammonia, which emits no emissions, the government can subsidize the green ammonia industry by paying a portion of the production cost for the green industry or giving consumers money when they buy greener products. Subsidies can lower the cost consumers would have to pay to buy the more expensive, greener products. In part, some of these subsidies could also be provided by the tax revenues that were received from the conventional industries.

To introduce this to the model, the variable S_b is introduced to the marginal cost equations. S_b is the subsidy per unit of green ammonia product. There are plenty of ways to implement the subsidy, such as giving rebates to consumers to increase buying power or giving it to the producers to subsidize their higher production costs. In this chapter, the latter is used. The marginal cost of producing the green ammonia with subsidy would be $C_G - S_b$.

Four policy cases were used to analyze the effects of taxes and subsidies on the equilibrium quantities and welfare.

1. No taxes and no subsidies (No T or S)
2. Only subsidies (S)
3. Only taxes (T)
4. Combined taxes and subsidies (T and S)

Then, the same analytical analysis was performed in 4.2 for each of the cases. The resulting quantities and prices are given by the expressions below in Table 4.4.

Table 4.4 Equilibrium Quantities and Prices Comparison With Subsidy

Product	No T or S	S	T	T and S
H	$\frac{C_G - 2\,C_H + \alpha_{X'}}{3\,\beta_{X'}}$	$\frac{C_G - 2\,C_H - S_b + \alpha_{X'}}{3\,\beta_{X'}}$	$\frac{C_G - 2\,C_H + \alpha_{X'} - 2\,\tau\,\xi_H}{3\,\beta_{X'}}$	$\frac{C_G - 2\,C_H + \alpha_{X'} - 2\,\tau\,\xi_H - S_b}{3\,\beta_{X'}}$

G_X	$\frac{C_H - 2\,C_G + \alpha_{X'}}{3\,\beta_{X'}}$	$\frac{C_H - 2\,C_G + 2\,S_b + \alpha_X}{3\,\beta_{X'}}$	$\frac{C_H - 2\,C_G + \alpha_{X'} + \tau\,\xi_H}{3\,\beta_{X'}}$	$\frac{C_H - 2\,C_G + \alpha_{X'} + \tau\,\xi_H + 2\,S_b}{3\,\beta_{X'}}$
Z	$-\frac{C_G - \alpha_Z}{2\,\beta_Z}$	$\frac{S_b - C_G + \alpha_Z}{2\,\beta_Z}$	$\frac{\alpha_Z - C_G}{2\,\beta_Z}$	$\frac{\alpha_Z - C_G + S_b}{2\,\beta_Z}$
$p(X')$	$\frac{C_G}{3} + \frac{C_H}{3} + \frac{\alpha_{X'}}{3}$	$\frac{C_G}{3} + \frac{C_H}{3} - \frac{S_b}{3} + \frac{\alpha_X}{3}$	$\frac{C_G}{3} + \frac{C_H}{3} + \frac{\alpha_{X'}}{3} + \frac{\tau\,\xi_H}{3}$	$\frac{C_G}{3} + \frac{C_H}{3} + \frac{\alpha_X}{3} + \frac{\tau\,\xi_H}{3} - \frac{S_b}{3}$
$p(Z)$	$\frac{C_G}{2} + \frac{\alpha_Z}{2}$	$\frac{C_G}{2} - \frac{S_b}{2} + \frac{\alpha_Z}{2}$	$\frac{C_G}{2} + \frac{\alpha_Z}{2}$	$\frac{C_G}{2} + \frac{\alpha_Z}{2} - \frac{S_b}{2}$

The table shows that adding the subsidy increases the quantity of green ammonia produced and decreases the amount of conventional ammonia produced, which is the opposite of the tax. A subsidy will also work to decrease the overall price of ammonia, which counteracts the increase in price that a tax would have. The increased quantities of green ammonia and decreased conventional ammonia increase total green ammonia firm profits and lower emissions.

Furthermore, the effects of the combined tax and subsidy policy on the quantities and prices seem to be the individual effects of the two policies added together analytically.

The welfare equation is adjusted to account for the spending that is made to fulfill the subsidies as given by Equation (20) below:

$$W = \pi_H + \pi_G + CS_X + CS_Z + TR - SC - TS \tag{20}$$

The welfare function subtracts the total subsidies provided as it is government expenditures. For simplicity, the exact analytical solutions for welfare and the welfare components are not provided directly in this chapter as they are long and complex. However, they are provided in the Appendix. Furthermore, a numerical analysis explores this further.

With the resulting welfare, optimal taxes and subsidies can be obtained for each case, as shown in Table 4.5. The optimal tax has a lower bound of zero and an upper bound that makes H equal zero. On the other hand, the optimal subsidy has a lower bound of zero and an upper bound of the marginal cost of green ammonia. The optimal tax increases with conventional production costs, social costs, and emissions but decreases with higher demand and cost of green ammonia. The optimal subsidy also increases with conventional costs, social costs, and emissions but decreases with green ammonia production. The key difference is that the optimal tax decreases with higher demand, while the optimal subsidy increases with higher demand. Both the tax and subsidy aim to shift the market towards the most cost-efficient firms.

Table 4.5 Optimal Tax and Subsidies for the Four Cases

Policy case	τ^*	S_b^*
No T or S	NA	NA
S	NA	$\frac{1}{9\,\beta_X+4\,\beta_Z}(16\,C_H\,\beta_Z-20\,C_G\,\beta_Z-9\,C_G\,\beta_X$ $+4\,\alpha_X\,\beta_Z+9\,\alpha_Z\,\beta_X$ $+12\,\beta_Z\,v\,\xi_H)$
T	$\frac{-4\,C_G+5\,C_H-\alpha_X+6\,v\,\xi_H}{\xi_H}$	NA
T and S	$\frac{1}{\beta_X\,\xi_H}(5\,C_H\,\beta_X-4\,C_G\,\beta_Z-5\,C_G\,\beta_X$ $+4\,C_H\,\beta_Z-\alpha_X\,\beta_X$ $+\alpha_Z\,\beta_X+6\,\beta_X\,v\,\xi_H$ $+4\,\beta_Z\,v\,\xi_H)$	$\frac{4\,C_H\,\beta_Z-4\,C_G\,\beta_Z-C_G\,\beta_X+\alpha_Z\,\beta_X+4\,\beta_Z\,v\,\xi}{\beta_X}$

4.3.4.1 Numerical analyses of the impact of taxes and subsidies

A numerical analysis was performed to add a subsidy of 160 CAD per tonne of ammonia with the baseline parameters. 160 CAD per tonne of ammonia was chosen as the subsidy because it equals the tax affecting the conventional firm per tonne. The tax is 80 CAD per tonne of CO_2, and conventional firms emit two tonnes of CO_2 per tonne of ammonia, which means that the tax would affect each conventional ammonia tonne by 160 CAD.

The estimated quantities and the net changes to the quantities across the introduction of the policies are displayed in Figure 4.8. The figure shows that both taxes and subsidies reduce the amount of conventional ammonia and increase the amount of green ammonia. When combined, the decrease in conventional ammonia is the sum of the decreases from each policy individually. The same applies to green ammonia used as fertilizer and energy storage: the combined change is the sum of the individual changes.

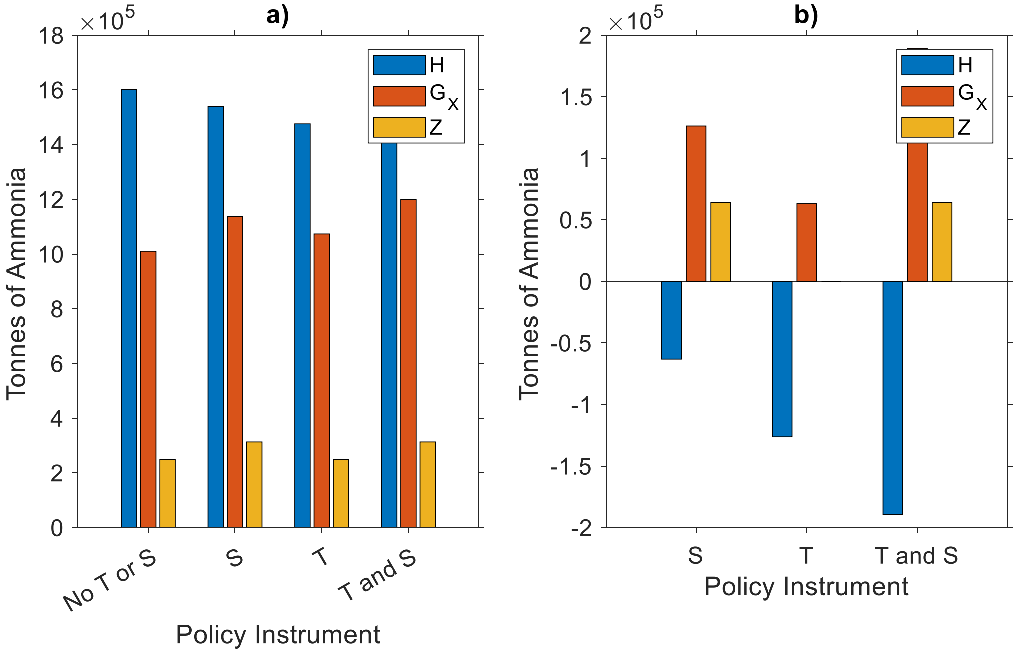


Figure 4.8 a) Quantities and b) change in quantities relative to the "No T or S" policy instrument case across the tax/subsidy policies

Now, concerning the welfare components, Figure 4.9 shows a stacked bar graph of the four different cases and the proportions of the welfare components. Alongside Table 4.6 it is interesting to see the changes in the variables relative to the no tax or subsidy case. The first column indicates that there are no changes when dividing by itself.

Firstly, it is shown that taxes increase the price of ammonia, while subsidies tend to decrease the overall price of ammonia. The quantities, prices, and emissions for combined policies are the sum of the effects of the individual policies. Emissions and social costs tend to decrease with the addition of taxes and subsidies.

Secondly, regarding welfare components, subsidies increase consumer surpluses while taxes decrease them. Both subsidies and taxes decrease conventional firms' profits and increase green firms' profits. However, the results for combined policies are not simply the sum of the individual effects due to the exponents present in the equations when solving analytically.

Lastly, both the subsidies and the combined tax and subsidy increase welfare, with the only subsidies policy increasing it the most. The tax-only policy decreases welfare in this with the baseline parameters. The subsidies help both the energy storage and fertilizer Krass et al. [112] observe a relevant trend, noting that a combined tax and subsidy policy is more effective than a tax-only policy. Although the combined policies increase the amount of green ammonia and reduce the amount of emissions the most, the reduction in profits of the conventional industry negatively impacts welfare. The subsidies-only policy is estimated to be optimal as it maximizes welfare.

