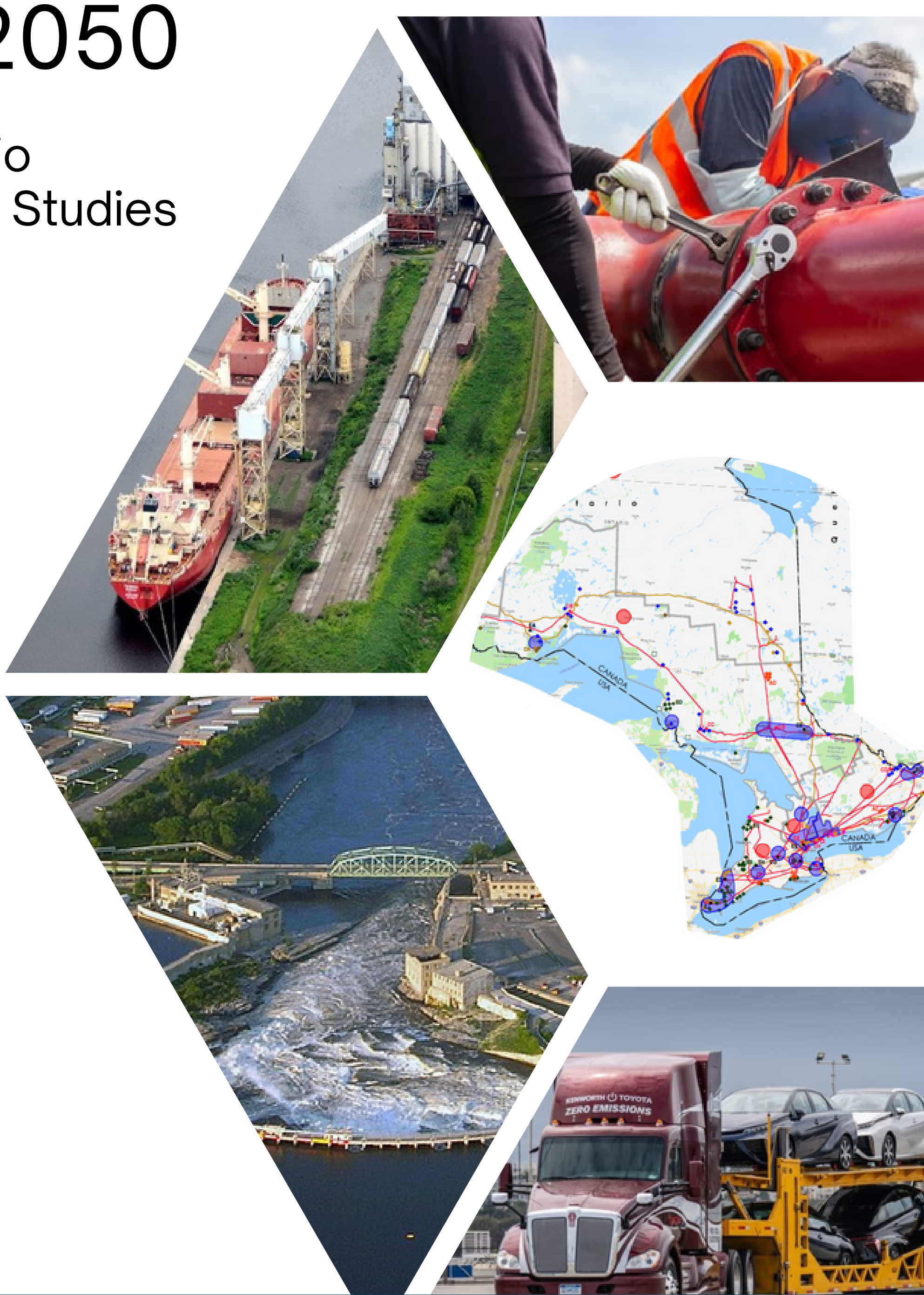
Forecasting **Low-Carbon Hydrogen Market Characteristics in Ontario** to 2050

Report 2 of the Ontario Hydrogen Foundation Studies



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Forecasting Low-Carbon Hydrogen Market Characteristics in Ontario to 2050

Report 2 of the Ontario Hydrogen Foundation Studies
An Initiative of H2GO Canada

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PREFACE

The Ontario Hydrogen Foundation Series

H2GO Canada is pleased to present this report, which is the second in a series of **Ontario Hydrogen Foundation Studies**. *Forecasting Low-Carbon Hydrogen Market Characteristics in Ontario to 2050* involved the building of an entirely new techno-economic assessment model. The forecast of hydrogen production and consumption for Ontario that is presented in this report represents a reference case to which the model has been calibrated. Other scenarios should be developed in consultation with communities, government and industry sectors having a stake in how the province's low-carbon hydrogen systems evolve. As an analytical tool to support market-wide planning and evaluation of prospective hydrogen systems, this model can be applied to the advancement of Ontario's low-carbon hydrogen strategy, published by the Government of Ontario in April 2022. It can also facilitate cross-sector coordination on hydrogen system development and help establish achievable targets for scaling up the flow of low-carbon hydrogen through the province's emerging markets.

H2GO Canada - background

H2GO Canada is a Not-for-Profit organization that was established in 2018 to advance a vision of hydrogen becoming a fully developed, low-carbon energy pathway for heat, power and mobility in Canada, as well as for de-carbonizing industrial production, supported by commercially vibrant supply chains. Its mission is to help make hydrogen systems a practical option for organizations in Canada that are seeking to reduce greenhouse gas emissions within their operations. Accordingly, the work of the organization focuses on cultivating conditions for hydrogen markets to develop, grow and thrive.

In 2019, H2GO Canada released its first report, *Developing a Sustainable Approach to Hydrogen Deployment in Canada*, as the product of a cross-Canada process of consultation with large employer organizations representing the primary sectors of the national economy. The policies and investment decisions of such organizations will determine in significant part the future of hydrogen systems adoption and expansion in Canada, simply as a matter of their importance and leverage within energy and material supply chains throughout the country. Input from this community-of-interest informed the seven guiding principles of hydrogen strategy development in Canada, set forth in H2GO Canada's inaugural report:

1. Prioritize a **net gain** in employment
2. Be guided by **analytical rigour**, basing deployment decisions on full life cycle analysis of sustainability criteria
3. Focus on the **development of markets** to accelerate scale-up
4. Build on international leadership to **secure growth in exports of technology**, services and expertise
5. Use hydrogen to help mobilize **Canada's resources for export**
6. Showcase the application of hydrogen to **integrated community energy system** design
7. Deliver **clean air** benefits to the public

These principles guided the development of the study presented herein.

Informal advisory group

H2GO Canada reached out to members of its community-of-interest and invited them to review the progress of the study team during the course of its work to produce this report. Representatives of industrial sectors with active operations in Ontario, as well as subject matter experts, generously contributed their time and talent as an informal advisory group. The insights and expertise of the advisory group members enriched the analysis carried out by the study team assembled by H2GO Canada, and helped to ensure that the content of this report is relevant to the needs of the principal stakeholders.

Model development and Study Team

Core to this study was the development of a new model to simulate the evolution of hydrogen systems in Ontario. Change Energy Services – an engineering consultancy based in Oakville, Ontario – was engaged to develop the *Hydrogen Growth in Ontario Techno-Economic Assessment Model*, referred to in short as the H2GrO-TEA Model.

G. Rymal Smith, P.Eng., was the chief architect of the H2GrO-TEA Model and led its development, assisted by Alyssa d'Cunha, P.Eng., and Gupar Kaur Punia, E.I.T., at Change Energy Services. This work constituted a significant dedication of in-kind support to the study, without which the forecasting for hydrogen production and use presented herein would not have been possible.

I am confident that this report will serve to build confidence in low-carbon hydrogen system planning and implementation in Ontario, by demonstrating the use of a new techno-economic assessment model that allows prospective systems to be costed and analyzed, such that the net benefits to Ontarians can be determined from an environmental, social and economic perspective.

Sincerely,

Bob Oliver
President and Member of the Board of Directors, H2GO Canada

ACKNOWLEDGEMENTS

The production of this report was made possible by the financial support of the following organizations, for which H2GO Canada expresses its gratitude.

H2GO Canada also gratefully recognizes Adam White and the team at Powerconsumer Inc. for their valued input to the study team's considerations on electricity grid supply scenarios, and Isadore Day, Wiindawtegowinini of Bimaadzwin for his perspectives on the opportunities for establishing hydrogen systems among Indigenous communities and by Indigenous-led enterprises in Ontario.

This report was written by Bob Oliver at H2GO Canada and by G. Rymal Smith, Gupar Kaur Punia and Alyssa D'Cunha at Change Energy Services. Maps and mapping analyses were produced by Al Davidson and Cheryl Robinson at Change Energy Services. Report editing and formatting was conducted by Heather Lindsay, at Change Energy Services.

The views expressed in this publication are the views of H2GO Canada and do not necessarily reflect those of any parties identified herein.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

Ontario's Low-Carbon Hydrogen Strategy establishes an ambition to lever the potential of hydrogen systems to advance environmental sustainability and support economic growth within the province. This aligns with a global movement in which leading nations have developed national plans for accelerating the production and use of hydrogen – among them, Canada. Global authorities on decarbonization, including the International Energy Agency and the International Renewable Energy Agency, report that low-carbon hydrogen systems will contribute significantly to achieving the goals of the Paris Agreement.

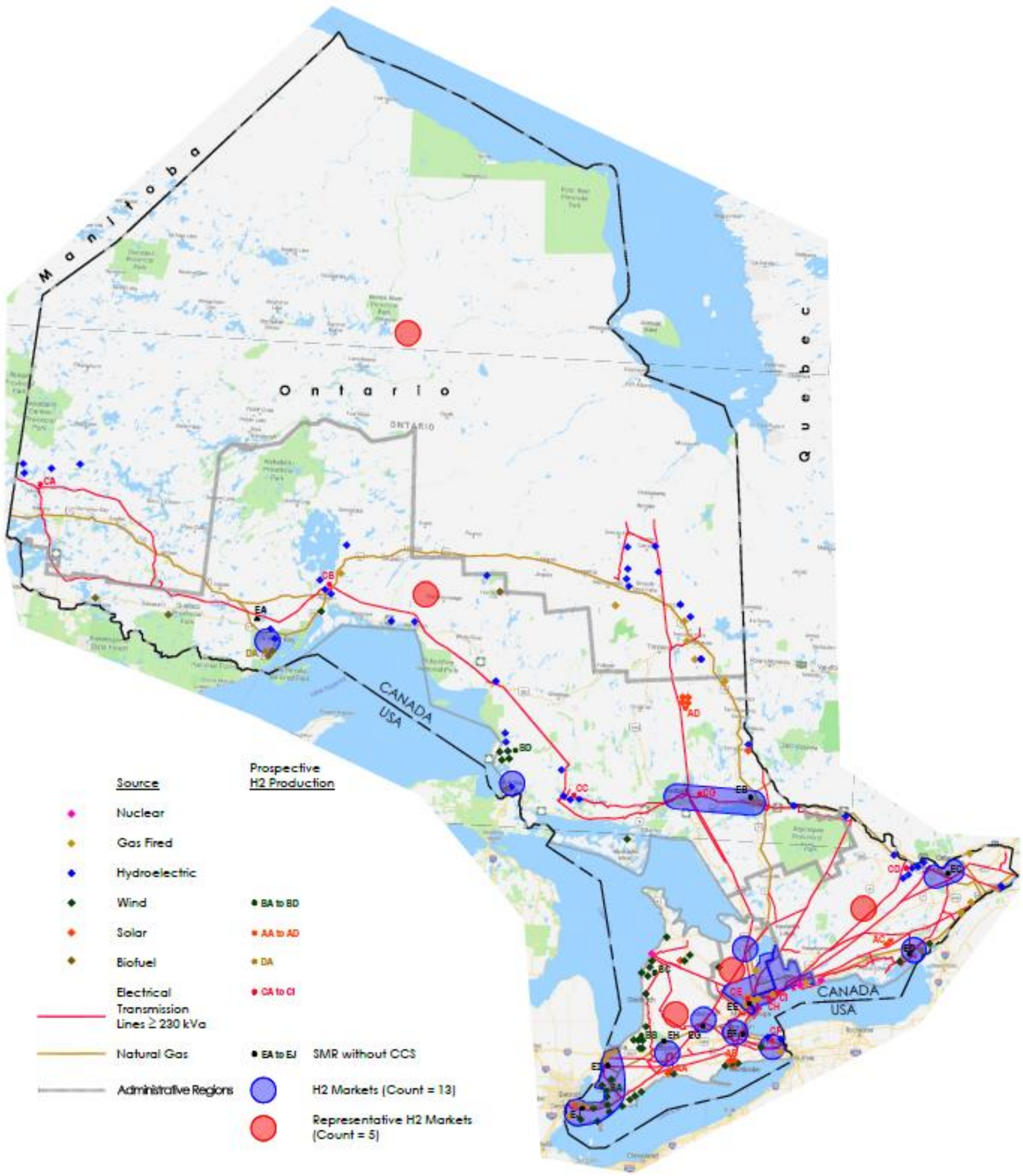
The size and diversity of Ontario's economy is a natural advantage, as it enables broad application of hydrogen systems throughout the province's many industry sectors. Exchange in low-carbon hydrogen could become a significant new source of value creation and a driver of innovation, adding to the future prosperity of all Ontarians. To realize this potential, careful planning is essential. Plans allow resources to be efficiently mobilized and decision-making to be coordinated among public and private sector stakeholders according to shared objectives. However, effective planning requires good information and comprehensive tools of analysis, so that alternatives can be comparatively assessed in terms of feasibility, costs, and benefits.