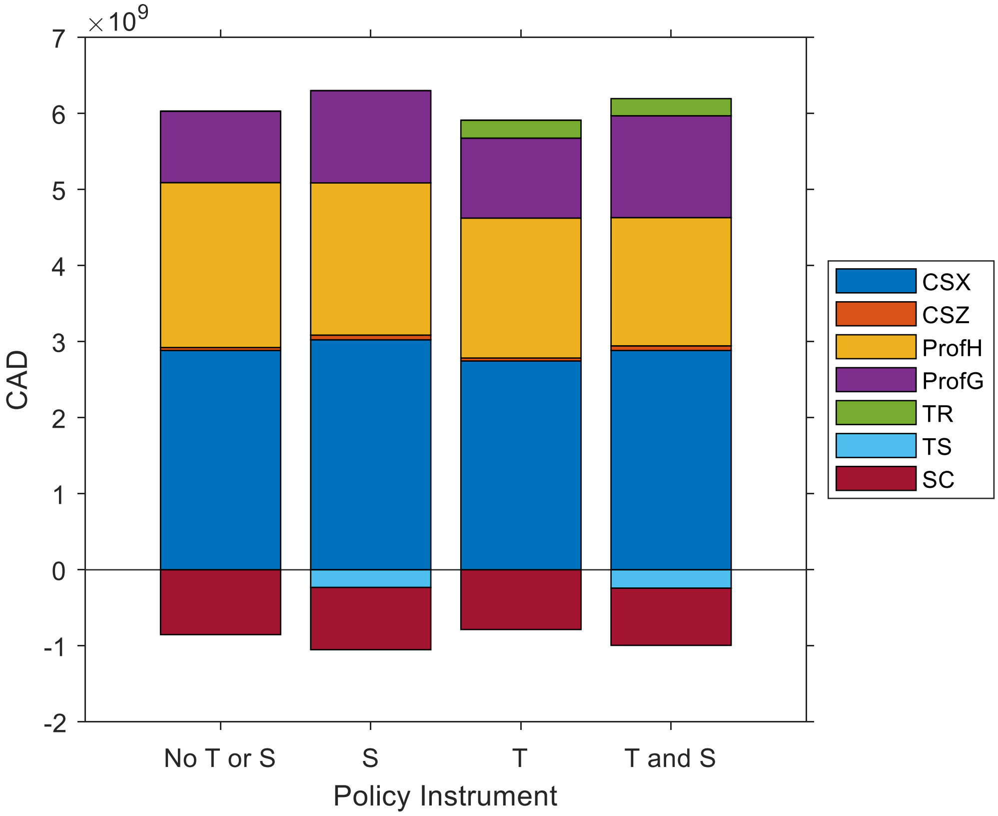
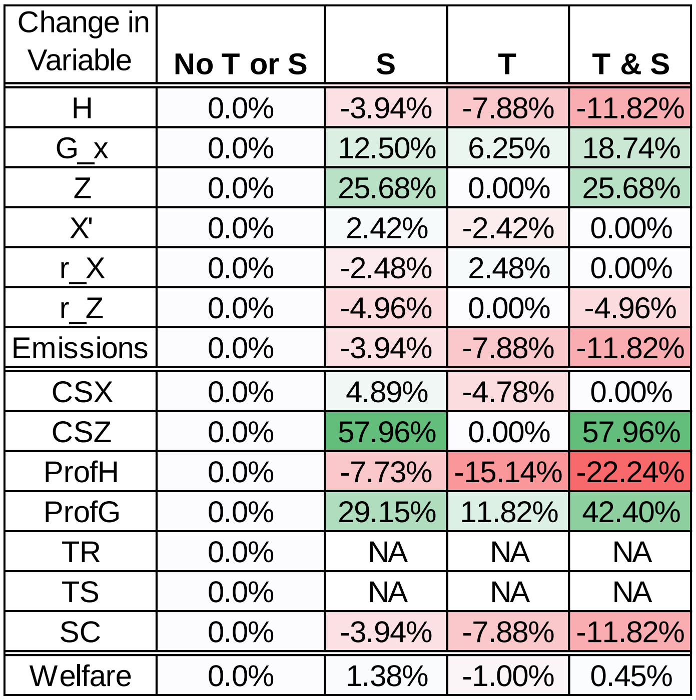


Figure 4.9 Welfare components across the different cases

Table 4.6 Change in Variables after each policy.



Change in Variable	No T or S	S	T	T & S
H	0.0%	-3.94%	-7.88%	-11.82%
G_x	0.0%	12.50%	6.25%	18.74%
Z	0.0%	25.68%	0.00%	25.68%
X'	0.0%	2.42%	-2.42%	0.00%
r_X	0.0%	-2.48%	2.48%	0.00%
r_Z	0.0%	-4.96%	0.00%	-4.96%
Emissions	0.0%	-3.94%	-7.88%	-11.82%
CSX	0.0%	4.89%	-4.78%	0.00%
CSZ	0.0%	57.96%	0.00%	57.96%
ProfH	0.0%	-7.73%	-15.14%	-22.24%
ProfG	0.0%	29.15%	11.82%	42.40%
TR	0.0%	NA	NA	NA
TS	0.0%	NA	NA	NA
SC	0.0%	-3.94%	-7.88%	-11.82%
Welfare	0.0%	1.38%	-1.00%	0.45%

The optimal tax rates and subsidies were calculated for each of the policies. They are displayed in Table 4.7. The optimal tax rate for all the policies was zero, while the optimal subsidy was the maximum subsidy possible (1300 CAD). The optimal policy is to subsidize the green ammonia costs completely is what is being said here. The complete subsidization would result in a welfare of around 5.51 billion CAD, which compared to the baseline scenario optimal with a tax rate of zero of 5.17 billion is significantly higher. The policy implications here from the numerical analysis show that the subsidies only policy with this model is the most effective in increasing welfare rather than the tax, which impacts the conventional firms significantly more than subsidies.

Table 4.7 Optimal tax and subsidies in each policy

Policy	τ^*	S_b^*
No T or S	NA	NA
S	NA	1300 CAD/tonne of ammonia
T	0 CAD/tonne of CO_2	NA

T and S	0 CAD/ tonne of CO_2	1300 CAD/tonne of ammonia

4.3.5 Effects of Capacity Constraints

In the default model, no capacity constraints are at play, and the firms stop producing ammonia once their marginal revenues equal their marginal costs. However, there are instances where demand is high, but supply is low. Presently, there are no large-scale green ammonia plants in Canada. However, there may come a time when green ammonia plants are present, but they may be constrained to a capacity lower than what is demanded. The capacity constraint may result in an allocation issue, and companies must decide how to allocate their resources. To model the capacity constraint issue, we introduce $\overline{G}$, which denotes the maximum capacity that the green firm can produce. In this model, the green firms will automatically produce that much. No capacity constraint is introduced for conventional ammonia firms as they produce at much larger scales presently. However, future models should consider the conventional firms' capacity constraint.

With a capacity constraint, four scenarios must be considered:

1. $\overline{G}$ is not reached.
2. $\overline{G}$ is reached, and all the ammonia produced is allocated for fertilizer use.
3. $\overline{G}$ is reached, and all the ammonia produced is allocated for energy storage use.
4. $\overline{G}$ is reached, some of the ammonia produced is allocated to fertilizer use, and the remaining is allocated to energy storage use.

There are interesting points to note. Scenario 2 or 3 may be the more realistic model at very low capacities. This is the case if the green energy storage market is very small but is the first to appear. Therefore, one would allocate it to just one of the two demand possibilities depending on the marginal revenue (fertilizer or energy storage). Then, as capacities increase, Scenario 4 would be in play, where there could be two markets for green ammonia and allocation must occur. Lastly, with very large capacity constraints, Scenario 1 is the case. Scenario 1 is the case because even if one has a large capacity, it would be as if there is no capacity constraint, as demand may not reach the limit of the capacity constraint. Presently, Scenarios 2 and 3 may be the case due to the very small capacity of electrolytic ammonia; however, as the supply of green ammonia continues to grow, Scenarios 1 and 4 may become more relevant.

Scenario 1 is not considered in this section as it ends up with the same results as the default model – which is as if there were no capacity constraints. This is because scenario 1 means that the firm can make the ammonia that is necessary to reach the optimum. In this scenario, one can still equate the marginal revenues with the marginal costs.

In Scenarios 2 to 4, the marginal cost and the marginal revenues cannot be equated. The marginal revenues and costs cannot be equated because the capacity does not meet the quantities demanded. Therefore, these scenarios encounter a problem regarding allocation. In this model, the firm will always choose to allocate to the one that provides the greatest profit. The one with the greatest profit at a certain quantity can be found by analyzing their marginal revenues and finding which one will be greater. Scenario 2 occurs when the marginal revenues from fertilizer ammonia are always greater than those for energy storage ammonia. Scenario 3 happens when the marginal revenues from energy storage ammonia is always greater than the one for fertilizer ammonia. Scenario 4 happens when the marginal revenues from fertilizer and energy storage ammonia are equal to some quantity of ammonia produced. The resulting analytical results are displayed in the following table.

Table 4.8 Analytical Equilibrium Quantities and Prices

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
H	$\frac{C_G - 2\,C_H + \alpha_{X'} - 2\,\tau\,\xi_H}{3\,\beta_{X'}}$	$-\frac{C_H - \alpha_{X'} + \bar{G}\,\beta_{X'} + \tau\,\xi_H}{2\,\beta_{X'}}$	$-\frac{C_H - \alpha_{X'} + \tau\,\xi_H}{2\,\beta_{X'}}$	$-\frac{1}{\beta_{X'}\,(3\,\beta_{X'} + 4\,\beta_Z)}(2\,C_H\,\beta_{X'}$ $+ 2\,C_H\,\beta_Z$ $- \alpha_{X'}\,\beta_{X'}$ $- 2\,\alpha_{X'}\,\beta_Z$ $- \alpha_z\,\beta_{X'}$ $+ 2\,\bar{G}\,\beta_{X'}\,\beta_Z$ $+ 2\,\beta_{X'}\,\tau\,\xi_H$ $+ 2\,\beta_{X'}\,\tau\,\xi_H)$
G_X	$\frac{C_H - 2\,C_G + \alpha_{X'} + \tau\,\xi_H}{3\,\beta_{X'}}$	$\bar{G}$	0	$\frac{C_H + \alpha_{X'} - 2\,\alpha_Z + 4\,\bar{G}\,\beta_Z + \tau\,\xi_H}{3\,\beta_{X'} + 4\,\beta_Z}$
Z	$\frac{\alpha_Z - C_G}{2\,\beta_Z}$	0	$\bar{G}$	$-\frac{C_H + \alpha_{X'} - 2\,\alpha_z - 3\,\bar{G}\,\beta_{X'} + \tau\,\xi_H}{3\,\beta_{X'} + 4\,\beta_z}$

$p(X')$	$\frac{C_G}{3}+\frac{C_H}{3}+\frac{\alpha_{X'}}{3}+\frac{\tau\,\xi_H}{3}$	$\frac{C_H}{2}+\frac{\alpha_{X'}}{2}+\frac{\tau\,\xi_H}{2}-\frac{\bar{G}\,\beta_{X'}}{2}$	$\frac{C_H}{2}+\frac{\alpha_{X'}}{2}+\frac{\tau\,\xi_H}{2}$	$\frac{1}{3\,\beta_{X'}+4\,\beta_z}(C_H\,\beta_{X'}+2\,C_H\,\beta_Z + \alpha_{X'}\,\beta_{X'} + 2\,\alpha_{X'}\,\beta_z + \alpha_z\,\beta_{X'} - 2\bar{G}\,\beta_{X'}\,\beta_z + \beta_{X'}\,\tau\,\xi_H + 2\,\beta_Z\,\tau\,\xi_H)$
$p(Z)$	$\frac{C_G}{2}+\frac{\alpha_Z}{2}$	NA	$\alpha_Z-\bar{G}\beta_Z$	$\frac{1}{3\,\beta_{X'}+4\,\beta_Z}(C_H\,\beta_Z+\alpha_Z\,\beta_Z + 3\,\alpha_Z\,\beta_{X'} + 2\,\alpha_Z\,\beta_Z - 3\bar{G}\,\beta_{X'}\,\beta_Z + \beta_z\,\tau\,\xi_H)$

The Table above shows that H decreases as $\bar{G}$ increases. It also shows that both the conventional and green firms act as a monopoly in Scenario 3. Scenario 3 monopolization occurs because each firm makes ammonia for their respective markets, i.e., conventional firm makes ammonia for fertilizer while green ammonia firm makes only for green energy storage. In general, increasing $\bar{G}$ decreases prices and the quantity of conventional ammonia but increases the quantity of total green ammonia. An increase in capacity of zero-emission ammonia for scenario 4, will impact energy storage ammonia rather than fertilizer ammonia about 50% more as seen through the coefficients in front of the $\bar{G}$.

Regarding consumer surpluses of both fertilizer and energy storage ammonia, the increase in $\bar{G}$ generally increases the consumer surplus by increasing the quantity of green ammonia and lowering the price. Profit of conventional ammonia generally decreases with an increase in $\bar{G}$. Increases in $\bar{G}$ also lower social costs and tax revenues. Regarding welfare, an increase in $\bar{G}$ will increase as long as C_G is low enough, but it depends on the scenario. For Scenario 2, it is as long as $C_G + \frac{\overline{G}\beta_X}{4} < \frac{\alpha_{X'}}{4} + \frac{3\,C_H}{4} + \frac{\tau\,\xi_H}{4} + \frac{v\,\xi_H}{2}$. While for Scenario 3, it is as long as $C_G + \overline{G}\,\beta_Z < \alpha_Z$. With analytical welfare expressions, one can find the optimal tax to maximize welfare, which is displayed in Table 4.9.

Table 4.9 Optimal Tax with Capacity Constraint

Scenario 1	Scenario 2	Scenario 3	Scenario 4

$\frac{-4\,C_g + 5\,C_h - \alpha_x}{\xi_H} + 6v$	$\frac{C_H - \alpha_{X'} + \overline{G}\,\beta_X}{\xi_H} + 2\,v$	$\frac{C_H - \alpha_{X'}}{\xi_H} + 2\,v$	$\frac{1}{\xi_H\,({\beta_X}^2 + 5\,\beta_X\,\beta_Z + 4\,{\beta_Z}^2)}(5\,C_H\,{\beta_X}^2$ $+ 4\,C_H\,{\beta_Z}^2 - 4\,\alpha_Z\,{\beta_X}^2 - \alpha_{X'}\,{\beta_X}^2$ $- 4\,\alpha_{X'}\,{\beta_Z}^2 + 6\,{\beta_X}^2\,v\,\xi_H$ $+ 8\,{\beta_Z}^2\,v\,\xi_H + 9\,C_H\,\beta_X\,\beta_Z$ $- 4\,\alpha_Z\,\beta_X\,\beta_Z - 5\,\alpha_{X'}\,\beta_X\,\beta_Z$ $+ 4\,\overline{G}\,\beta_X\,{\beta_Z}^2 + 5\overline{G}\,{\beta_X}^2\,\beta_Z$ $+ 14\,\beta_X\,\beta_Z\,v\,\xi_H)$

In general, the increase in capacity constraint will increase the optimal tax. The increase in optimal tax is because as green ammonia capacity increases, there is more incentive to shift the market towards green ammonia. However, it occurs only if green ammonia costs are sufficiently low.

4.3.5.1 Numerical Analysis of the Impact of the Presence of a Capacity Constraint

A numerical analysis was performed for the baseline scenario parameters but with a capacity of 500,000 tonnes of green ammonia produced yearly. This number is taken from Canada's agreement with Germany [96]. To see which scenario the capacity constraint would result in, from the parameters, one can generate a graph with the width of $\bar{G}$, electrolytic ammonia marginal cost (*MC*) line, and with the marginal revenue (*MR*) line for fertilizer use going from left to right and the marginal revenue line going from right to left for energy storage use, with the marginal cost modelled after Baylis et al. [128]. The graph generated is displayed in Figure 4.10. The graph shows that the marginal revenue for fertilizer use will always be greater than that for energy storage use with the baseline parameters. Since marginal revenues for fertilizer would be greater than for energy storage, that would mean that Scenario 2 is the relevant one, and companies would allocate the ammonia to fertilizer use rather than energy storage use.

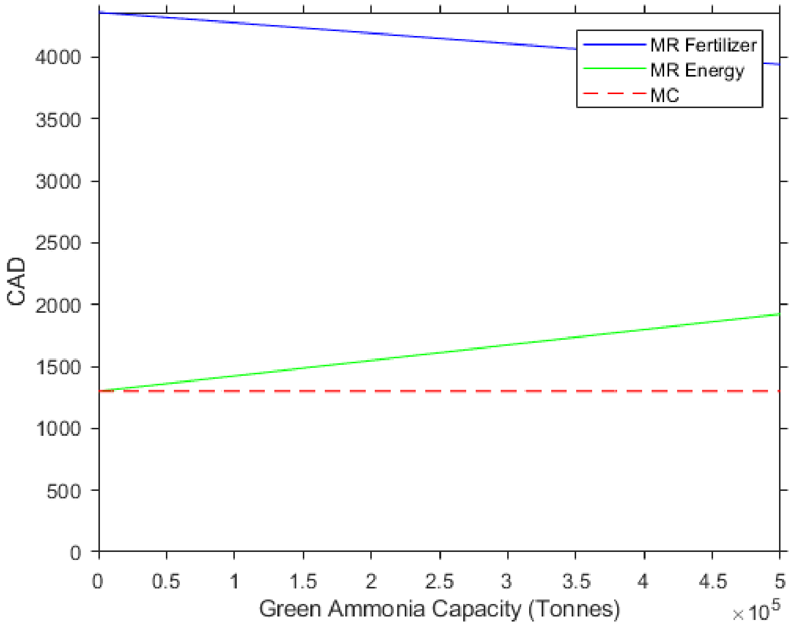


Figure 4.10 Green Ammonia Capacity with Marginal Revenue and Cost Lines Displayed

To analyze the welfare change that results from the presence of a capacity constraint, a stacked bar graph with the size of the components displayed was generated in Figure 4.11. The graph shows that the capacity constraint results in lower consumer surpluses, higher conventional profits, lower electrolytic ammonia profits, higher tax revenues, and greater social costs. The higher conventional profits, lower consumer surplus, are due to the higher prices due to lower ammonia quantities. The 500,000 tonne capacity-constrained welfare estimated is around 8% lower than the welfare that is estimated with no capacity constraints. To check for sensitivity to the choice of the production capacity for green ammonia, a capacity constraint changes of 25% less or more relative to the 500,000 tonnes was also conducted and the resulting welfare was around 10 and 7% less than the no capacity constraint counterparts, respectively.

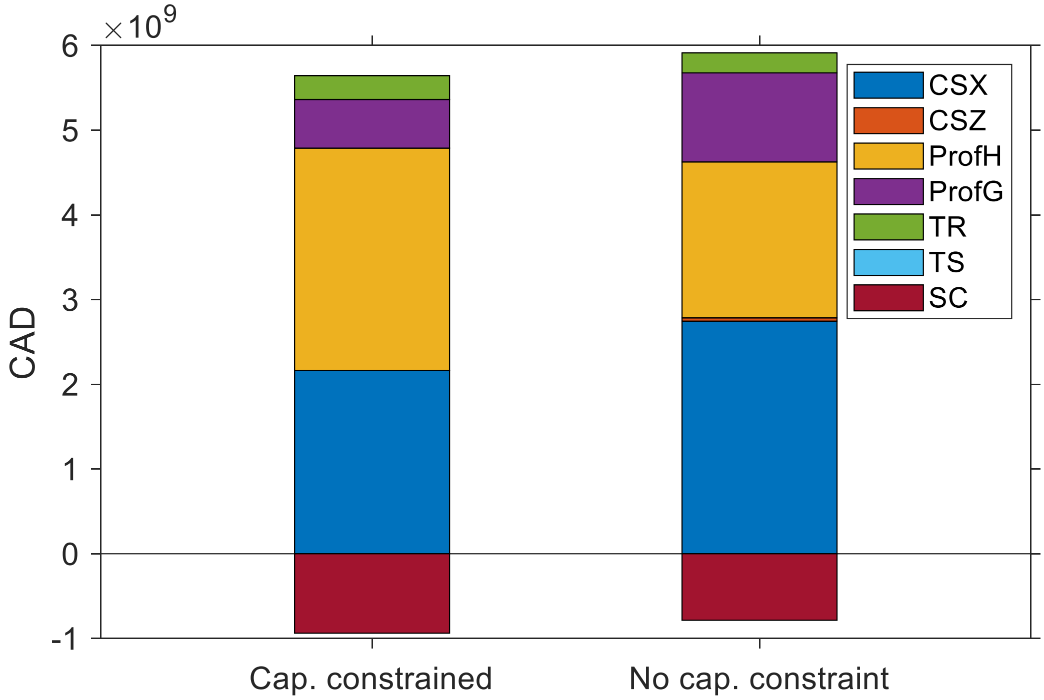


Figure 4.11 Welfare comparison with capacity constraint.

The capacity constraint mainly reduces welfare because of the reduced quantity of ammonia in the market, which raises prices and reduces consumer surplus. There is also an increased social cost and decreased profits from the green industry. Figure 4.12 shows the reduced quantities of green ammonia, which would also reduce the total quantity of ammonia used for fertilizer. The conventional ammonia firm will reduce total supply to optimize its profits. The figure also shows that there would be no allocation to energy storage ammonia with the capacity constraint.

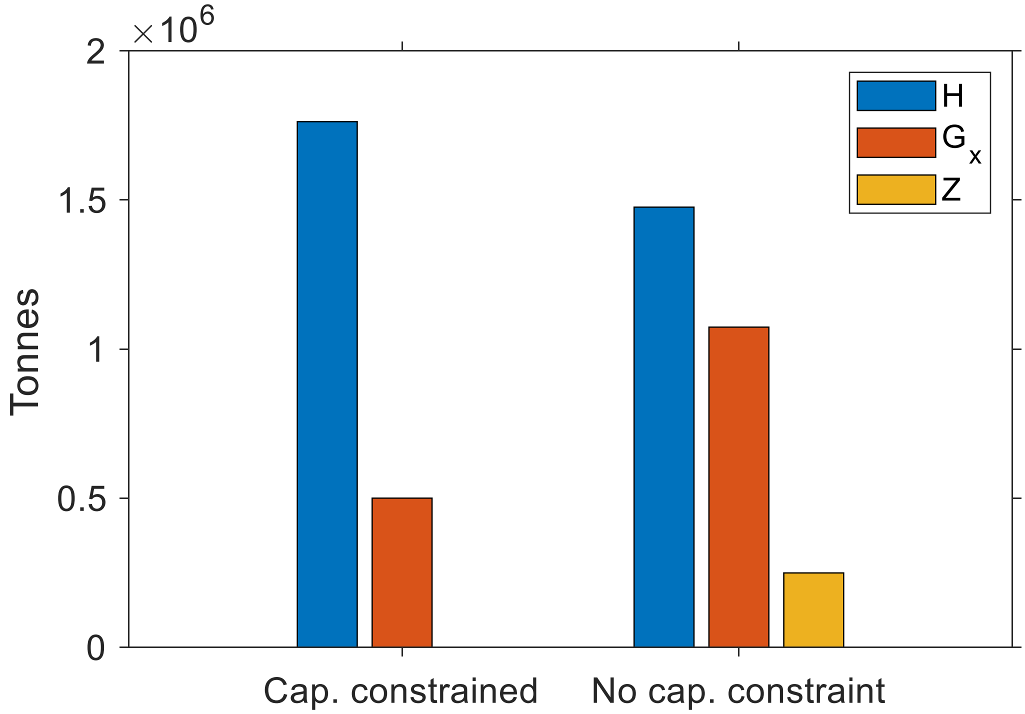


Figure 4.12 Quantity comparison with capacity constraint

The numerical analyses show that there needs to be policies to incentivize energy storage ammonia if there is a capacity constraint since its demand will be much lower than the demand for ammonia as a fertilizer. It is also shown that welfare increases when the total capacity constraint of green ammonia increases, so policies to increase capacities would help increase welfare in the future and reduce greenhouse social costs.