To help develop this analytical capacity in Ontario, H2GO Canada commissioned the development of a new tool, called the *Hydrogen Growth in Ontario Techno-Economic Assessment* (H2GrO-TEA) *Model*. The H2GrO-TEA Model enables scenarios of hydrogen value chain development to be defined and quantitatively simulated, sector by sector and throughout different regions of the province. The model generates estimates for volumes of hydrogen production and use, as well as the associated capital investments, operating expenses, job creation, and changes in greenhouse gas (GHG) emissions, for each year to 2050. Using this tool, stakeholders can iterate through many different scenarios of hydrogen market development to better understand the implications of different choices, to test sensitivities to different market characteristics and, ultimately, to prioritize the hydrogen projects that are foundational to fulfilling Ontario's vision and strategy.

This report presents a detailed description of a scenario for hydrogen production and use in Ontario that is rooted in conservative assumptions about market constraints and growth potentials, and draws on currently available data and commercial product information. Named the Base Case scenario, it demonstrates the use of the new H2GrO-TEA Model to generate forecasts to 2050 of hydrogen throughput in numerous sectors and subsectors comprising Ontario's economy. The effects on GHG emissions and job creation are also quantified, and the associated levelized costs are assessed. Key outputs of the Base Case scenario simulation are summarized in the following table.

Base Case scenario – H2GrO-TEA Model outputs	
Rate of hydrogen production by 2050	1.1 million tonnes per year
Rate of hydrogen consumption by 2050	3.7 million tonnes per year
Cumulative GHG emissions reductions by 2050	874 megatonnes
Cost of hydrogen delivered to end-user (approx.)	$14 per kilogram
Levelized cost GHG emissions avoided (approx.)	\$438/tonne-CO_2
Peak jobs created in one year	161 thousand
Total capital invested in production and distribution infrastructure	C$85 billion

The H2GrO-TEA Model calculates the cost of hydrogen delivered within geographic areas of population density supporting a diverse range of end-uses, often called hydrogen market hubs, and also between these market hubs, which allows for regional balancing of supply and demand. As well, hydrogen production and use occurring outside of the population-based market hubs is simulated in the model by defining distinct regions of the province as having market hub functionalities but are distributed over larger areas. These are called representative hubs. The map below (appearing in Section 5.1 of this report) illustrates the placement of local market hubs and regional, representative hubs as defined in the Base Case scenario.



The inclusion of a geographic dimension in the H2GrO-TEA Model allows distribution and delivery costs to be more accurately estimated, including the import and export of hydrogen between Ontario and neighbouring jurisdictions, as needed to balance hydrogen supply and demand within the province. Through the modeling undertaken for this report, it was discovered that regional disparities between hydrogen production capacity and rates of consumption can have profound impacts on the economic performance of such scenarios. For example, in the Base Case scenario, hydrogen use outpaces growth in domestic supply potential by more than three times by 2050, meaning that most of the hydrogen used in the province must be imported. To compare the effects of matching supply to demand, two modifications to the Base Case scenario were simulated: Mod-1, in which the efficiency of hydrogen production was increased so that production would match consumption rates in 2050 (i.e., 3.8 million tonnes), and Mod-2, in which demand was constrained so that it did not exceed domestic supply capacities. The tables below summarize the key changes to the Base Case scenario arising from the Mod-1 and Mod-2 variations to the supply and demand inputs.

Base Case scenario Mod-1 – H2GrO-TEA Model outputs	
Rate of hydrogen production by 2050 – *increased*	3.8 million tonnes per year
Rate of hydrogen consumption by 2050 – *unchanged*	3.7 million tonnes per year
Cumulative GHG emissions reductions by 2050 – *no change*	874 megatonnes
Cost of hydrogen delivered to end-user (approx.)	**$5 per kilogram**
Levelized cost GHG emissions avoided (approx.)	**-$35/tonne-$CO_2$**
Peak jobs created in one year	231 thousand
Total capital invested in production and distribution infrastructure	C$132 billion
Base Case scenario Mod-2 – H2GrO-TEA Model outputs	
Rate of hydrogen production by 2050 – *unchanged*	1.1 million tonnes per year
Rate of hydrogen consumption by 2050 – *constrained*	1.0 million tonnes per year
Cumulative GHG emissions reductions by 2050 – *declines*	317 megatonnes
Cost of hydrogen delivered to end-user (approx.)	$16 per kilogram
Levelized cost GHG emissions avoided (approx.)	$257/tonne-$CO_2$
Peak jobs created in one year	144 thousand
Total capital invested in production and distribution infrastructure	C$57 billion

The key finding arising from this analysis is that prioritizing hydrogen production in Ontario, so that it can keep pace with year-over-year increases in rates of consumption (across all of Ontario's hydrogen market hubs), results in a much lower average cost of hydrogen delivered to users, at approximately $5/kg in 2050, as well as a negative cost of carbon abatement, at approximately -$35/tonne of CO_2. By contrast, constraining demand for hydrogen drives up unit costs while yielding less mitigation of GHG emissions and fewer jobs.

These sample outputs emphasize the importance of technoeconomic modeling of hydrogen scenarios and provide Ontario stakeholders with an analytical tool to support comprehensive planning and resource mobilization in the pursuit of Ontario's Low-Carbon Hydrogen Strategy. The H2GrO-TEA Model can also be used to determine the conditions necessary to achieve a prescribed outcome and to identify the manner, timing, and scale of investments needed. This provides an opportunity for businesses and individuals in Ontario to use the tool to inform their decisions related to decarbonization, new ventures, and utilizing hydrogen as a more sustainable energy or chemical commodity.

In addition to project planning and investment, the H2GrO-TEA Model can also inform policy development. Some of the insights emerging from the Base Case scenario-play described in this report include the following:

- Ontario can be self-sufficient in low-carbon hydrogen <u>and</u> be a net exporter by prioritizing its productive capacity. Increasing production hinges on new technology development for efficient conversion of available feedstocks to hydrogen.

- Increasing renewable and nuclear power capacity will feed into (and support) least-cost hydrogen pathways in Ontario.

- Optimizing economic and environmental benefits of low-carbon hydrogen production in Ontario is synergistic with the province's strengths in low-carbon power generation, as well as its natural gas distribution system and carbon capture, use and storage potential.

- By focusing on applications that consume higher volumes of hydrogen with less reliance on capital-intensive infrastructure, demand can scale up faster at lower costs of delivered hydrogen during the initial years of market scale-up.

This report concludes with an assessment of the current limitations of the H2GrO-TEA Model and makes recommendations for next steps to enhance and expand the simulation capabilities. As well, a process of engaging with government, non-government and industry stakeholders is proposed to workshop revisions to the model – sector by industry sector – to improve the accuracy of the input data and continuously improve its calibration with observed, real-world technology performance and commercial dynamics. This will help build a general familiarity with the H2GrO-TEA Model and broad-based trust in its application.

1.0 INTRODUCTION

The Governments of Canada and of its Provinces have established *The Pan-Canadian Framework on Clean Growth and Climate Change*, which lays out the dual objectives of reducing greenhouse gas emissions to a level that is consistent with the goals of the Paris Agreement of 2015 and growing the economy in all regions of the country, propelled in part through the adoption of innovative, low-carbon intensity fuels and technologies.

The production, distribution and use of hydrogen is central to the decarbonization plans of many jurisdictions, including (and within) Canada. This is because the hydrogen molecule, H_2, is free of carbon and can be used as a versatile commodity having attractive qualities as a fuel or chemical agent. Hydrogen exists in a gaseous state at normal atmospheric temperature and pressure. Like natural gas, it can be burned to heat homes and buildings, cook food or generate heat needed for industrial manufacturing processes. Hydrogen can be used as a fuel in combustion engines that power vehicles and electricity generators. Using a fuel cell, hydrogen can be used to produce electricity directly. The reverse is also true: electrical energy can, in essence, be stored as hydrogen, through the process of electrolysis. Since hydrogen can be stored as a compressed gas indefinitely, it can facilitate seasonal energy storage, in which electrical energy is accumulated and held for timespans lasting weeks or months. Not only is hydrogen storable, it is also portable. It can be transported by truck, rail, ship, or pipeline just like other fuels and commodities.

In these myriad applications of hydrogen, note the repeated use of the verb *can* instead of *is*. That is because the supporting infrastructure and distribution systems that would make hydrogen easily accessible to users is not yet established. Similarly, in the sectors of society where hydrogen has potential as a novel, low-carbon alternative, most technicians and authorities generally do not hold the requisite experience for operation and maintenance. As with novel and disruptive energy systems that emerged throughout the 20th century, such as electricity, natural gas and oil, it will take time, investment and education to build up the physical and human infrastructure needed to fully realize the advantages of hydrogen at-scale.

Notwithstanding the challenges, hydrogen can help to satisfy society's demands for heat, power, and mobility. When hydrogen is combusted for heat or is converted to electricity in a fuel cell, no carbon dioxide is produced in these reactions. The main by-product is water. Furthermore, if hydrogen is produced using energy and feedstocks that are low in carbon-intensity, then it can support the decarbonization of these energy end-uses. As an industrial chemical, this low-carbon hydrogen (as it is often called) can also help reduce the carbon-intensity of produced materials, such as iron and steel, ammonia and fertilizers, petrochemicals and many other products.

In 2022, the International Energy Agency (IEA) reported that 26 countries have national plans for building up low-carbon hydrogen systems or targets for production or use [1]. The IEA also estimates that achieving net-zero greenhouse gas emissions in 2050 will require 520 megatonnes (Mt) of low-carbon hydrogen, globally [2]. The International Renewable Energy Agency calculates that hydrogen could account for 12 per cent of total world energy use in 2050 under a scenario where the global temperature rise does not exceed the 1.5^{o}C threshold defined in the Paris Agreement [3].

Ontario is poised to participate in this global hydrogen market, contributing to and benefiting from its development. Ontario's Low-Carbon Hydrogen Strategy, presented to the public on April 7th, 2022, establishes the province's ambition to fully lever the potential of hydrogen systems to achieve environmental sustainability and support economic growth [4]. As described in its Strategy, Ontario's electricity supply mix is very low in carbon-intensity, which makes hydrogen produced via electrolysis a compelling opportunity. Ontario also has an extensive natural gas distribution system, which supports the hydrogen strategy by making methane widely available as a feedstock for hydrogen production. Moreover, the natural gas pipeline network can be progressively modified and repurposed over time to mobilize hydrogen, thus serving as a starting point for the development of hydrogen transmission infrastructure. Ontario's economy is Canada's largest and most diverse, meaning that hydrogen can find broad application throughout the province. Exchange in low-carbon hydrogen could become a significant new source of value creation and economic growth, as well as a driver of innovation in many sectors. The versatility of hydrogen and its potential for integration with existing energy systems also presents opportunities for isolated and off-grid communities that are seeking new means to advance their plans for energy independence and prosperity.

However, a strategy needs a plan to implement, and any plan must first be considered for its feasibility and value proposition. Put simply, what will Ontarians *get* out of hydrogen and what will it *take*? To answer that question, a means is needed for identifying and characterizing the system elements that enable the production of hydrogen, its distribution and use. These elements must interconnect and function as a technologically real system. So much hydrogen will require so much compressor capacity, power, piping, storage tanks and so on. Depending on the feedstocks for making hydrogen, a certain number of production plants will be needed in certain locations across the province. Siting these facilities must also account for practical proximities to hydrogen users, and the supply chain must evolve to meet market demand. Essentially, a model is needed to simulate the physical dynamics of a complex hydrogen system, in which key variables can be changed to reflect the best available data and assumptions.

It is also necessary to assess the performance of the modeled hydrogen system from an economic, social, and environmental perspective. What types and level of capital expenditures are needed to build the prospective hydrogen supply chains in Ontario, and when would the outlays occur? What are the ongoing operating expenses? How much labour must be mobilized to build, operate, and maintain the hydrogen technologies and infrastructure? What return on investment can be expected? How many new jobs will be created in the modeled scenario? Perhaps most importantly, what level of greenhouse gas (GHG) emissions reduction can be realized? After all, decarbonization is the main driver of interest in low-carbon hydrogen.

Techno-economic assessment model development

To address this set of needs, the tools of techno-economic assessment (TEA) are often employed. TEA is an established method of analyzing processes and industrial systems to determine economically optimal designs and throughput capacity, which directly inform planning, prioritizing, and decision-making. TEA often involves (and enables) sensitivity analyses on variables where a high degree of uncertainty may exist, to better understand the risks posed to the modeled system.

H2GO Canada believes that this kind of modeling capacity is needed to develop roadmaps and implementation plans that fulfill *Ontario's Low-carbon hydrogen future*, as articulated in the strategy:

> *Ontario's vision for the low-carbon hydrogen strategy is to develop a self-sustaining low-carbon hydrogen economy in Ontario that would create local jobs, attract investment, and reduce GHG emissions.*
>
> *The core objectives of Ontario's strategy are to:*
>
> - *Generate Economic Development and Jobs*
> - *Reduce Greenhouse Gas Emissions*
> - *Promote Energy Diversity*
> - *Promote Innovation and Investment*
> - *Strengthen Collaboration*

Accordingly, H2GO Canada engaged Change Energy Services – an engineering firm specializing in the analysis and design of gaseous energy systems – to build a new techno-economic assessment model that enables scenarios of hydrogen value chain development to be simulated numerically in quantitative terms. The model generates estimates for capital investments, operating expenses, and job creation for each year to 2050, based on volumes of hydrogen produced and used. As an effect of the growing use of hydrogen in various applications, changes to GHG emissions are also generated, sector-by-sector. The model outputs enable levelized costs of the hydrogen scenarios to be calculated, in terms of the amount of hydrogen active in the market or the magnitude of reductions in GHG emissions.

Construction of the model occurred in a Microsoft Excel environment and took several months in 2022 to complete. It is composed of an extensive set of linked spreadsheets with data tables representing input variables and foundational assumptions, as well as formulae to generate outputs for different aspects of the hydrogen system. A database of real equipment pricing and maintenance requirements is drawn upon to generate system cost estimates.

The insights provided by the model can inform hydrogen system planning by region and on a sector-by-sector basis, prioritizing hydrogen market development, and the development of supporting policy. As a tool of analysis, the model is oriented to high-level, market-wide assessment, as opposed to analyzing specific applications or projects. In the absence of available data, the study team was obliged to rely on informed guesswork. However, having the model built, tested, and demonstrated in this report, the opportunity now exists to workshop the assumptions on a sector-by-sector basis with Ontario industry stakeholders.

What comes next? Stakeholder workshops and continuous model improvement

As the model inputs and variables are successively refined in consultation with industry groups and experts, the precision and accuracy of the simulations will be improved. The hope of the study team is that this model will be embraced by stakeholders in Ontario's low-carbon hydrogen future and used as a shared tool to support the planning and coordination of hydrogen value chains and markets.

Learning from the reference case

The purpose of this report is to introduce the new TEA model as applied to hydrogen value chains in Ontario and demonstrate its utility by simulating a reference case of hydrogen market evolution in the province. Through this exercise, the underlying relationships and constraints that will govern the development of low-carbon hydrogen markets in Ontario can begin to be understood.

2.0 BUILDING A MODEL OF ONTARIO LOW-CARBON HYDROGEN SYSTEMS

In his 2014 book, *Our Mathematical Universe*, M.I.T. professor Max Tegmark hypothesizes that the universe and everything in it is not simply *described* using mathematics, but it actually *is* math. He proposes that the mathematical equations used to so perfectly predict the nature of matter and energy are all we need to fully understand the universe, and that the words we use to explain the math is nothing more than "baggage."

If we accept Dr. Tegmark's proposition, then this report can be considered the baggage that accompanies a mathematical model built to help describe the nature of how low-carbon hydrogen markets can evolve in Ontario. It is the study team's attempt to describe its modelling construct, clumsily, in English, instead of the elegant math in which it was written.

To develop a reference forecast of the prospective growth of low-carbon hydrogen markets in Ontario, extending from the present to 2050, a numerical model of hydrogen production, distribution and use must first be established. As described in the previous section, Change Energy Services was engaged by H2GO Canada to build such a model for the purpose of simulating user-defined scenarios to generate estimates of the overall costs and benefits. Thereby, the implications of different low-carbon hydrogen systems can be studied and explored in an Ontario context, including the risks and opportunities, as well as the pivotal developments that would need to happen to reach future goals.

The name chosen by the study team for the model is the ***Hydrogen Growth in Ontario Techno-Economic Assessment Model***, referred to in short as the **H2GrO-TEA Model**. The H2GrO-TEA model comprises five discrete modules that generate outputs used to characterize Ontario's hydrogen ecosystem:

1) Regional scan module. This module generates the foundational inputs for both the hydrogen production and the hydrogen consumption modules. These inputs are based on scans of distinct market areas within Ontario, each having a unique set of hydrogen opportunities based on industrial and population characteristics. However, this module also receives outputs from other modules (namely, production, consumption, and emissions, described below) to produce scores of the relative impact, or importance, of the hydrogen production pathways and the consuming applications in a region.
2) Production module. Receiving inputs from the regional scan module, which define the relative availability of feedstocks for the various types for hydrogen production, this module determines hydrogen production volumes for each region and their associated attributes, such as production technology efficiencies, costs and carbon-intensity estimates.
3) Consumption module. Receiving inputs from the regional scan module, this module calculates the hydrogen consumption potential in each region, according the relevant end-use applications.
4) Ecosystem assessment module. The outputs of the production, consumption, and delivery modules provide input to the ecosystem assessment module, which is configured to assess and characterize a wide range of outputs. Outputs currently include overall capital and operating expenses, timing of capital expenditures, extent and timing of job creation and resulting GHG emissions reductions.

5) Delivery module. This module generates information necessary to determine intra-provincial shipping costs, as well as import requirements or export opportunities, which vary according to the scenario under consideration. Inputs to the delivery module are received from the production and consumption modules, and its outputs feed into the ecosystem assessment module.

The H2GrO-TEA model is visualized as a flowchart in Figure 1 below.

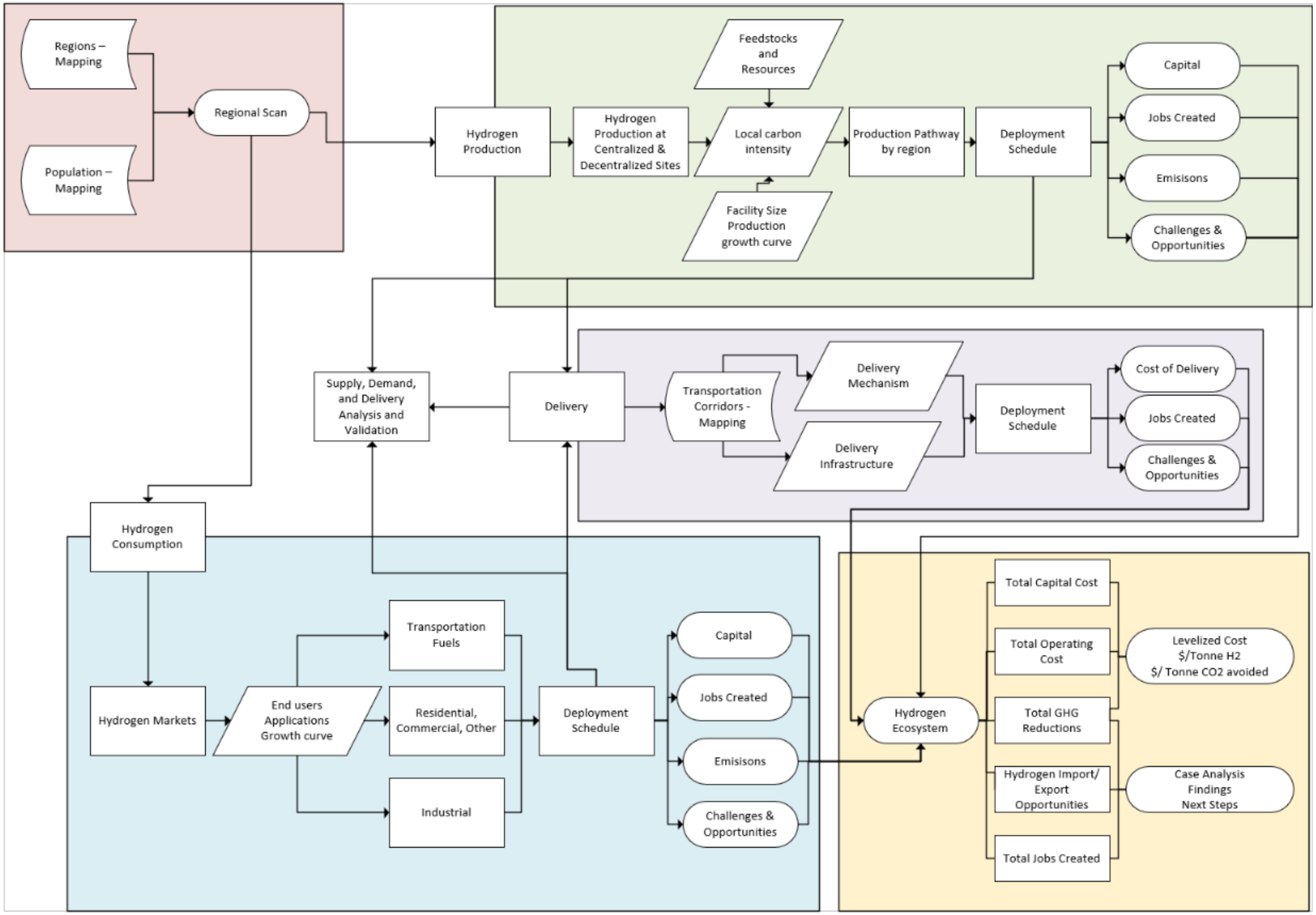


Figure 1: Visual Methodology of the H2GrO-TEA Model

An initial reference case was needed to provide the starting data around which to build the H2GrO-TEA model, and to verify the proper flow of information between the modules. This reference case also facilitated calibration of the model to known information. An important source of reference data was a companion report by H2GO Canada, *Scoping the Commercial Potential for Carbon Capture, Utilization and Storage and Hydrogen Storage in Ontario to 2035*, which provided the geographic locations of potential hydrogen market hubs; that is, where production and use of low-carbon hydrogen occurs in close proximity among numerous participants, forming localized commercial relationships of mutual reliance and benefit. Hubs are expected to be the anchoring nodes of optimal value creation, interconnecting to form a broader web of hydrogen trade across the province and between other jurisdictions. The companion report also provided estimates on where hydrogen production was likely to become established and the transport corridors that could be used to move low-carbon hydrogen to market.