4.4 Conclusions and Recommendations

4.4.1 Summary of Work

To answer the question of, “How can social welfare be maximized in the ammonia industry using government instruments?” this chapter uses a simplified Cournot model involving two industries with emissions asymmetry. This model uses linear inverse demand functions and constant marginal costs of production, and it assumes zero emissions for the green industry. The analysis reveals that the marginal costs of production in one industry have a notable impact on the output quantities of both industries. As measured and analytically addressed in this model, social welfare is influenced by many factors. These include the production costs of each industry, the tax rates imposed, the social cost of carbon, the specific characteristics of demand functions, the number of firms in each industry, the existence and scale of subsidies, and the presence of capacity constraints. Taxation plays a dual role in this context: it not only raises production costs for the conventional industry by reducing its output but also makes the green ammonia industry more competitive, thereby increasing its output. The optimal tax rate, therefore, has a direct relationship with the marginal costs of the conventional industry, while it is inversely related to the marginal costs of the green industry.

Numerical analyses related to the model indicate that, given the estimated parameters, the optimal tax should be zero to maximize welfare. Conversely, a subsidy that supports green ammonia production costs is desired and would enhance welfare; the analyses suggest that even full subsidization may be beneficial. Additionally, the numerical analyses demonstrate that both a combined policy and a subsidy-only policy improve welfare, whereas a tax-only policy may result in lower welfare. The analyses also highlight the necessity of incentivizing energy storage, as its demand may be lower than fertilizer, especially when capacity constraints are an issue.

4.4.2 Policy Implications

The results from the Cournot model analysis suggest several policy implications for improving the viability and environmental impact of green ammonia production. A primary objective should be to find effective ways to lower the costs of green ammonia. Lowering these costs is crucial because it can significantly impact the equilibrium, making green ammonia more competitive relative to conventional ammonia. When green ammonia costs decrease relative to conventional ammonia, it can result in an increased quantity of green ammonia being produced and, consequently, an improvement in overall social welfare. Policy measures to reduce green ammonia costs can include subsidizing the purchase price or production costs, as indicated in this analysis. The most effective approach would be to focus on reducing the base marginal cost through technological advancements, which would create a more sustainable and long-term reduction in production costs. Or this could be done economically by subsidizing the production cost of green ammonia, which is suggested by the numerical analysis.

It is important to note that merely incentivizing a greater number of green firms to enter the market might not necessarily result in reduced emissions. This could lead to an increased production of conventional ammonia. Therefore, the central focus should remain on lowering the costs of green ammonia to make it more competitive rather than simply increasing the number of green firms. Similarly, expanding green production capacity alone does not inherently lead to increased social welfare unless cost reductions in green ammonia production accompany it. Therefore, policies should aim to align capacity increases with cost-reduction strategies to maximize welfare benefits.

Another key policy implication is the strategic use of taxes to shift production from less efficient to more efficient sources. Taxes are directly related to the costs of conventional ammonia production. As the production costs for conventional ammonia increase, the optimal tax should also increase, making conventional ammonia less efficient than green ammonia. This adjustment helps to reduce the production of conventional ammonia while promoting the production of green ammonia. Conversely, if the costs of green ammonia rise, the optimal tax should be reduced to maintain a balanced and efficient market system. Subsidies work the opposite way by making green ammonia more competitive cost-wise without increasing the cost of conventional ammonia. Subsidies in this industry may be the best way to go along, not taxes, due to the lower social cost of carbon.

4.4.3 Recommendations for Future Work

This work can lead to many paths for future research. The current model utilizes Cournot modeling, which is based on firms choosing quantities, which does not account for the first-mover advantage that could be prevalent in real-world scenarios. Given the established presence of the conventional ammonia industry, it may initially engage in overproduction, thereby creating barriers to market entry for green ammonia. To address this difficulty with decision timing, future research could explore how alternative oligopoly market models like Bertrand and Stackelberg work with this industry. The Bertrand model, focusing on price competition, and the Stackelberg model, emphasizing leader-follower dynamics, could reveal how strategic interactions differ from the Cournot framework, especially concerning market entry and pricing strategies.

Secondly, implementing a version of the model where the conventional industry can pay for emissions abatement rather than merely shifting production to another firm could add a layer of realism. In practice, firms often can use abatement or buy carbon credits instead of giving up market share to new entrants. This approach would recognize that firms may prefer to invest in emission reduction technologies or purchase carbon offsets rather than lose profits to emerging competitors without established market positions.

Thirdly, the current model's time-static nature limits its ability to capture dynamic processes that occur over time, such as learning curves and research and development (R&D) impacts. A time-dependent model could incorporate these, which would allow for a more comprehensive understanding of how the market could unfold. This dynamic perspective could provide valuable insights into the temporal aspects of market transitions. This transition being one to a greener industry.

Lastly, incorporating different cost and demand functions could provide good insights, given the economies of scale associated with ammonia production. The current model assumes constant marginal costs of production, which may not reflect the reality where larger scales of production could lead to declining marginal costs. Examining variable marginal costs concerning production scales could offer a more nuanced understanding of cost structures and their influence on market competition and social welfare. This extension would align the model more closely with the operational characteristics of industries where scale economies play a significant role.

Chapter 5 Conclusions and Recommendations

In conclusion, this master's thesis examines how policies may impact ammonia production and competitive economics, drawing insights from two main analyses:

1. **Cost Benefit Analysis of Canadian Grid-Based Power-to-Ammonia Production across Provinces**

   Using LCOA techniques, it is clear to see that the use of CNZ policies makes grid-based electrolytic ammonia production (P3) more viable to use. Despite this, P3 needs major improvements to rival conventional ammonia production (P1) and CCS integrated methods (P2). Right now, P3 costs 450-650 CAD more per tonne than conventional methods, while P2 costs about 200 CAD more. However, when SCC is factored in, the P3 process can match P1 showing how crucial it is to include environmental costs and damages in the economic evaluation. Each province has different production costs because of varying grid emissions and power prices, with CCS still being the most cost-efficient way to cut down on carbon in Canadian ammonia production for most of the provinces. AB and SK are the best provinces for P2 while MB and QB are the best provinces for P3. Lowering grid emissions and costs are essential to the viability of electrolytic grid-based ammonia.

2. **Incentives and Effects of Green Ammonia Production**

   Several important insights can be derived from this chapter's simplified Cournot model involving two industries with emissions asymmetry. This model uses linear inverse demand functions and constant marginal costs of production, and it assumes zero emissions for the green industry. The analysis reveals that the marginal costs of production in one industry have a notable impact on the output quantities of both industries. Social welfare considers production costs, taxes, SCC, demand changes, the number of firms, capacity limits, and subsidies. Adding taxes and subsidies can boost social welfare by changing production costs and shifting the market towards the most efficient. Taxes can up the costs of conventional ammonia. This cuts its output and makes greener options more competitive. Subsidies can lower production costs for green ammonia, increasing the quantity of green ammonia and lowering conventional ammonia output. If energy storage ammonia is desired, there must be incentives in place to buy it as demand for relative to fertilizer may be lower. If capacity constraints exist, there must be incentives to buy energy storage ammonia because ammonia bought for fertilizer can make more money for the green company. This chapter found that the best tax was to have no tax for conventional ammonia for the industry. The optimal tax is zero because the social cost is low compared to fertilizer demand. Instead, subsidies should be in place to promote green ammonia.

This paper’s conclusions emphasize the need for policies on technological advancements and specific tax or subsidy policies. These steps can guide Canada toward sustainable ammonia production to meet CNZ goals. This paper also provides an exciting look into the use of the social cost of carbon. Future research should be involved in lowering green ammonia costs and analyzing more accurate cost structures. Also, future research should explore alternative economic models such as Bertrand or Stackelberg and time-dynamic approaches to better understand market structures and inform better policies.

Finally, this study highlights some of the challenges and opportunities in Canada's shift toward sustainable ammonia production. Chapter 3 shows the challenges related to grid-based power to ammonia production across the different provinces. The electrical grid is often cost-inefficient and emissions-intensive which is estimated to result in more harm than good in some provinces. CCS ammonia may be the prudent solution for now. From Chapter 4, one can see the challenges in generating policies and estimating the welfare that certain decisions can make. The role of taxes and subsidies and the interplay between them with marginal costs and demands was conveyed in this conclusion. Subsidies, rather than taxes, may be the most beneficial way to deal with promoting sustainable ammonia in the present.

References

[1] "Net-Zero Emissions by 2050 - Canada.ca." Accessed: Nov. 17, 2022. [Online]. Available: https://www.canada.ca/en/services/environment/weather/climatechange/climate-plan/net-zero-emissions-2050.html

[2] C. Smith, A. K. Hill, and L. Torrente-Murciano, "Current and future role of Haber–Bosch ammonia in a carbon-free energy landscape," *Energy Environ. Sci.*, vol. 13, no. 2, pp. 331–344, 2020, doi: 10.1039/C9EE02873K.

[3] C. J. Cunanan, C. A. Elorza Casas, M. Yorke, M. Fowler, and X.-Y. Wu, "Design and Analysis of an Offshore Wind Power to Ammonia Production System in Nova Scotia," *Energies*, vol. 15, no. 24, Art. no. 24, Jan. 2022, doi: 10.3390/en15249558.

[4] A. E. Yüzbaşıoğlu, C. Avşar, and A. O. Gezerman, "The current situation in the use of ammonia as a sustainable energy source and its industrial potential," *Curr. Res. Green Sustain. Chem.*, vol. 5, p. 100307, Jan. 2022, doi: 10.1016/j.crgsc.2022.100307.

[5] C. Muratore, L. Espen, and B. Prinsi, "Nitrogen Uptake in Plants: The Plasma Membrane Root Transport Systems from a Physiological and Proteomic Perspective," *Plants*, vol. 10, no. 4, p. 681, Apr. 2021, doi: 10.3390/plants10040681.

[6] K. E. Wyer, D. B. Kelleghan, V. Blanes-Vidal, G. Schauberger, and T. P. Curran, "Ammonia emissions from agriculture and their contribution to fine particulate matter: A review of implications for human health," *J. Environ. Manage.*, vol. 323, p. 116285, Dec. 2022, doi: 10.1016/j.jenvman.2022.116285.