The reference case scenario should not be construed as the study team's prediction of a future system in Ontario. It goes without saying that predicting the future is not possible. Guesses may come true on a roll of the dice, but the purpose of TEA models is to assess the implications of a scenario, which simply represents one possible future. The benefit of scenario play is to simulate the effects of the system under different conditions. Sensitivities and patterns of behaviour can be gleaned, and these can be very valuable in informing strategic planning.

The key inputs and outputs of each module of the H2GrO-TEA model are summarized in Table A.

Table A: Key Inputs & Outputs of the Ontario Hydrogen Supply & Demand Model

Module	**Key Inputs**	**Key Outputs**
Regional Scan	• Population by market hub • Energy consumption by market hub • Potential hydrogen distribution infrastructure • Local carbon intensity of pathway • Policies and programs • Potential for hydrogen production • Potential for hydrogen consumption • Local cost of hydrogen by pathway • Access to low-carbon feedstock	• Scores by production pathway • Scores by end-use • Opportunities associated with each pathway • Opportunities associated with each end-use
Hydrogen Production	• Feedstock availability • Feedstock pricing • Production facility sizes (e.g., 1/20/100 MW) • Potential production facility growth rate and curve shape • Equipment availability	• Production facility development schedule • Production facility capital • Maintenance and operating costs • Feedstock import requirements • Jobs created • Hydrogen production volume

Module	Key Inputs	Key Outputs
	• Equipment pricing • Scores by pathway and region	• GHG emissions
Hydrogen Consumption	• End use applications • Population • Industrial activity • Technology readiness level • Growth rate and curve shape of consumption • Equipment pricing • Regional end-use scores	• End-use equipment capital • End-use equipment deployment schedule • Jobs created • GHG emissions • Hydrogen consumption requirements
Delivery	• Production potential across the region • Production growth rate and curve shape • Consumption end-uses across the region • Consumption growth rate and curve shape • Distances between production and end-use hubs • Delivery cost elements	• Hydrogen surplus/shortfall • Applicable delivery mechanisms • Delivery infrastructure deployment schedule • Delivery infrastructure capital • Delivery cost by mechanism • Jobs created
Hydrogen Ecosystem	• Hydrogen production • Hydrogen consumption • Hydrogen surplus/shortfall • Delivery costs • Jobs created • GHG emissions	• Levelized cost of hydrogen per kg • Levelized cost of CO_2 per tonne avoided • Import/export opportunities • Jobs created

In the sections that follow, this report will describe each of the base modules of the H2GrO-TEA model in further detail, including how assumptions were made, sources for input data and any notable numerical methods that were used. For each section, the major outputs of the associated module will also be visualized in charts, along with points of discussion that the study team think are relevant and helpful for the reader to understand.

Through this process of explanation, the study team aims to encourage interest in the H2GrO-TEA Model and promote its use. The more widely the model is worked, the more feedback its developers can receive, which will drive continuous improvement. The better the model becomes at generating outputs of interest to stakeholders, the more value it will have as a tool to support hydrogen system planning. The outcome is a virtuous cycle of assessment that results in more efficient deployment of capital and resources to accelerate the building of Ontario's low-carbon hydrogen future, one project at a time.

3.0 REGIONAL SCAN

No matter how you look at it, Ontario is a big province. By population and economy, it’s Canada’s largest subnational jurisdiction; by land area, it’s third largest behind Nunavut and Quebec. Within this large area, Ontario is regionally diverse. The economy, industrial activities, climate, and community lifestyles in the southern areas of the province differ markedly from its north. To model the prospective development of hydrogen markets throughout Ontario, it is therefore helpful to break down the province into smaller geographic regions, each having its own distinctive characteristics. This is similar to how statistical information is currently gathered and reported by, for example, the Ontario Ministry of Labour, Immigration, Training and Skills Development [5]. This approach allows the model to simulate the development of hydrogen markets in a consistent manner for regions that differ widely in population density and the nature of the anchoring industry sectors. Without this segmentation, the comparatively high populations, and concentrations of economic activity in southern areas would distort the analysis and de-emphasize the importance and opportunities for hydrogen production and use in less populated regions.

Figure 2: Hydrogen Opportunities
Source: Walters [6]

The regional scan module involves some qualitative judgement by the study team in setting the region boundaries, such that the regions encompass population and economic characteristics that can sustain low-carbon hydrogen market activities. These are sometimes referred to as administrative regions by the study team. Using population data and energy end-use information for Ontario, both of which are published and available, regional demand profiles for energy were developed based on per-capita consumption rates. This provides an indicator of the opportunity for adoption of low-carbon hydrogen, especially in heating and transportation applications. The study team chose to divide the area of Ontario in six administration regions, the boundaries of which are mapped as shown in Figure 3 below.

Figure 3: Administrative Regional Boundaries
Source: Adapted from Government of Ontario [5]

With the region defined, an assessment for each was conducted for its distinct hydrogen supply and demand potentials. These were determined by considering population (which is an indicator of residential, commercial and transportation end-uses), the presence of major industrial facilities, energy source and commodity availability (having potential for input to low-carbon hydrogen production), presence of distribution infrastructure that can be purposed for hydrogen and access to low-carbon electricity supply. The highlights of the characterizations are summarized as follows.

West region (1)

Low-carbon hydrogen production opportunities in this region largely map to the significant industrial, manufacturing and agricultural sector activities and facilities present. These sectors also influence the assignment of hydrogen consumption potentials. Agriculture and industrial wastes and by-products also elevate the relevant feedstock supplies for hydrogen production in this region. The many urban centers in this region and its proximity to the U.S. border imply a broad array of hydrogen end-use applications.

Central regions (2 & 3)

The central regions (i.e., west and east) are assigned the greatest potential for hydrogen consumption based on highest population densities, which support significant market adoption potentials for transportation, residential and commercial hydrogen end-use applications. There is also significant demand opportunity in the regions' manufacturing base, which can also yield waste and by-product materials that can serve as feedstock for low-carbon hydrogen production. The east and west central regions are similar in most ways, but combined they represent half the population of the entire province. Separating the regions into east and west keeps the population of each at a more reasonable scale, which otherwise would skew the representation of results and possibly diminish the apparent opportunities in less populated regions.

> **Central West region (2) –** This region is part of the Greater Toronto and Hamilton Area, one of the most populated areas in Ontario.

> **Central East region (3) –** This region includes the city of Toronto, the most populated city in the province and in Canada.

East region (4)

Several urban centers populate this region, which informs the assignment of many low-carbon hydrogen consumption opportunities. Its heavy agricultural activity most influences the assignment of hydrogen production opportunity. In this way, it is similar to the West region but with less industrial base.

North region (5)

A dispersed population in this region limits the range of hydrogen consumption opportunities and elevates distribution costs. Mining and forestry operations are the most promising opportunities for hydrogen production and consumption, and around these sites hydrogen markets can develop to some extent. A comparatively small but important feature of this region is the development of small-scale, highly localized production and use of low-carbon hydrogen.

Far North region (6)

This is the largest geographic administrative region defined in this report for Ontario. It is characterized by few population centres, which are quite dispersed. The hydrogen production opportunity is similar to the North region, but the markets face different challenges due to the lack of energy infrastructure in this area.

As described in the sections on hydrogen delivery and ecosystem effects, the jurisdictional scan establishes a basis for *distances* between prospective points of the hydrogen production and markets where it is consumed. This allows for the tracking of simulated imports and exports of some quantity hydrogen *between* the defined regions in Ontario, and the calculated delivery costs associated with this transport. The intent is for the model to reflect a more realistic picture of hydrogen being traded as a commodity throughout Ontario, as opposed to a more simplistic scenario of hydrogen being used only in the immediate vicinity of where it is produced.

4.0 HYDROGEN PRODUCTION

Hydrogen is the most abundant element in the universe and here on earth. It is all around us everywhere, but it is locked up in molecular bonds with other elements in common substances, such as in water, hydrocarbons and carbohydrates. This presents a problem, because for hydrogen to be useful as a carbon-free fuel or chemical feedstock, it needs to be separated from its host substance to yield pure hydrogen (i.e., H_2, in its molecular state). It takes energy – either electricity, heat or a combination thereof – applied to a hydrogen-rich substance, such as water (H_2O) or natural gas (CH_4), to produce pure hydrogen.

Fortunately, in Ontario there is a rich and diverse supply of energy and material feedstocks with which to produce hydrogen. Consider the Sankey Diagram, below, representing the flows of energy resources and commodities through the province. At the left of the diagram, the volumes of energy resources imported to Ontario or harvested within are visually represented. These are converted into useful energy commodities and services for different sector applications (e.g., transport, buildings and industrial end uses) which are summed at the right of the diagram as shares of energy put to good use versus energy losses in the system, mostly in the form of unutilized waste heat.

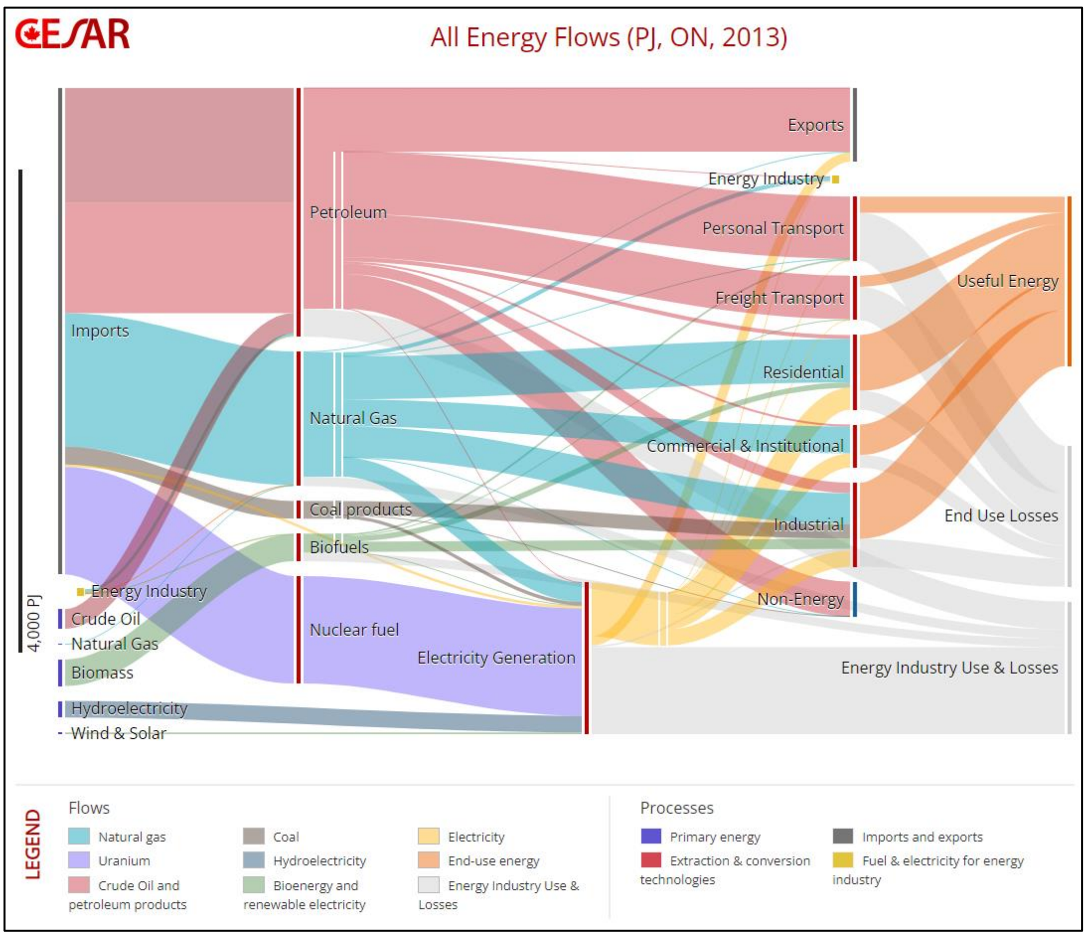


Figure 4: Energy Resource and Commodity Flows in Ontario
Source: Canadian Energy Systems Analysis Research (CESAR) [7]

Currently, natural gas is the most common feedstock for hydrogen production worldwide, but the process releases carbon dioxide to the atmosphere (unless captured and stored, or used in a manner that either permanently sequesters the carbon, or displaces consumption of additional fossil fuels.). Using electricity to split water into hydrogen and oxygen is also an established production method. As evident in the diagram, Ontario has ample flows of natural gas and electricity generated from nuclear, renewable and natural gas-fired power sources. Indeed, the electricity supply mix in Ontario is more diverse than most provinces, and among the lowest in carbon-intensity (i.e., GHGs emitted per unit of electrical energy supplied). The Independent Electricity System Operator reports annually on the sources energizing the provincial grid system (2021 mix shown).