[7] S. Ghavam, M. Vahdati, I. A. G. Wilson, and P. Styring, "Sustainable Ammonia Production Processes," *Front. Energy Res.*, vol. 9, 2021, Accessed: Apr. 18, 2023. [Online]. Available: https://www.frontiersin.org/articles/10.3389/fenrg.2021.580808

[8] "Ammonia Production Greenhouse Gas Emissions Benchmarking." Fertilizer Canada, Oct. 2023. [Online]. Available: https://fertilizercanada.ca/wp-content/uploads/2023/10/Nitrogen-Benchmarking-Report-Final.pdf

[9] G. W. Kim, M. A. Alam, J. J. Lee, G. Y. Kim, P. J. Kim, and M. I. Khan, "Assessment of direct carbon dioxide emission factor from urea fertilizer in temperate upland soil during warm and cold cropping season," *Eur. J. Soil Biol.*, vol. 83, pp. 76–83, Nov. 2017, doi: 10.1016/j.ejsobi.2017.10.005.

[10] "Hydrogen," Royal Society of Chemistry. Accessed: Feb. 28, 2024. [Online]. Available: https://www.rsc.org/periodic-table/element/1/hydrogen

[11] K. T. Møller, T. R. Jensen, E. Akiba, and H. Li, "Hydrogen - A sustainable energy carrier," *Prog. Nat. Sci. Mater. Int.*, vol. 27, no. 1, pp. 34–40, Feb. 2017, doi: 10.1016/j.pnsc.2016.12.014.

[12] "Heat values of various fuels," World Nuclear Association. Accessed: Feb. 28, 2024. [Online]. Available: https://world-nuclear.org/information-library/facts-and-figures/heat-values-of-various-fuels.aspx

[13] E. Rivard, M. Trudeau, and K. Zaghib, "Hydrogen Storage for Mobility: A Review," *Materials*, vol. 12, no. 12, p. 1973, Jun. 2019, doi: 10.3390/ma12121973.

[14] "Ammonia," American Chemical Society. Accessed: Feb. 08, 2024. [Online]. Available: https://www.acs.org/molecule-of-the-week/archive/a/ammonia.html

[15] M. Aziz, A. T. Wijayanta, and A. B. D. Nandiyanto, "Ammonia as Effective Hydrogen Storage: A Review on Production, Storage and Utilization," *Energies*, vol. 13, no. 12, Art. no. 12, Jan. 2020, doi: 10.3390/en13123062.

[16] S. Chatterjee, R. K. Parsapur, and K.-W. Huang, “Limitations of Ammonia as a Hydrogen Energy Carrier for the Transportation Sector,” *ACS Energy Lett.*, vol. 6, no. 12, pp. 4390–4394, Dec. 2021, doi: 10.1021/acsenergylett.1c02189.

[17] E. Spatolisano, L. A. Pellegrini, A. R. de Angelis, S. Cattaneo, and E. Roccaro, “Ammonia as a Carbon-Free Energy Carrier: NH3 Cracking to H2,” *Ind. Eng. Chem. Res.*, vol. 62, no. 28, pp. 10813–10827, Jul. 2023, doi: 10.1021/acs.iecr.3c01419.

[18] “Ammonia Technology Roadmap: Towards more sustainable nitrogen fertiliser production,” International Energy Agency, Oct. 2021. doi: 10.1787/f6daa4a0-en.

[19] C. Scholz, “Nova Scotia’s EverWind signs green ammonia deal with Germany’s Uniper,” *The Globe and Mail*, Aug. 23, 2022. Accessed: Sep. 12, 2022. [Online]. Available: https://www.theglobeandmail.com/business/article-nova-scotia-everwind-green-ammonia-uniper/

[20] “Japan, South Korea to build supply chain for hydrogen and ammonia,” Nikkei Asia. Accessed: Feb. 28, 2024. [Online]. Available: https://asia.nikkei.com/Spotlight/Supply-Chain/Japan-South-Korea-to-build-supply-chain-for-hydrogen-and-ammonia

[21] “Ammonia,” Chemical Safety Facts. Accessed: Feb. 07, 2024. [Online]. Available: https://www.chemicalsafetyfacts.org/chemicals/ammonia/

[22] A. Yadav and B. Jeong, “Safety evaluation of using ammonia as marine fuel by analysing gas dispersion in a ship engine room using CFD,” *J. Int. Marit. Saf. Environ. Aff. Shipp.*, vol. 6, no. 2–3, pp. 99–116, Jul. 2022, doi: 10.1080/25725084.2022.2083295.

[23] “Canadian Ammonia Producers Benchmarking Energy Efficiency and Carbon Dioxide Emissions,” Natural Resources Canada, Ottawa, Canada, 2008. [Online]. Available: https://publications.gc.ca/collections/collection_2009/nrcan/M144-155-2007E.pdf

[24] “Hydrogen Production: Natural Gas Reforming,” Energy.gov. Accessed: Jan. 15, 2024. [Online]. Available: https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming

[25] M. F. Ahmad Kamaroddin *et al.*, “Membrane-Based Electrolysis for Hydrogen Production: A Review,” *Membranes*, vol. 11, no. 11, Art. no. 11, Nov. 2021, doi: 10.3390/membranes11110810.

[26] N. Mac Dowell *et al.*, “The hydrogen economy: A pragmatic path forward,” *Joule*, vol. 5, no. 10, pp. 2524–2529, Oct. 2021, doi: 10.1016/j.joule.2021.09.014.

[27] E. R. Morgan, “Techno-economic feasibility study of ammonia plants powered by offshore wind,” Ph.D., University of Massachusetts Amherst, United States -- Massachusetts. Accessed: Nov. 01, 2021. [Online]. Available: https://www.proquest.com/docview/1323774328/abstract/F1615FD50DD44C5FPQ/1

[28] V. N. Sagel, K. H. R. Rouwenhorst, and J. A. Faria, “Green ammonia enables sustainable energy production in small island developing states: A case study on the island of Curaçao,” *Renew. Sustain. Energy Rev.*, vol. 161, p. 112381, Jun. 2022, doi: 10.1016/j.rser.2022.112381.

[29] A. Ajanovic, M. Sayer, and R. Haas, “The economics and the environmental benignity of different colors of hydrogen,” *Int. J. Hydrog. Energy*, vol. 47, no. 57, pp. 24136–24154, Jul. 2022, doi: 10.1016/j.ijhydene.2022.02.094.

[30] D. R. MacFarlane *et al.*, “A Roadmap to the Ammonia Economy,” *Joule*, vol. 4, no. 6, pp. 1186–1205, Jun. 2020, doi: 10.1016/j.joule.2020.04.004.

[31] I. Garagounis, A. Vourros, D. Stoukides, D. Dasopoulos, and M. Stoukides, “Electrochemical Synthesis of Ammonia: Recent Efforts and Future Outlook,” *Membranes*, vol. 9, no. 9, p. 112, Aug. 2019, doi: 10.3390/membranes9090112.

[32] C. R. Santhosh and R. Sankannavar, “A comprehensive review on electrochemical green ammonia synthesis: From conventional to distinctive strategies for efficient nitrogen fixation,” *Appl. Energy*, vol. 352, p. 121960, Dec. 2023, doi: 10.1016/j.apenergy.2023.121960.

[33] “Mineral commodity summaries 2023,” U.S. Geological Survey, 2023, 2023. doi: 10.3133/mcs2023.

[34] “Canadian fertilizer production, by product type and fertilizer year, cumulative data.” Accessed: Feb. 07, 2023. [Online]. Available: https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210003701

[35] “Nutrien 2022 Fact Book,” Nutrien, Jun. 2022. Accessed: Feb. 07, 2023. [Online]. Available: https://www.nutrien.com/nutrien-fact-book

[36] “Proud to be Producing Lower Carbon Ammonia,” Nutrien. Accessed: Apr. 13, 2023. [Online]. Available: https://www.nutrien.com/what-we-do/stories/proud-be-producing-lower-carbon-ammonia

[37] “Greenhouse Gas Reporting Program data search.” Accessed: Apr. 13, 2023. [Online]. Available: https://climate-change.canada.ca/facility-emissions/

[38] “Canada Ammonia; anhydrous exports by country | 2019 | Data.” Accessed: Feb. 07, 2023. [Online]. Available: https://wits.worldbank.org/trade/comtrade/en/country/CAN/year/2019/tradeflow/Exports/partner/ALL/product/281410

[39] “Fertilizer shipments to Canadian agriculture and export markets, by product type and fertilizer year, cumulative data.” Accessed: Feb. 28, 2024. [Online]. Available: https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210003801

[40] A. Mussell and A. Poirier, “Understanding the Risks and Vulnerabilities Facing the Canadian Agricultural Fertilizer Market,” The Canadian Agri-Food Policy Institute, Ottawa, Canada, Dec. 2022. [Online]. Available: https://capi-icpa.ca/wp-content/uploads/2022/12/2022-12-16-Understanding-the-Risks-and-Vulnerabilities-Facing-the-Canadian-Agricultural-Fertilizer-Market-EN-1-1.pdf

[41] “Hydrogen Production - Steam Methane Reforming (SMR).” New York State Energy Research and Development Authority. [Online]. Available: https://www.amiqweb.es/app/download/9343795/6hydrogenproductionsteammethanereforming.pdf

[42] P. C. Jain, “Greenhouse effect and climate change: scientific basis and overview,” *Renew. Energy*, vol. 3, no. 4, pp. 403–420, Jun. 1993, doi: 10.1016/0960-1481(93)90108-S.

[43] “Understanding Global Warming Potentials.” Accessed: Dec. 06, 2023. [Online]. Available: https://www.epa.gov/ghgemissions/understanding-global-warming-potentials

[44] “Global warming potentials.” Accessed: Feb. 28, 2024. [Online]. Available: https://www.canada.ca/en/environment-climate-change/services/climate-change/greenhouse-gas-emissions/quantification-guidance/global-warming-potentials.html

[45] “What Are The Sustainable Development Goals And Why Should You Care?” Accessed: Feb. 28, 2024. [Online]. Available: https://plancanada.ca/en-ca/stories/what-are-the-sdgs?gad_source=1&gclid=CjwKCAiA0PuuBhBsEiwAS7fsNbli7jaEObstnXlpDzZt4vkpAeYz_gVw_yPNK8xpZQT3dGIB1143pxoCKiUQAvD_BwE

[46] K. Calvin *et al.*, “IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland.,” Intergovernmental Panel on Climate Change (IPCC), Jul. 2023. doi: 10.59327/IPCC/AR6-9789291691647.

[47] K. Abbass, M. Z. Qasim, H. Song, M. Murshed, H. Mahmood, and I. Younis, “A review of the global climate change impacts, adaptation, and sustainable mitigation measures,” *Environ. Sci. Pollut. Res.*, vol. 29, no. 28, pp. 42539–42559, Jun. 2022, doi: 10.1007/s11356-022-19718-6.

[48] W. Nordhaus, “Estimates of the Social Cost of Carbon: Concepts and Results from the DICE-2013R Model and Alternative Approaches,” *J. Assoc. Environ. Resour. Econ.*, vol. 1, no. 1/2, pp. 273–312, Mar. 2014, doi: 10.1086/676035.

[49] “Social cost of greenhouse gas emissions.” Accessed: Dec. 11, 2023. [Online]. Available: https://www.canada.ca/en/environment-climate-change/services/climate-change/science-research-data/social-cost-ghg.html

[50] *Valuing Climate Changes: Updating Estimation of the Social Cost of Carbon Dioxide*. Washington, D.C.: National Academies Press, 2017. doi: 10.17226/24651.