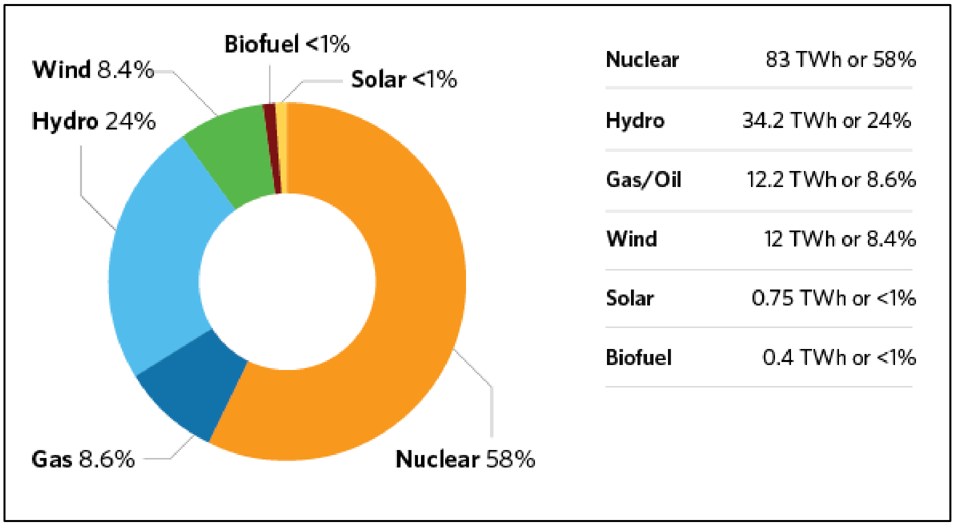


Figure 5: Ontario Electricity Supply Mix
Source: Independent Electricity System Operator (IESO) [34]

Thus, Ontario can exploit numerous hydrogen production pathways to meet its market demand, tapping into several different feedstocks and energy supplies. The Hydrogen Production Module in the H2GrO-TEA Model provides for various pathways to be defined and characterized, such that hydrogen supply mixes in the province can be represented and simulated. This section of the report describes the pathways currently established in the model by the study team, discusses how regional hydrogen production potentials are evaluated and provides commentary on the site criteria considered. More pathways can be added in the future to simulate the effect of new production innovations. For now, the most likely pathways to be built by 2050, based on the availability of production feedstocks and technologies, are included.

Note that there are also potential volumes of by-product hydrogen that could be captured in Ontario and put to valuable use. For example, chlor-alkali plants, which produce chlorine, also emit hydrogen as a waste. Hydrogen is non-toxic and rises quickly to disperse in the atmosphere, so safely venting it as a gas is common practice. However, emerging research indicates that while hydrogen is not itself a GHG, it can interact with other compounds in the upper atmosphere to produce a greenhouse effect. This phenomenon is being studied and its effect quantified. For now, it stands as one more reason not to waste hydrogen, but to capture hydrogen and use it to displace carbon-intensive fuels instead.

4.1 Hydrogen Production Module – Logic and Design

The Hydrogen Production module of the H2GrO-TEA Model calculates the potential annual hydrogen production for each pathway represented (described in the preceding subsection). Drawing on information sources available to the study team and a measure of informed judgement, a reference dataset was established. Referred to as the Base Case (and sometimes as Base Case 1) in the model, this data has two functions. First, it establishes the mathematical relationships between stages in the hydrogen value chain. For example, the amount of hydrogen produced is a function of a particular technology applied to the conversion of a certain feedstock, and this is given by a unique relation in the model (i.e., a formula or equation). Second, the Base Case dataset is required to perform an initial calibration of the model, which ensures that the relations are correct and are yielding sensible results. Put simply, an initial dataset is needed to generate initial outputs, which are then used to finetune the inputs further, correct any errors in the relations between the modules, as well as any operations within the modules.

Low-carbon hydrogen will be a part of low-carbon energy system in Ontario, and the H2GrO-TEA Model makes projections to 2050. So, a reference case for the broader energy system in Ontario in 2050 is needed. Fortunately, Canada's Energy Future, published by the Canada Energy Regulator, provides forecasts of energy production and use in Canada, sector by sector and regionally. The online interactive tool (see web-capture image below) was used by the study team to develop estimates of the share of energy feedstocks and end-use energy demands (e.g., residential, commercial, industrial, transport) that could be represented by low-carbon hydrogen, within a spectrum of other decarbonization solutions.

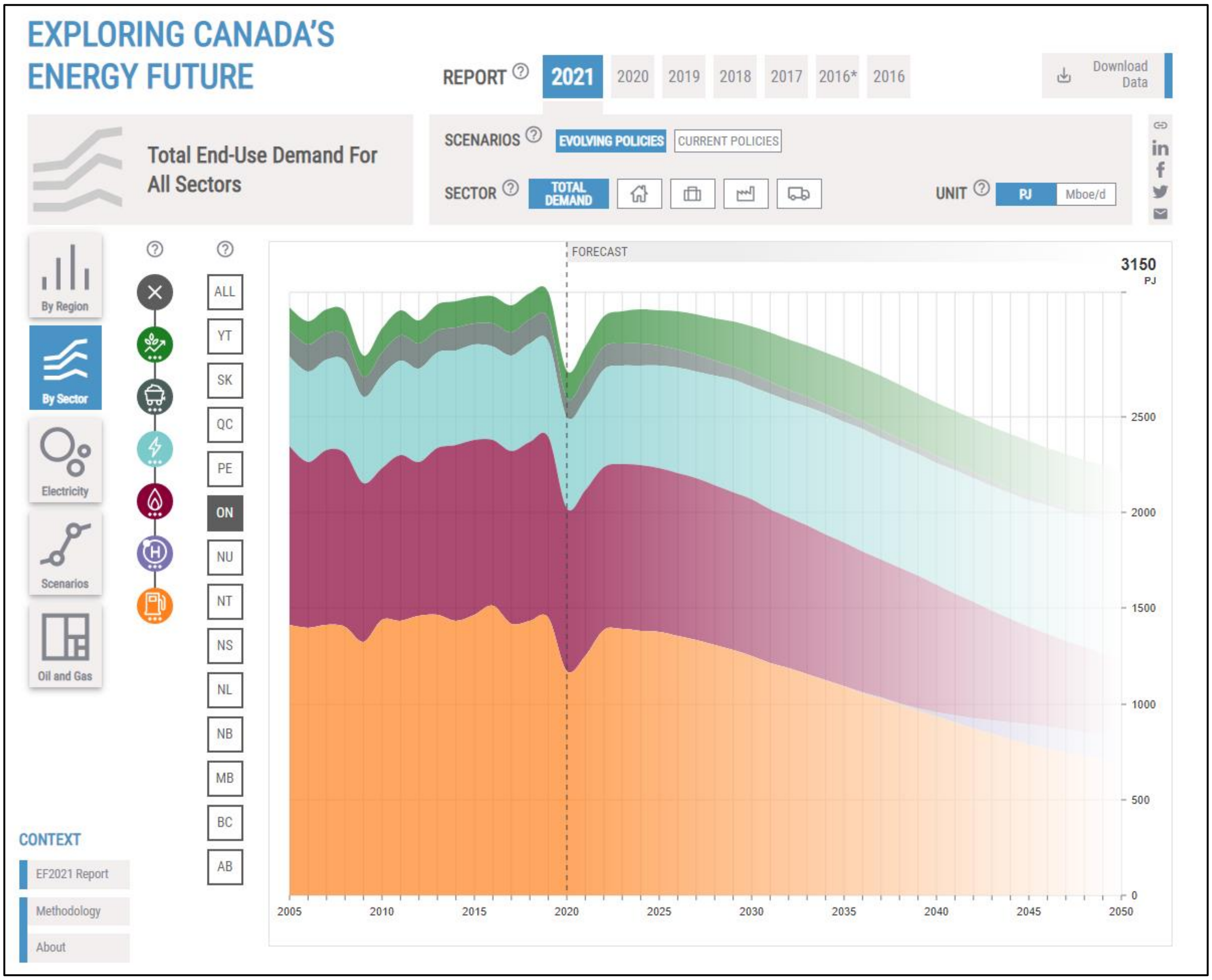


Figure 6: Canada's Energy Future – Supply and Demand Projections to 2050
Source: Canada Energy Regulator [8]

Recognizing the competing demands for energy in Ontario, especially for electricity, is important for the model to generate appropriately conservative estimates of hydrogen production. Electrification is central to the decarbonization plans of many energy end-uses, such as the transition from gasoline to plug-in power for electric vehicles. The study team endeavoured to reflect these constraints when assessing the availability of energy feedstocks in the production module. For example, the Base Case assumes that any hydrogen production pathways requiring grid-supplied power would make use of no more than 50 per cent of the unutilized generation capacity (i.e., the difference between the grid supply potential and actual electricity consumption) by 2050.

To formulate hydrogen production within the production module, the study team used a series of logical steps, as follows.

1) A means of hydrogen production, based on a specific feedstock and using a particular extraction technology, is given a designation.
2) The amount of hydrogen produced annually under the designation is determined by a conversion factor applied to the feedstock (this is a function of the technology used).
3) Feedstock availability is assessed based on the total potential supply from which is deducted the share dedicated to purposes other than hydrogen production, where relevant. The possible locations of hydrogen production are also a feedstock-dependent characteristic – siting is a factor that applies to cost calculations in other modules.
   - If there is a credible reference on which to base feedstock availability estimates, then these are noted in the model. Otherwise, a best guess is used and declared in the model. These can be refined as new data become available.
   - For the purpose of scenario play, feedstock availability values can be chosen to test the effect of hypothetical volumes (e.g., what if a certain amount of nuclear reactor capacity were purpose-built for hydrogen production?)
4) A growth function is applied to the feedstock availability. Usually, data on feedstock volumes are only available for a recent year, or as a short-term forecast. Projections to 2050 are therefore applied generated by applying an independent growth function to the initial data. Growth functions are chosen to reflect estimated constraints on feedstock supplies. In some cases, these constraints are infrastructural, such as pipeline or transmission capacities. Thus, the hydrogen production volumes calculated in the module are rooted in feedstock analysis.
   - The growth functions are defined by the factors: starting year volume, volume in 2050 (end year), growth rate curves shaped to represent either slow, medium or fast rates of market adoption.

The following subsections examine these steps in more detail.

4.2 Hydrogen Production Options (Pathways) Designated in the Module

The Hydrogen Production Module of the H2GrO-TEA Model was built upon an initial set of feedstock-conversion options, each with its own set of characteristics, such as the carbon-intensity of the production process, and constraints, such as feedstock availability. These initial production pathways represent the means that are commonly used in industry today or are considered to be nearing market-readiness. The H2GrO-TEA Model is future-prepped to accommodate additional production designations for Ontario, as needed. Existing pathways can also be revised to reflect improvements in process attributes, such as conversion efficiency. The current designations in the module are described below, in terms of feedstocks and technologies used to produce low-carbon hydrogen.