[51] C. D. Kolstad, *Environmental Economics*, 2nd ed. New York: Oxford University Press, 2011.

[52] J. M. Harris, B. Roach, and A.-M. Codur, “The Economics of Global Climate Change.” Global Development And Environment Institute, Tufts University, 2017. [Online]. Available: https://www.bu.edu/eci/files/2019/06/The_Economics_of_Global_Climate_Change.pdf

[53] “Carbon pollution pricing systems across Canada.” Accessed: Feb. 07, 2024. [Online]. Available: https://www.canada.ca/en/environment-climate-change/services/climate-change/pricing-pollution-how-it-will-work.html

[54] “Update to the Pan-Canadian Approach to Carbon Pollution Pricing 2023-2030.” Accessed: Feb. 07, 2024. [Online]. Available: https://www.canada.ca/en/environment-climate-change/services/climate-change/pricing-pollution-how-it-will-work/carbon-pollution-pricing-federal-benchmark-information/federal-benchmark-2023-2030.html

[55] “How carbon pricing works.” Accessed: Feb. 27, 2024. [Online]. Available: https://www.canada.ca/en/environment-climate-change/services/climate-change/pricing-pollution-how-it-will-work/putting-price-on-carbon-pollution.html

[56] “Cap and Trade Basics,” Center for Climate and Energy Solutions. Accessed: Feb. 27, 2024. [Online]. Available: https://www.c2es.org/content/cap-and-trade-basics/

[57] S. A. Greenlaw and D. Shapiro, *Principles of Microeconomics 2e*, 2nd ed. OpenStax, 2012. [Online]. Available: https://sites.bu.edu/manove-ec101/files/2019/04/OpenstaxMicroeconomics2e.pdf

[58] “2023 Fall Economic Statement.” Accessed: Feb. 27, 2024. [Online]. Available: https://www.budget.canada.ca/fes-eea/2023/home-accueil-en.html

[59] D. Saygin *et al.*, “Ammonia Production from Clean Hydrogen and the Implications for Global Natural Gas Demand,” *Sustainability*, vol. 15, no. 2, Art. no. 2, Jan. 2023, doi: 10.3390/su15021623.

[60] “Oligopoly markets - OECD.” Accessed: Feb. 27, 2024. [Online]. Available: https://www.oecd.org/daf/competition/oligopoly-markets.htm

[61] E. Wolfstetter, Ed., “Oligopoly and Industrial Organization,” in *Topics in Microeconomics: Industrial Organization, Auctions, and Incentives*, Cambridge: Cambridge University Press, 1999, pp. 65–132. doi: 10.1017/CBO9780511625787.004.

[62] B. K. Kirui, “Reconciling Cournot and Bertrand Outcomes: A Review”.

[63] C. H. Tremblay and V. J. Tremblay, “Oligopoly Games and the Cournot–Bertrand Model: A Survey,” *J. Econ. Surv.*, vol. 33, no. 5, pp. 1555–1577, 2019, doi: 10.1111/joes.12336.

[64] “Ammonia Market | 2021 - 26 | Industry Share, Size, Growth - Mordor Intelligence.” Accessed: Dec. 14, 2021. [Online]. Available: https://www.mordorintelligence.com/industry-reports/ammonia-market

[65] “Global ammonia annual production capacity,” Statista. Accessed: Feb. 21, 2024. [Online]. Available: https://www.statista.com/statistics/1065865/ammonia-production-capacity-globally/

[66] M. Capdevila-Cortada, “Electrifying the Haber–Bosch,” *Nat. Catal.*, vol. 2, no. 12, Art. no. 12, Dec. 2019, doi: 10.1038/s41929-019-0414-4.

[67] *Ammonia: zero-carbon fertiliser, fuel and energy store*. London: Royal Society, 2020.

[68] “An introduction to Green Ammonia.” Accessed: Feb. 21, 2024. [Online]. Available: https://www.clarksons.com/home/news-and-insights/2022/an-introduction-to-green-ammonia/

[69] A. Tullo, “Is ammonia the fuel of the future?,” *Chemical & Engineering News*, vol. 99, no. 8, Mar. 08, 2021. Accessed: Feb. 21, 2024. [Online]. Available: https://cen.acs.org/business/petrochemicals/ammonia-fuel-future/99/i8

[70] L. R. A. Vargas, “Analysis of Negative Emission Ammonia Fertilizer (urea) Process,” KYH Royal Institute of Technology, Stockholm, Sweden, 2020.

[71] “From Fertilizer to Fuel: Can ‘Green’ Ammonia Be a Climate Fix?,” Yale E360. Accessed: Feb. 21, 2024. [Online]. Available: https://e360.yale.edu/features/from-fertilizer-to-fuel-can-green-ammonia-be-a-climate-fix

[72] “Carbon Dioxide Emissions From Electricity - World Nuclear Association.” Accessed: Feb. 21, 2024. [Online]. Available: https://world-nuclear.org/information-library/energy-and-the-environment/carbon-dioxide-emissions-from-electricity.aspx

[73] “A clean electricity standard in support of a net-zero electricity sector: discussion paper.” Accessed: Feb. 21, 2024. [Online]. Available: https://www.canada.ca/en/environment-climate-change/services/canadian-environmental-protection-act-registry/achieving-net-zero-emissions-electricity-generation-discussion-paper.html

[74] D. Bennett, “Danielle Smith invokes sovereignty act on green electricity, concedes it’s for symbolic effect,” *CTV News*, Edmonton, Nov. 27, 2023. Accessed: Feb. 21, 2024. [Online]. Available: https://edmonton.ctvnews.ca/danielle-smith-invokes-sovereignty-act-on-green-electricity-concedes-it-s-for-symbolic-effect-1.6662159

[75] D. Postey, “‘Bills would more than double’: Sask. says making province’s electrical grid net-zero by 2035 is impossible,” *CTV News*, Regina, Nov. 21, 2023. Accessed: Feb. 21, 2024. [Online]. Available: https://regina.ctvnews.ca/bills-would-more-than-double-sask-says-making-province-s-electrical-grid-net-zero-by-2035-is-impossible-1.6654090

[76] “Canada’s Energy Future Data Appendices.” Canada Energy Regulator, 2016. doi: 10.35002/ZJR8-8X75.

[77] M. Mersch *et al.*, “A comparative techno-economic assessment of blue, green, and hybrid ammonia production in the United States,” *Sustain. Energy Fuels,* 2024, doi: 10.1039/D3SE01421E.

[78] C. Arnaiz del Pozo and S. Cloete, “Techno-economic assessment of blue and green ammonia as energy carriers in a low-carbon future,” *Energy Convers. Manag.*, vol. 255, p. 115312, Mar. 2022, doi: 10.1016/j.enconman.2022.115312.

[79] N. Campion, H. Nami, P. R. Swisher, P. Vang Hendriksen, and M. Münster, “Techno-economic assessment of green ammonia production with different wind and solar potentials,” *Renew. Sustain. Energy Rev.*, vol. 173, p. 113057, Mar. 2023, doi: 10.1016/j.rser.2022.113057.

[80] K. Lee, X. Liu, P. Vyawahare, P. Sun, A. Elgowainy, and M. Wang, “Techno-economic performances and life cycle greenhouse gas emissions of various ammonia production pathways including conventional, carbon-capturing, nuclear-powered, and renewable production,” *Green Chem.*, vol. 24, no. 12, pp. 4830–4844, Jun. 2022, doi: 10.1039/D2GC00843B.

[81] R. Michael Nayak-Luke and R. Bañares-Alcántara, “Techno-economic viability of islanded green ammonia as a carbon-free energy vector and as a substitute for conventional production,” *Energy Environ. Sci.*, vol. 13, no. 9, pp. 2957–2966, 2020, doi: 10.1039/D0EE01707H.

[82] R. Kajaste and M. Hurme, “Cement industry greenhouse gas emissions – management options and abatement cost,” *J. Clean. Prod.*, vol. 112, pp. 4041–4052, Jan. 2016, doi: 10.1016/j.jclepro.2015.07.055.

[83] K. Gillingham and J. H. Stock, “The Cost of Reducing Greenhouse Gas Emissions,” *J. Econ. Perspect.*, vol. 32, no. 4, pp. 53–72, Nov. 2018, doi: 10.1257/jep.32.4.53.

[84] C. E. Finke, H. F. Leandri, E. T. Karumb, D. Zheng, M. R. Hoffmann, and N. A. Fromer, “Economically advantageous pathways for reducing greenhouse gas emissions from industrial hydrogen under common, current economic conditions,” *Energy Environ. Sci.*, vol. 14, no. 3, pp. 1517–1529, Mar. 2021, doi: 10.1039/D0EE03768K.

[85] “CER – Executive Summary.” Accessed: Mar. 13, 2024. [Online]. Available: https://www.cer-rec.gc.ca/en/data-analysis/canada-energy-future/2023/executive-summary/

[86] A. Wiskich and T. Rapson, “Economics of Emerging Ammonia Fertilizer Production Methods – a Role for On-Farm Synthesis?,” *ChemSusChem*, vol. 16, no. 22, p. e202300565, 2023, doi: 10.1002/cssc.202300565.

[87] M. Jain, R. Muthalathu, and X.-Y. Wu, “Electrified ammonia production as a commodity and energy storage medium to connect the food, energy, and trade sectors,” *iScience*, vol. 25, no. 8, p. 104724, Jul. 2022, doi: 10.1016/j.isci.2022.104724.

[88] E. and C. C. Canada, “Pre-publication: Updated carbon intensities for Canadian grid electricity and excess electricity to grid processes.” Accessed: Jul. 16, 2024. [Online]. Available: https://www.canada.ca/en/environment-climate-change/services/managing-pollution/fuel-life-cycle-assessment-model/updated-carbon-intensity-electricity.html

[89] “Innovation Outlook: Renewable Ammonia,” IRENA, May 2022. [Online]. Available: https://www.irena.org/publications/2022/May/Innovation-Outlook-Renewable-Ammonia

[90] D. Saygin, M. van den Broek, A. Ramírez, M. K. Patel, and E. Worrell, “Modelling the future CO2 abatement potentials of energy efficiency and CCS: The case of the Dutch industry,” *Int. J. Greenh. Gas Control*, vol. 18, pp. 23–37, Oct. 2013, doi: 10.1016/j.ijggc.2013.05.032.

[91] “Ammonia Plants.” Accessed: Mar. 13, 2024. [Online]. Available: https://thyssenkrupp-uhde.com/en/products-and-technologies/fertilizer-technologies/ammonia-plants

[92] “CER – Provincial and Territorial Energy Profiles – Canada.” Accessed: Mar. 13, 2024. [Online]. Available: https://www.cer-rec.gc.ca/en/data-analysis/energy-markets/provincial-territorial-energy-profiles/provincial-territorial-energy-profiles-canada.html

[93] A. E. Attema, W. B. F. Brouwer, and K. Claxton, “Discounting in Economic Evaluations,” *Pharmacoeconomics*, vol. 36, no. 7, pp. 745–758, 2018, doi: 10.1007/s40273-018-0672-z.

[94] G. Collodi, G. Azzaro, N. Ferrari, and S. Santos, “Techno-economic Evaluation of Deploying CCS in SMR Based Merchant H2 Production with NG as Feedstock and Fuel,” *Energy Procedia*, vol. 114, pp. 2690–2712, Jul. 2017, doi: 10.1016/j.egypro.2017.03.1533.