4.2.1 Electrolysis Designations

Electrolysis is a process by which water molecules are separated into molecules of hydrogen and oxygen, by the application of voltage. Water and electricity are thus the principal feedstocks and the electrochemical reactions are visually generalized in Figure 7 below.

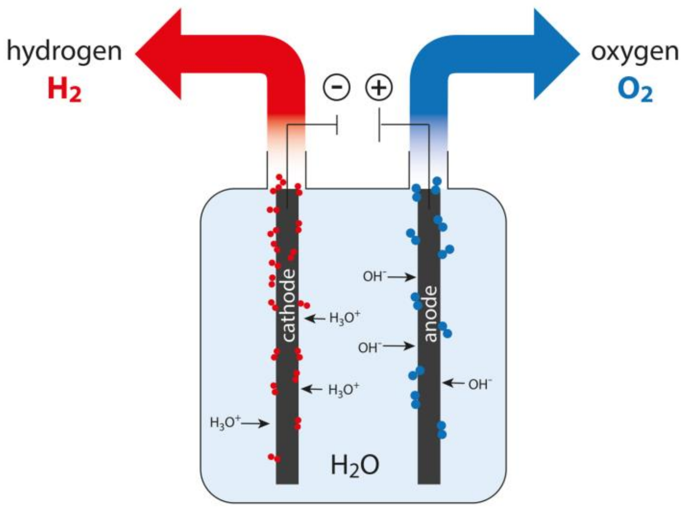


Figure 7: Electrolysis of Water – Basic Electrochemical Reactions
Source: Pratt [9]

There are three distinct types of electrolysis technology that are commercially mature, scalable and deployable: Polymer Electrolyte Membrane (PEM), Alkaline and Solid Oxide. These are mainly distinguished by the electrolyte substance that facilitates ion exchange between a cathode and an anode. PEM systems use a polymer electrolyte that is consumed during use and must be periodically replaced. PEM electrolysis plants need only potable water and electricity to operate. Alkaline systems rely on a caustic solution as the electrolyte that must be replenished periodically. They are simple, durable and have been used for many decades worldwide. Solid oxide systems are the least commonly used. These employ a ceramic electrolyte and must be heated to several hundred degrees to operate, making them ideal where waste heat is available to supplement the electrical energy input. None of these electrolysis systems is inherently superior to the others, and selection depends on the situation.

The carbon-intensity of the hydrogen produced is mostly determined by that of the input electricity and is not substantially dependent on the type of electrolysis process. In the model, electrolysis pathways are designated according to the supply of electrical energy, including:

- the provincial grid (i.e., transmission system),
- directly from solar- or wind-farms (i.e., not through the provincial grid), and
- biomass-fired power plants (i.e., forest biomass).

4.2.2 Steam Methane Reformation Designations

The vast majority of hydrogen used in industrial applications today is extracted from methane molecules, which are the dominant component of natural gas. The principle of steam methane reforming (SMR) is applied in the conversion systems built for this means of hydrogen production, which are generally fall into one of two categories of technology: steam methane reformers and autothermal reformers. The choice of technology used is a matter of the specific application, but for the purpose of the H2GrO-TEA Model, the conversion factor is based on data from steam methane reformer plants. Autothermal reformers can have higher conversions efficiencies, but this marginal gain is ignored by the study team as bias toward conservative estimation (reliable cost information is also slim and, where available, indicates comparable levelized cost of hydrogen production [10]). The main feedstocks in this pathway are natural gas and water. The main products of SMR are hydrogen and carbon dioxide. As with electrolysis, SMR systems are scalable and readily deployable.

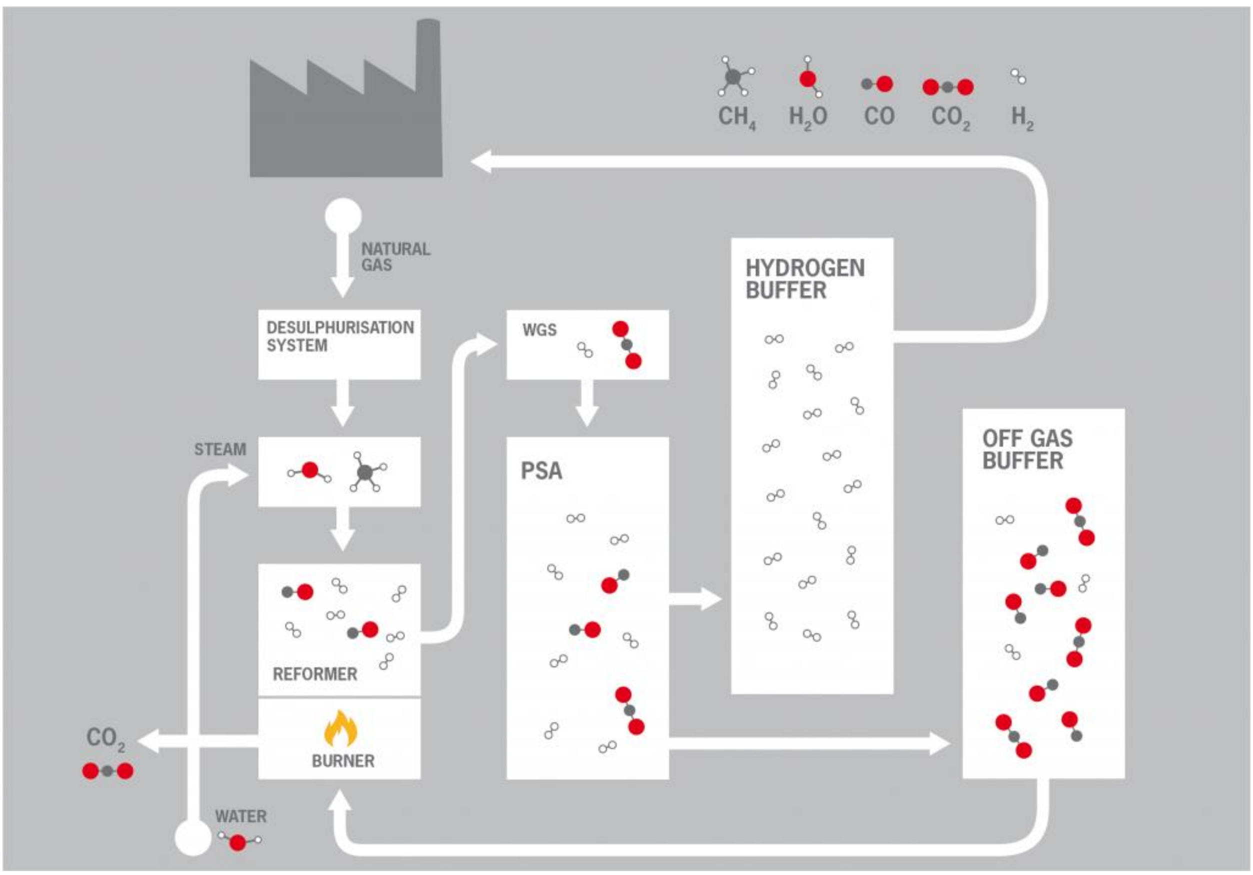


Figure 8: Steam Methane Reforming (SMR) Process
Source: HyGear [11]

The carbon-intensity of hydrogen produced via SMR in the model is mainly dependent on the GHGs emitted through the process (mostly CO_2 and methane, CH_4), as well as the GHGs emitted in the production, refining and delivery of the natural gas feedstock. Note that the carbon-intensity of hydrogen produced via SMR can be substantially reduced if coupled with a carbon capture, use and storage (CCUS) solution that would permanently prevent subsequent release of CO_2 to the atmosphere. Accordingly, the module designations include SMR and

SMR+CC (carbon capture), with higher and lower carbon-intensities, respectively. The Base Case assumes a 90 per cent carbon capture rate from flue gas; but this results in a carbon-intensity reduction of only about two-thirds compared to SMR without CC, accounting for the increase in energy needed to power the entire process.

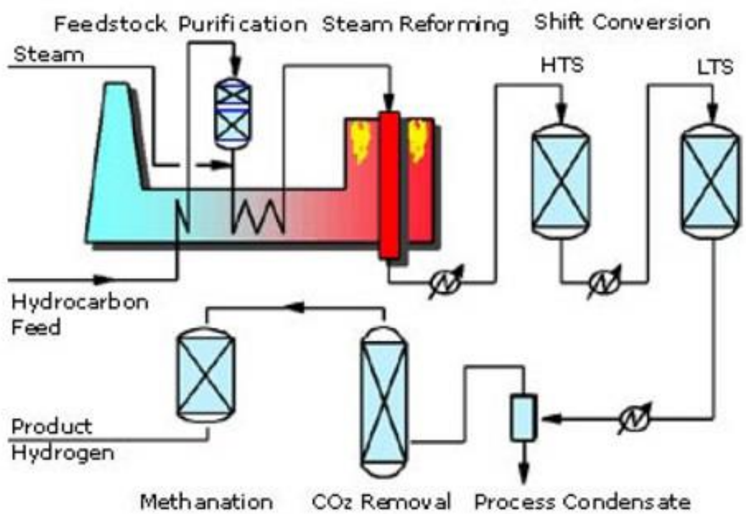


Figure 9: SMR with Integrated Carbon Capture
Source: Making-Hydrogen.com [12]

4.2.3 Pyrolysis of Forest Biomass and Agriculture Biomass Designations

The application of pyrolysis is a commercially emerging approach to hydrogen production. Pyrolysis involves a thermochemical conversion of carbohydrate feedstocks under anerobic conditions (i.e., the absence of oxygen) that produces hydrogen, hydrocarbon gases, char and bio-oils. The feedstock is usually the source of heat energy and hydrogen; thus, the carbon-intensity of a pyrolysis process is dependent on that of the feedstocks used. The lifecycle emissions are generally lower than the process of burning biomass to generate electricity for electrolysis. Currently, most pyrolysis applications in Ontario are mobile, small scale, and specific to a given feedstock.

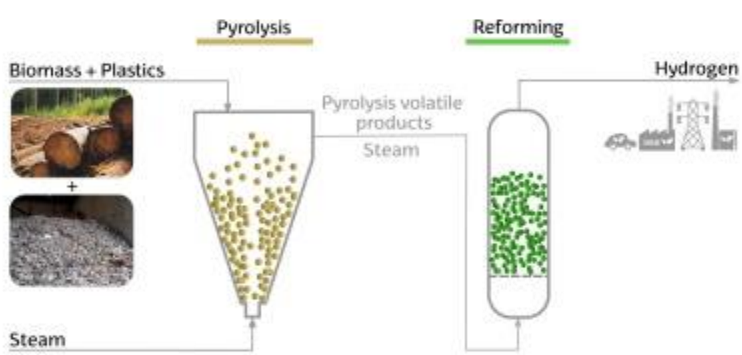


Figure 10: Pyrolysis Process
Source: Arregi *et al* [13]

While biomass pyrolysis has been designated in the model, it does not contribute significantly to production volumes calculated in the Base Case. There are two reasons for this; firstly, there is a lack of clear information regarding potential for forest and agriculture biomass to be dedicated to hydrogen production and, secondly, the value of biomass as a feedstock for renewable liquid fuels is expected to exceed its value as a hydrogen feedstock. More likely, low-carbon hydrogen would be consumed in the production renewable liquid fuels. Hydrogen from biomass pyrolysis processes will usually require significant purification, which can add cost. Regardless of the Base Case, the H2GrO-TEA Model is ready to simulate scenarios in which biomass is mobilized more intensively to meet demand for low-carbon hydrogen.

Note that pyrolysis can also be applied to non-biogenic feedstocks, such as waste tires or plastics, which are rich in carbon and hydrogen.

4.2.4 Gasification of Forest Biomass and Agriculture Biomass Designations

Gasification of biomass for hydrogen production is a mature technology. As with pyrolysis, gasification involves a thermochemical conversion of carbon-based feedstocks. However, the gasification process occurs under reactive aerobic conditions (i.e., oxygenated), which yields hydrogen along with tar and other hydrocarbon gases. The carbon-intensity of the gasification process is similar to that of pyrolysis because they generally use the same biomass feedstocks. The same feedstock limitations with pyrolysis apply to gasification; so, while this production pathway is designated in the model, it does not contribute significantly to production volumes calculated in the Base Case.

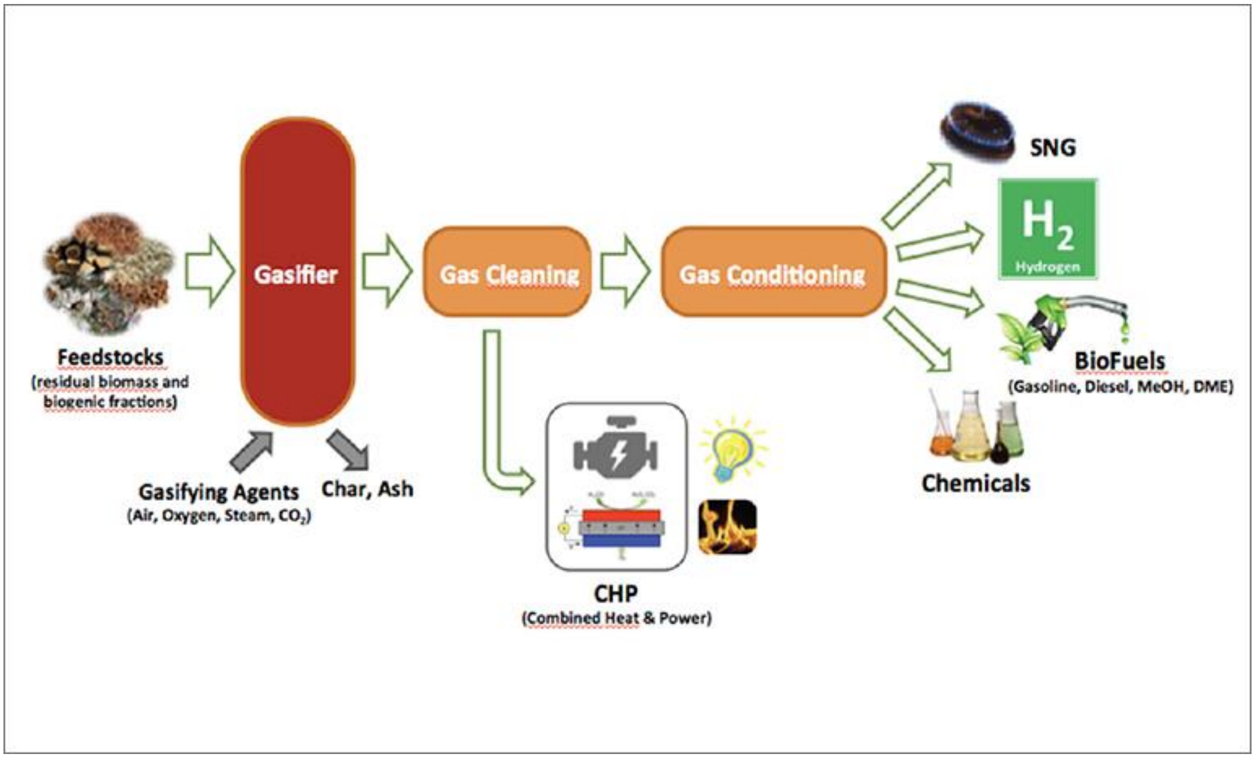


Figure 11: Biomass Gasification Process
Source: Barisano [14]

4.2.5 Commercially Emerging Hydrogen Production Processes

The following technologies are not included in the Base Case as there is insufficient information available for a process or economic analysis. However, these technologies may well become commercially viable prior to 2050. Short descriptions are included here, as scenarios to simulate their emergence into the market can be modeled.

4.2.5.1 Biomass Digestion

In digestion (or fermentation) systems, microorganisms are used to break down organic matter to produce hydrogen. This typically involves multiple intermediate reactions and research is being done to increase the yield and rate of hydrogen production. Microbial electrolysis cells are one example whereby organisms are used to produce an electric current, which can increase the rate at which hydrogen is extracted from the biomass. The carbon-intensity for hydrogen produced by digestion systems will depend on the input feedstocks used.

4.2.5.2 Water Splitting Without Electrolysis (Artificial Photosynthesis)

Technology is under development that mimics natural photosynthesis, in which plants use sunlight (i.e., energy from solar radiation) to split water into oxygen and hydrogen. Plants need the free hydrogen to build carbohydrates that support their growth and lifecycle. Engineered water splitting is considered a photolytic process because it uses light energy in an analogous manner. The majority of the energy needed to produce hydrogen comes from sunlight, although a small amount of externally-supplied activation energy may be needed to sustain the process.

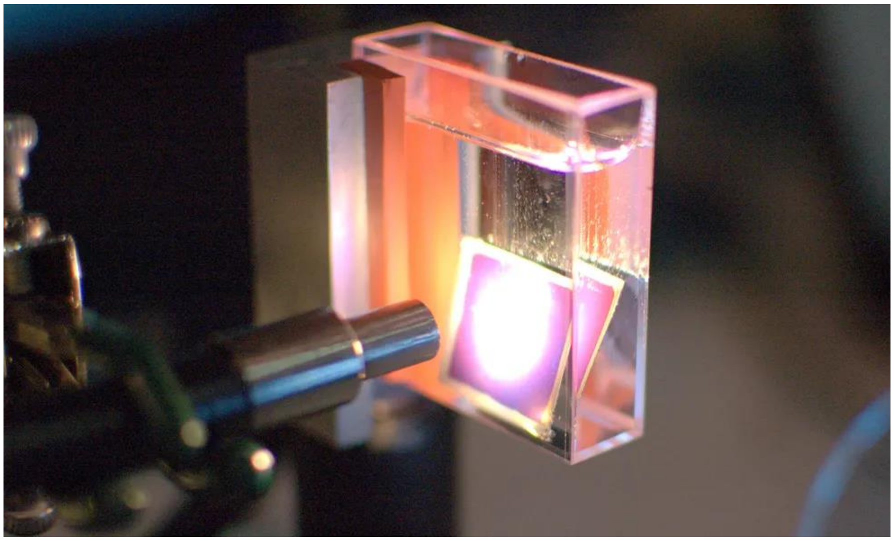


Figure 12: Artificial Leaf producing hydrogen from sunlight conducted by fibreoptic
Source: LaMonica [15]

The potential to harness the energy of sunlight to directly produce hydrogen from water is compelling. Not only would it represent a very low carbon-intensive source of hydrogen at potentially very low cost, it could also enable highly distributed, small-scale production. Water splitting is not designated in the H2GrO-TEA Model, but it should be included in future versions of the production module when data for commercial simulations becomes available.

4.2.5.3 Molten Alloy

Molten alloy production methods decompose methane into hydrogen and solid carbon. Development of this technology is currently underway with support from the Canadian Gas Association’s Natural Gas Innovation Fund. As this technology is in the prototype development stage it still has a low commercial readiness level.

4.2.5.4 Microwave Catalytic Reformation

This technology is also in the protype development phase. It is being developed by Alberta based Nu:ionic Technologies with support from the NGIF. The carbon-intensity of this process and time to market are unknown to the study team.

4.2.5.5 Microwave Pyrolysis

Pyrolysis of natural gas is a commercially emerging process in which the methane molecule is separated into hydrogen and solid carbon. Unlike steam methane reforming, in which the carbon is released as carbon dioxide, methane pyrolysis yields pure carbon in a granular, solid form. Microwaves heat the natural gas into a form of plasma, supplying the energy to break the methane molecules. The carbon-intensity of this hydrogen production process can be very low, as the carbon is retained in solid form, and the electrical energy to power the microwave emitter can be drawn from low-carbon sources.

Aurora Hydrogen (with offices in Ontario) has received government funding to help commercialize their version of microwave pyrolysis, expected to be market-ready by 2025 [16].

The pure carbon produced, some grades of which may qualify as carbon black, may have increasing market value in the future as novel, carbon-based materials are developed. Even today, the solid carbon output of microwave pyrolysis of methane may have value among current market applications, such as pigment for rubber products. However, modeling this opportunity and its prospective impacts is beyond the scope of this study and requires further research of carbon black supply chains.

4.2.5.6 Thermochemical Water Splitting with a Copper-Chlorine Cycle

In this method of producing hydrogen, the energy to split water relies more on heat than electricity. Heated water cycled through a series of reactions involving copper and chlorine, the effect of which is to significantly reduce the electricity input compared to conventional electrolysis. An advantage of this process is that waste heat can be used, which can yield a hydrogen that is very low in cost and carbon-intensity. It can thus play an important role in high-efficiency, integrated energy systems. Several companies are working to commercialize the development of this process, some of which are Ontario-based.

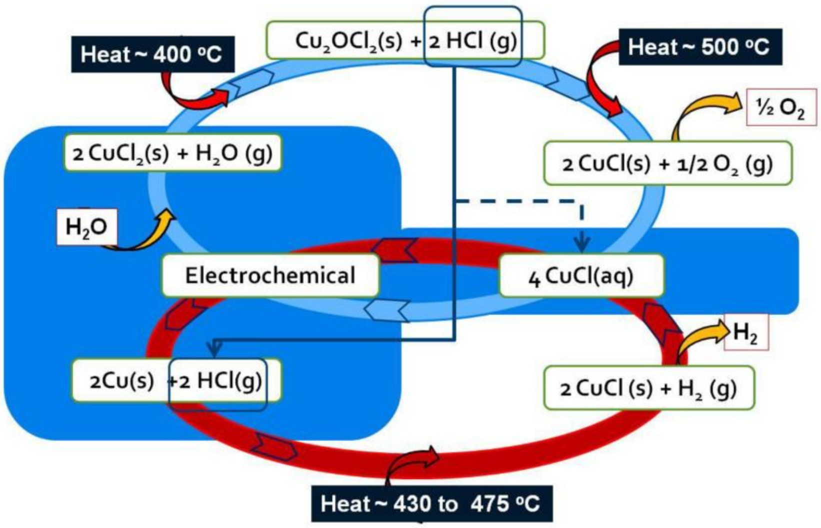


Figure 13: Copper-Chlorine cycle for hydrogen production, University of Ontario Institute of Technology
Source: Trevani [17]

4.3 Hydrogen Feedstock Availability and Production Siting in the Module

In the H2GrO-TEA Model Hydrogen Production module, feedstock availability is a way to add practical constraints to the amount of hydrogen generated under each of the pathway designations. Feedstocks are both material (i.e., the substance, such as water or methane, from which the hydrogen will be extracted) and energy (i.e., the input energy needed to separate and capture the hydrogen for use, such electricity or heat). Availability of feedstocks are often limited according to geography. The model represents hydrogen production as occurring at defined locations, as opposed to non-specified, generalized production occurring in a distributed manner across regions. The study team numerically represented these sites in the production module based on a geospatial analysis – that is, a mapping study – conducted for development of the H2GrO-TEA Model, as well as for a companion study by H2GO Canada, *Scoping the Commercial Potential for Carbon Capture, Utilization and Storage and Hydrogen Storage in Ontario to 2035*. Sites were selected where sufficient volumes of material and energy feedstocks were known to exist and that were proximate to significant consumers of hydrogen, which can be populated areas where many end-use applications aggregate to significant demand, or large industrial facilities with large off-take potential.

With potential locations filtered for the proximity criteria, access to feedstock is then considered. The criteria chosen by the study team are:

- Where electricity supplied from the provincial grid is a key energy feedstock, the electrolysis facility must be within 50 km of a transmission corridor.
- Where electrolysis uses power direct from renewable sources, sites are coincident.
- Where natural gas is the feedstock, steam methane reforming (SMR) facilities must be with 10 km of an existing natural gas pipeline. Sites that can be serviced for the transport and storage (or use) of captured carbon are favoured.

This approach yielded 28 unique sites for hydrogen production in Ontario, tabulated as follows.