[95] “The Chemical Engineering Plant Cost Index ®,” Chemical Engineering. Accessed: Mar. 14, 2024. [Online]. Available: https://www.chemengonline.com/pci-home/

[96] “EverWind Secures Offtake from Key German Partner | Uniper.” Accessed: Apr. 18, 2023. [Online]. Available: https://www.uniper.energy/news/everwind-secures-offtake-from-key-german-partner-uniper-for-canadas-first-green-hydrogen-hub-in-nova-scotia

[97] C. Hepburn and W. Beckerman, “Ethics of the Discount Rate in the Stern Review on the Economics of Climate Change,” *World Econ.*, vol. 8, pp. 187–210, Feb. 2007.

[98] R. G. Newell and W. A. Pizer, “Uncertain discount rates in climate policy analysis,” *Energy Policy*, vol. 32, no. 4, pp. 519–529, Mar. 2004, doi: 10.1016/S0301-4215(03)00153-8.

[99] United Nations Economic Commission for Europe, *Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources*. in ECE Energy Series. United Nations, 2022. doi: 10.18356/9789210014854.

[100] “Frequently Asked Questions (FAQs) - U.S. Energy Information Administration (EIA).” Accessed: Mar. 13, 2024. [Online]. Available: https://www.eia.gov/tools/faqs/faq.php

[101] C. E. R. Government of Canada, “CER – Provincial and Territorial Energy Profiles – Newfoundland and Labrador.” Accessed: Jul. 17, 2024. [Online]. Available: https://www.cer-rec.gc.ca/en/data-analysis/energy-markets/provincial-territorial-energy-profiles/provincial-territorial-energy-profiles-newfoundland-labrador.html

[102] J. Rising, M. Tedesco, F. Piontek, and D. A. Stainforth, “The missing risks of climate change,” *Nature*, vol. 610, no. 7933, pp. 643–651, Oct. 2022, doi: 10.1038/s41586-022-05243-6.

[103] K. Branker, J. Jeswiet, and I. Y. Kim, “Greenhouse gases emitted in manufacturing a product—A new economic model,” *CIRP Ann.*, vol. 60, no. 1, pp. 53–56, Jan. 2011, doi: 10.1016/j.cirp.2011.03.002.

[104] A. A. M. Farhat and V. I. Ugursal, “Greenhouse gas emission intensity factors for marginal electricity generation in Canada,” *Int. J. Energy Res.*, vol. 34, no. 15, pp. 1309–1327, 2010, doi: 10.1002/er.1676.

[105] S. A. H. Zahabi, L. Miranda-Moreno, Z. Patterson, P. Barla, and C. Harding, “Transportation Greenhouse Gas Emissions and its Relationship with Urban Form, Transit Accessibility and Emerging Green Technologies: A Montreal Case Study,” *Procedia - Soc. Behav. Sci.*, vol. 54, pp. 966–978, Oct. 2012, doi: 10.1016/j.sbspro.2012.09.812.

[106] C. R. Taylor and D. L. Moss, “The Fertilizer Oligopoly: The Case for Global Antitrust Enforcement,” The American Antitrust Institute, 2013.

[107] N. Salmon, R. Bañares-Alcántara, and R. Nayak-Luke, “Optimization of green ammonia distribution systems for intercontinental energy transport,” *iScience*, vol. 24, no. 8, p. 102903, Aug. 2021, doi: 10.1016/j.isci.2021.102903.

[108] S. C. Government of Canada, “Canadian fertilizer production, by product type and fertilizer year, cumulative data.” Accessed: May 17, 2024. [Online]. Available: https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210003701

[109] J. Lim, C. A. Fernández, S. W. Lee, and M. C. Hatzell, “Ammonia and Nitric Acid Demands for Fertilizer Use in 2050,” *ACS Energy Lett.*, vol. 6, no. 10, pp. 3676–3685, Oct. 2021, doi: 10.1021/acsenergylett.1c01614.

[110] K. Fu, Y. Li, H. Mao, and Z. Miao, “Firms’ production and green technology strategies: The role of emission asymmetry and carbon taxes,” *Eur. J. Oper. Res.*, vol. 305, no. 3, pp. 1100–1112, Mar. 2023, doi: 10.1016/j.ejor.2022.06.024.

[111] D. Buccella, L. Fanti, and L. Gori, “Environmental Policies in a Polluting Duopoly: A Simple Comparison,” *Ital. Econ. J.*, Apr. 2024, doi: 10.1007/s40797-024-00277-3.

[112] D. Krass, T. Nedorezov, and A. Ovchinnikov, “Environmental Taxes and the Choice of Green Technology,” *Prod. Oper. Manag.*, vol. 22, no. 5, pp. 1035–1055, 2013, doi: 10.1111/poms.12023.

[113] J. Guo and R. Huang, “A carbon tax or a subsidy? Policy choice when a green firm competes with a high carbon emitter,” *Environ. Sci. Pollut. Res.*, vol. 29, no. 9, pp. 12845–12852, Feb. 2022, doi: 10.1007/s11356-020-12324-4.

[114] Y. Yi, Y. Wang, C. Fu, and Y. Li, "Taxes or subsidies to promote investment in green technologies for a supply chain considering consumer preferences for green products," *Comput. Ind. Eng.*, vol. 171, p. 108371, Sep. 2022, doi: 10.1016/j.cie.2022.108371.

[115] L. Vidal-Meliá, E. Camacho-Cuena, and M. Ginés-Vilar, "Market size asymmetry and strategic environmental policy in a Cournot model," *Front. Environ. Econ.*, vol. 2, Mar. 2023, doi: 10.3389/frevc.2023.1099336.

[116] G. Hu, L. Wang, Y. Chen, and B. Bidanda, "An oligopoly model to analyze the market and social welfare for green manufacturing industry," *J. Clean. Prod.*, vol. 85, pp. 94–103, Dec. 2014, doi: 10.1016/j.jclepro.2014.01.016.

[117] N. Norouzi, M. Fani, and A. Behzadi Forough, "Green tax as a path to greener economy: A game theory approach on energy and final goods in Iran," *Renew. Sustain. Energy Rev.*, vol. 156, p. 111968, Mar. 2022, doi: 10.1016/j.rser.2021.111968.

[118] L. Liu, C. Z. Huang, G. Huang, B. Baetz, and S. M. Pittendrigh, "How a carbon tax will affect an emission-intensive economy: A case study of the Province of Saskatchewan, Canada," *Energy*, vol. 159, pp. 817–826, Sep. 2018, doi: 10.1016/j.energy.2018.06.163.

[119] O. Edenhofer, M. Franks, and M. Kalkuhl, "Pigou in the 21st Century: a tribute on the occasion of the 100th anniversary of the publication of The Economics of Welfare," *Int. Tax Public Finance*, vol. 28, no. 5, pp. 1090–1121, 2021, doi: 10.1007/s10797-020-09653-y.

[120] R. D. Simpson, "Optimal pollution taxation in a Cournot duopoly," *Environ. Resour. Econ.*, vol. 6, no. 4, pp. 359–369, Dec. 1995, doi: 10.1007/BF00691819.

[121] F. Carlsson, "Environmental Taxation and Strategic Commitment in Duopoly Models," *Environ. Resour. Econ.*, vol. 15, no. 3, pp. 243–256, Mar. 2000, doi: 10.1023/A:1008362222639.

[122] "Urea - Monthly Price - Commodity Prices - Price Charts, Data, and News - IndexMundi." Accessed: Jul. 03, 2024. [Online]. Available: https://www.indexmundi.com/commodities/?commodity=urea&months=180

[123] "Report-Illinois Production Cost Report (Bi-weekly) | MMN." Accessed: Jul. 03, 2024. [Online]. Available: https://mymarketnews.ams.usda.gov/viewReport/3195

[124] R. Fazeli, F. J. Beck, and M. Stocks, "Recognizing the role of uncertainties in the transition to renewable hydrogen," *Int. J. Hydrog. Energy*, vol. 47, no. 65, pp. 27896–27910, Jul. 2022, doi: 10.1016/j.ijhydene.2022.06.122.

[125] "Executive summary – Global Hydrogen Review 2021 – Analysis," IEA. Accessed: Jul. 03, 2024. [Online]. Available: https://www.iea.org/reports/global-hydrogen-review-2021/executive-summary

[126] "U.S. ammonia prices rise in response to higher international natural gas prices - U.S. Energy Information Administration (EIA)." Accessed: Jul. 18, 2024. [Online]. Available: https://www.eia.gov/todayinenergy/detail.php?id=52358

[127] K. Okuguchi, "Quasi-Competitiveness and Cournot Oligopoly," *Rev. Econ. Stud.*, vol. 40, no. 1, pp. 145–148, 1973, doi: 10.2307/2296748.

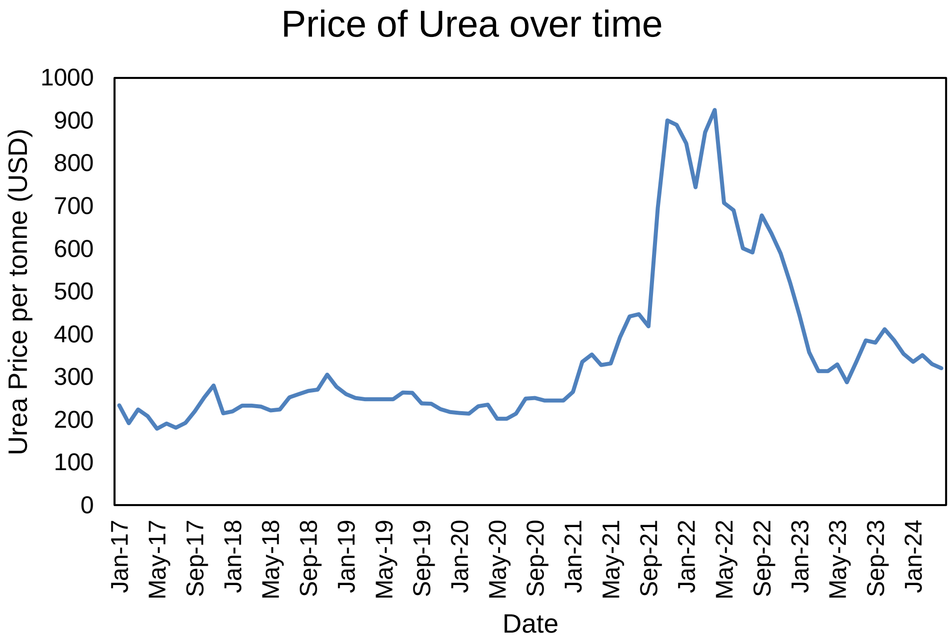
[128] K. Baylis and J. M. Perloff, "Capacity-Constrained Monopoly," *J. Ind. Organ. Educ.*, vol. 3, no. 1, pp. 1–11, Jan. 2008, doi: 10.2202/1935-5041.1022.

Appendix A

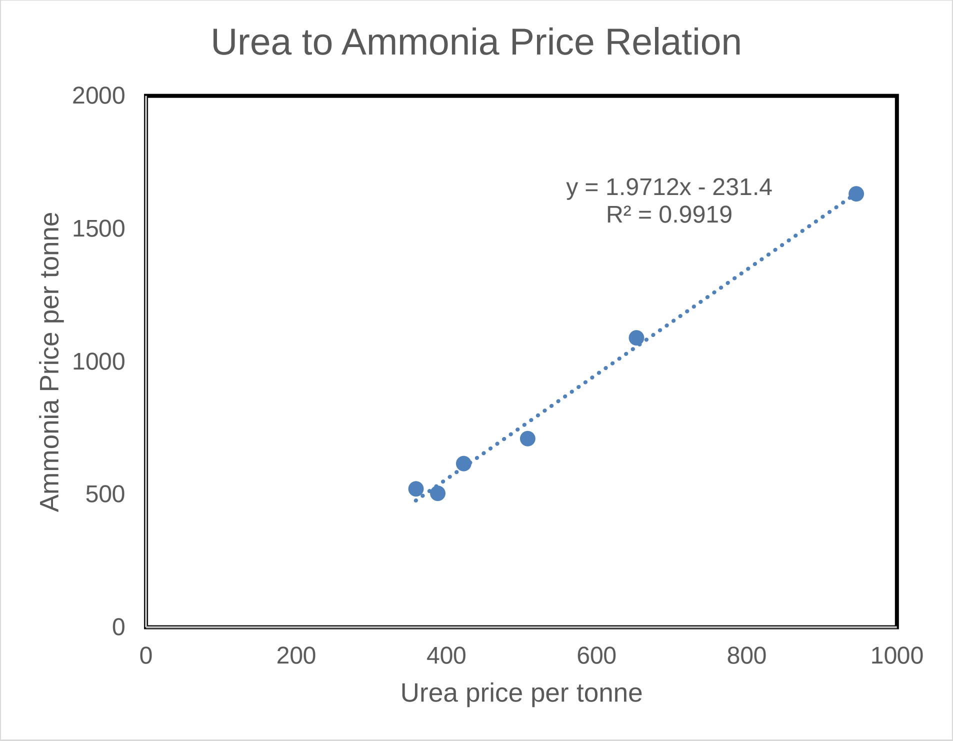
Baseline Parameters

Obtaining demand parameters for fertilizer (α_X and β_X)

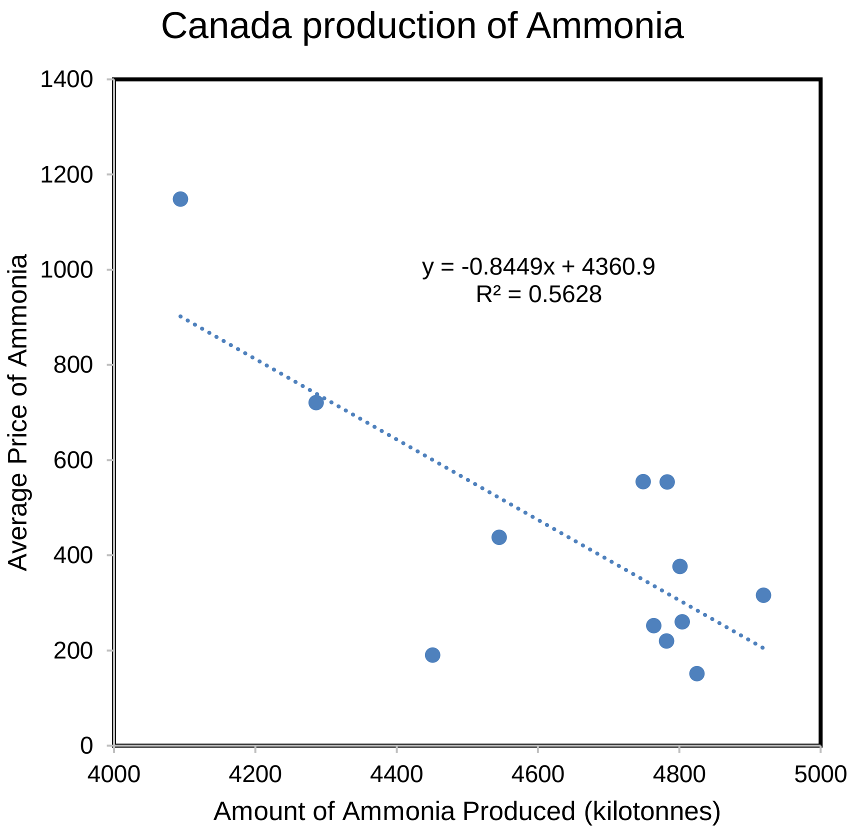
1. Obtained historical urea prices from [122].



2. Found urea and ammonia relationship from Illinois Production Cost Report [123] using data from the last week of May from 2017-2024.



3. Convert the historical urea prices from step 1. to ammonia prices. Convert to CAD using 0.75 ratio and compare to annual Canadian production [108]. Use linear regression to find linear best fit and use line parameters to find the α_X and β_X



4. α_X = 4360.9 CAD and β_X = 0.8449 CAD per ktonne of ammonia

Obtaining demand parameters for ammonia as energy storage (α_Z and β_Z)

1. Find price elasticity of Hydrogen in relation to energy [124]. ϵ =0.58
2. Find price of hydrogen and convert to CAD using 0.75 ratio. 1300 USD per tonne of hydrogen. [125] which means a 1733.33 CAD per tonne of hydrogen.
3. Convert price of hydrogen to price of ammonia using relationship of 4.8. The cost of ammonia is the price of ammonia per tonne divided by 4.8. 4.8 was retrieved using calculations from chapter 3 and [3] . This means around a 306.93 CAD per tonne of ammonia.
4. Find quantity of energy storage ammonia. 500,000 tonnes is used in this analysis [96].
5. Use price elasticity formula $\epsilon = -\frac{\Delta Q}{\Delta P} * \frac{P}{Q} = -\frac{1}{m} * \frac{P}{Q}$ and find m. m = -0.00125 CAD per tonne of ammonia.

6. Use m, price, and quantity to find y-intercept which would equal the α_Z.
7. α_Z = 1923 CAD and β_Z = 0.00125 CAD per tonne of ammonia

Appendix B

Welfare component values of Baseline Scenario to make Figure 4.2

Component	**Value**	**Unit**
CS_X	2,745,500,000	CAD
CS_Z	38,812,900	CAD
π_H	1,840,400,000	CAD
π_G	1,051,200,000	CAD
Social Cost	785,170,000	CAD
Tax Revenue	236,140,000	CAD
Welfare	5,126,900,000	CAD
Optimal Tax	0	CAD/tonne of CO_2

Appendix C

Analytical Expressions for Welfare for Tax and Subsidies section

No T or S

$$\frac{1}{72\,\beta_X\,\beta_Z}\big(27\,C_G{}^2\,\beta_X + 44\,C_G{}^2\,\beta_Z + 44\,C_H{}^2\,\beta_Z + 32\,\alpha_X{}^2\,\beta_Z + 27\,\alpha_Z{}^2\,\beta_X - 56\,C_G\,C_H\,\beta_Z - 32\,C_G\,\alpha_X\,\beta_Z - 54\,C_G\,\alpha_Z\,\beta_X - 32\,C_H\,\alpha_X\,\beta_Z \\ - 24\,\alpha_X\,\beta_Z\,v\,\xi_H - 24\,C_G\,\beta_Z\,v\,\xi_H + 48\,C_H\,\beta_Z\,v\,\xi_H\big)$$

Only S

$$\frac{1}{72\,\beta_X\,\beta_Z}\big(27\,C_G{}^2\,\beta_X + 44\,C_G{}^2\,\beta_Z + 44\,C_H{}^2\,\beta_Z - 9\,S_b{}^2\,\beta_X - 4\,S_b{}^2\,\beta_Z + 32\,\alpha_X{}^2\,\beta_Z + 27\,\alpha_Z{}^2\,\beta_X - 56\,C_G\,C_H\,\beta_Z - 18\,C_G\,S_b\,\beta_X - 40\,C_G\,S_b\,\beta_Z \\ + 32\,C_H\,S_b\,\beta_Z - 32\,C_G\,\alpha_X\,\beta_Z - 54\,C_G\,\alpha_Z\,\beta_X - 32\,C_H\,\alpha_X\,\beta_Z + 8\,S_b\,\alpha_X\,\beta_Z + 18\,S_b\,\alpha_Z\,\beta_X + 24\,S_b\,\beta_Z\,v\,\xi_H \\ - 24\,\alpha_X\,\beta_Z\,v\,\xi_H - 24\,C_G\,\beta_Z\,v\,\xi_H + 48\,C_H\,\beta_Z\,v\,\xi_H\big)$$

Only T

$$-\frac{1}{72\,\beta_{X'}\,\beta_Z}\big(56\,C_G\,C_H\,\beta_Z - 44\,C_G{}^2\,\beta_Z - 44\,C_H{}^2\,\beta_Z - 32\,\alpha_{X'}{}^2\,\beta_Z - 27\,\alpha_Z{}^2\,\beta_{X'} - 27\,C_G{}^2\,\beta_{X'} + 32\,C_G\,\alpha_{X'}\,\beta_Z + 54\,C_G\,\alpha_Z\,\beta_{X'} + 32\,C_H\,\alpha_{X'}\,\beta_Z \\ + 4\,\beta_Z\,\tau^2\,\xi_H{}^2 + 8\,\alpha_{X'}\,\beta_Z\,\tau\,\xi_H + 24\,\alpha_{X'}\,\beta_Z\,v\,\xi_H - 48\,\beta_Z\,\tau\,v\,\xi_H{}^2 + 32\,C_G\,\beta_Z\,\tau\,\xi_H - 40\,C_H\,\beta_Z\,\tau\,\xi_H + 24\,C_G\,\beta_Z\,v\,\xi_H \\ - 48\,C_H\,\beta_Z\,v\,\xi_H\big)$$

Combined T and S

$$\frac{1}{72\,\beta_X\,\beta_Z}\big(27\,C_G{}^2\,\beta_X + 44\,C_G{}^2\,\beta_Z + 44\,C_H{}^2\,\beta_Z - 9\,S_b{}^2\,\beta_X - 4\,S_b{}^2\,\beta_Z + 32\,\alpha_X{}^2\,\beta_Z + 27\,\alpha_Z{}^2\,\beta_X - 56\,C_G\,C_H\,\beta_Z - 18\,C_G\,S_b\,\beta_X - 40\,C_G\,S_b\,\beta_Z \\ + 32\,C_H\,S_b\,\beta_Z - 32\,C_G\,\alpha_X\,\beta_Z - 54\,C_G\,\alpha_Z\,\beta_X - 32\,C_H\,\alpha_X\,\beta_Z - 4\,\beta_Z\,\tau^2\,\xi_H{}^2 + 8\,S_b\,\alpha_X\,\beta_Z + 18\,S_b\,\alpha_Z\,\beta_X + 8\,S_b\,\beta_Z\,\tau\,\xi_H \\ + 24\,S_b\,\beta_Z\,v\,\xi_H - 8\,\alpha_X\,\beta_Z\,\tau\,\xi_H - 24\,\alpha_X\,\beta_Z\,v\,\xi_H + 48\,\beta_Z\,\tau\,v\,\xi_H{}^2 - 32\,C_G\,\beta_Z\,\tau\,\xi_H + 40\,C_H\,\beta_Z\,\tau\,\xi_H - 24\,C_G\,\beta_Z\,v\,\xi_H \\ + 48\,C_H\,\beta_Z\,v\,\xi_H\big)$$