Table B: Hydrogen Production Sites by Pathway Designation

Electrolysis solar power A	Electrolysis wind power B	Electrolysis grid-supplied power (mixed source), C	Electrolysis forest biomass power, D	Steam-methane reformation E
AA	BA	CA	DA	EA
AB	BB	CB		EB
AC	BC	CC		EC
AD	BD	CD		ED
		CE		EE
		CF		EF
		CG		EG
		CH		EH
		CI		EI
				EJ

The first letter of the label designates the primary feedstock and the second letter is just an index uniquely assigned to each site. These hydrogen production sites are shown on the map below (Figure 14). By region, the sites can be tabulated as follows.

Table C: Regional Hydrogen Production Sites

Region	Map label	Production designation	Site count
Far North	CA	grid power	1
North	CB	grid power	2
	CC	grid power	3
	CG	grid power	4
	AD	solar power direct	5
	BD	wind power direct	6
	EA	SMR+CC	7
	EB	SMR+CC	8
	DA	forest biomass power direct	9
West	CF	grid power	10
	AA	solar power direct	11
	AB	solar power direct	12
	BA	wind power direct	13
	BB	wind power direct	14
	BC	wind power direct	15
	EF	SMR+CC	16
	EG	SMR+CC	17
	EH	SMR+CC	18
	EI	SMR+CC	19
	EJ	SMR+CC	20
Central West	CE	grid power	21
	EE	SMR+CC	22
Central East	CH	grid power	23
	CI	grid power	24
East	CD	grid power	25
	AC	solar power direct	26
	EC	SMR+CC	27
	ED	SMR+CC	28

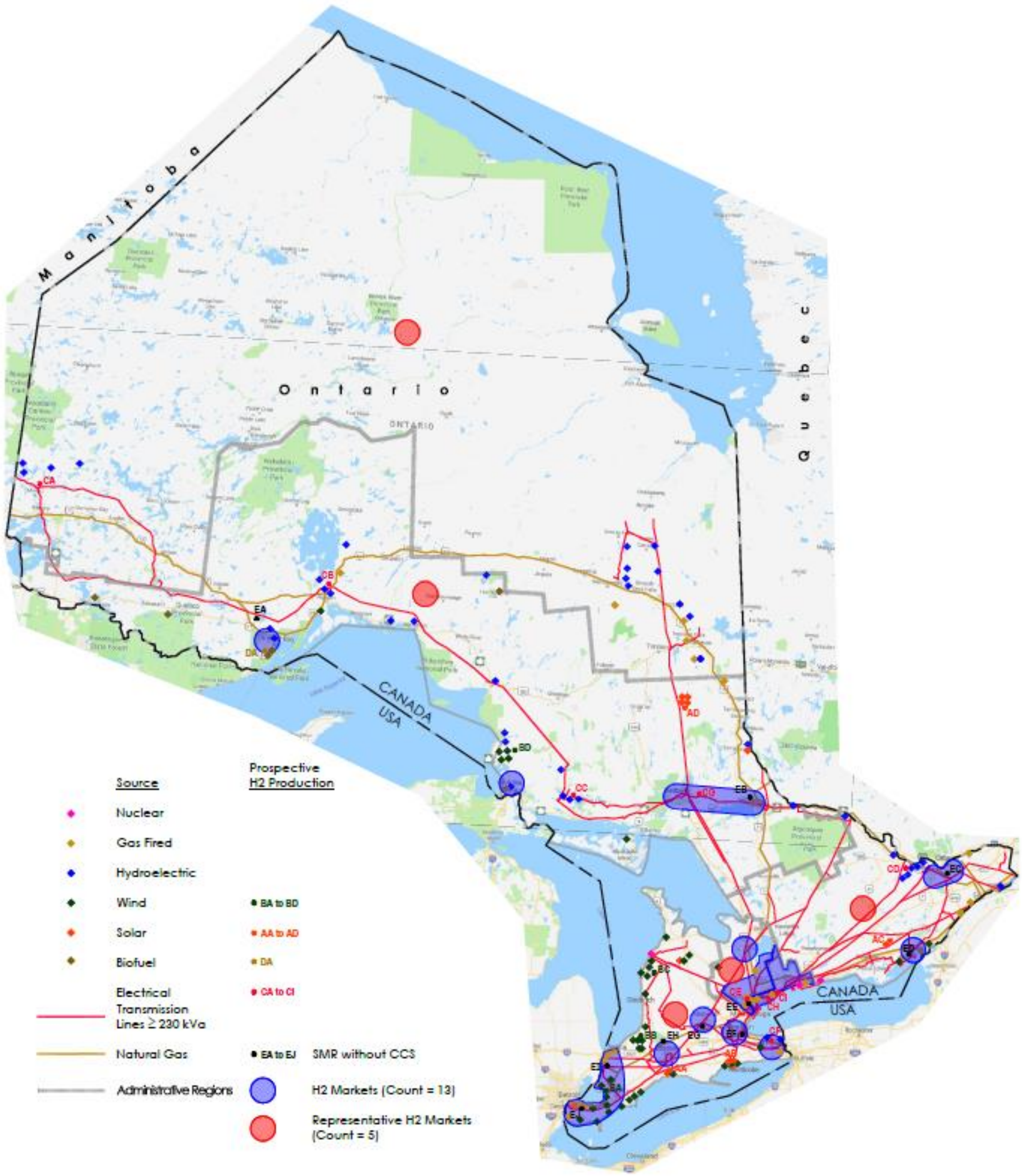


Figure 14: Potential H_2 Production Sites
Source: Adapted from Government of Ontario [5], IESO [18], Canada Energy Regulator [19], OEB [20]

In reality, hydrogen production could occur in a distributed manner throughout the province using smaller-scale facilities. However, choosing to simulate hydrogen production based on a small number of sites (i.e., 28 in the Base Case) allows for a more precise estimation of costs for facilities and for delivery of the hydrogen to identified markets. Furthermore, capital costs are likely to drive investments in larger-scale production, at least in the 2050 timeframe. From an operating expense perspective, it is usually more efficient to make the hydrogen as close as possible to where it will be used, since building new hydrogen delivery infrastructure will cost more than relying on the electricity and natural gas systems that already exist. Notwithstanding this choice of the study team, the H2GrO-TEA Model Hydrogen Production module is capable of representing a share of hydrogen production from distributed, small-scale facilities, but the overall impact to costs of hydrogen production and the changes in GHG emissions calculated by the model is not expected to be substantial.

As explained, siting reflects a constraint on feedstock for hydrogen production, which is further limited in the production module by availability factors. Using information reported by Ontario's Independent Electricity System Operator (IESO), the variations between demand for power and the installed baseload power generation capacity were considered by the study team. Most often through the year, demand is lower that potential supply. Ontario's nuclear reactors generate power at a fairly constant rate, while passive renewables fluctuate in their output potential. The difference can be quite large at times, during which the balance of generating output can be exported to neighbouring jurisdictions sharing in interconnected, regional grids. Occasionally, demand will exceed supply, and power must be imported to Ontario. A share of this difference (i.e., generating capacity minus actual demand) can be allocated to hydrogen production via electrolysis. Based on published data regarding Ontario's electricity generating capacity and provincial demand (on an annual basis), the model uses the difference as the upper limit of the electrical energy feedstock available. Of this upper limit, the amount that can be allocated to hydrogen production can be set by the user. The study team chose to gradually increase the allocation to a maximum of 50 per cent in the Base Case. Later in this report, a discussion on the impact of altering this setting is explored in two variations of the Base Case.

This approach biases the assumed feedstock supplies in the model toward more conservative estimates, which helps to reflect localized grid constraints. This acknowledges that, even when the generating capacity exists to support hydrogen production at a province-wide level, the capacity of the grid to accommodate the increased flow of electricity can vary by geography, especially at the local distribution level. As an alternative to conservative guesswork, higher resolution modeling of power allocation is possible within the H2GrO-TEA Model. If data at the distribution grid level is available, then more accurate predictions of feedstock availability can be made.

Analogous limits to natural gas are not defined in the production module. There are two reasons for this. Presently, natural gas supplies to Ontario (mainly exports from western Canada) are not significantly constrained by production or pipeline capacities. Carbon pricing may affect the market for natural gas, but the impacts could be uneven in the coming decades. As a fossil fuel, demand for natural gas would be expected to *decrease*, yet its use as an alternative to more carbon-intensive fuels (e.g., diesel, gasoline) could serve to *boost* demand. Moreover, hydrogen could displace natural gas in many end-uses under a decarbonizing scenario in Ontario, making *more* natural gas available for production of hydrogen. Therefore, the transition to hydrogen is not expected stress the limits of Ontario's natural gas supply.

Regarding forest and agriculture biomass as feedstock, the Hydrogen Production Module currently works on an assumption that the pathway used is using electricity from biomass-fired power plants to power electrolysis facilities. No significant contributions from pyrolysis or gasification of biomass resources are represented in the Base Case, since such facilities do not currently exist at the size contemplated in the production module, but up to 4,000 MW of electrical generating capacity from biomass in Ontario is defined as available for electrolysis should the model user wish to test various biomass-based scenarios.

4.4 Carbon-Intensity of Hydrogen Produced by Designated Pathways in the Module

The tables in the preceding section (above) distinguish between electrolysis-based hydrogen production that draws electricity from the provincial grid from those that draw directly from solar or wind farms or biomass-fired power plants (i.e., *not* via the grid). Grid-supplied power has a carbon-intensity that is a weighted average of the many energy sources that feed the grid, including nuclear, hydroelectric, firing of natural gas or biomass, wind and solar generating facilities. The carbon-intensity of grid-supplied electricity can thus change over time, and the production module can reflect such variations by updating the input tables. This allows the effects of technological change, new investment or anticipated policies to be represented (e.g., the Clean Electricity Regulations proposed by the Government of Canada).

Also distinguished in the preceding tables are the sites where hydrogen is produced via SMR from those sites where SMR facilities include carbon capture systems. In the Base Case, all SMR facilities built from the early-2030s onward include carbon capture (i.e., SMR+CC); prior to this, SMR facilities have no carbon capture capability.

The carbon-intensity values shown in Table D, below, are used to calculate the emissions associated with the different hydrogen production pathways. Table E, further below, shows the values used in calculations for emissions avoided when using hydrogen to displace an incumbent fuel. This is further discussed in section 7.2. The values were sourced from the lifecycle assessment model, GHGenius, with some adjustment by the study team to reflect Ontario mix of grid-supplied power.

Table D: Carbon Intensity (CI) of Hydrogen by Production Pathway

Hydrogen Production Pathway		Lifecycle CI (kg CO_2/GJ)
Electrolysis	Grid Electricity	31.05
	Solar Electricity	2.57
	Wind Electricity	2.62
	Forest Biomass Electricity	13.97
SMR	w/o CCS	87.80
	w/ CCS	28.59
Pyrolysis	Forest Biomass	4.55
	Agriculture Biomass	4.55
Gasification	Forest Biomass	4.55
	Agriculture Biomass	4.55
Other	New & Emerging Technologies	0.00

Table E: Carbon Intensity (CI) of Incumbent Fuels Displaceable by Hydrogen

Fuel Type	Lifecycle CI (kg CO_2/GJ)
Diesel	106.95
Gasoline	97.12
Natural Gas	68.27
Propane	77.74

4.5 Growth Rates to 2050 in the Module

For each hydrogen production pathway designated in the model, a growth rate is applied. The growth rate is a mathematical function in which certain constants can be defined, such as the current level of hydrogen production limited by feedstock availability and the estimated level of market adoption in 2050 as a share of total end-use demand. Figure 15 below, shows three growth curve profiles that can be selected, with the vertical axis representing the degree of market penetration (i.e., 0 to 100 per cent). Similar functions are used in other parts of the model, such as the growth of demand in different sectors. The uptake of a new technology seldom follows a linear path. The H2GrO-TEA Model Hydrogen Production module provides for the selection of an appropriate growth curve for each hydrogen production pathway on a region-by-region basis. This gives the user the flexibility to create a scenario that more accurately reflects how a technology may actually deploy. For example, in Base Case 1 the study team conservatively set a slow growth rate for the production pathways that are commercially ready but not yet at scale, such as pyrolysis, gasification.

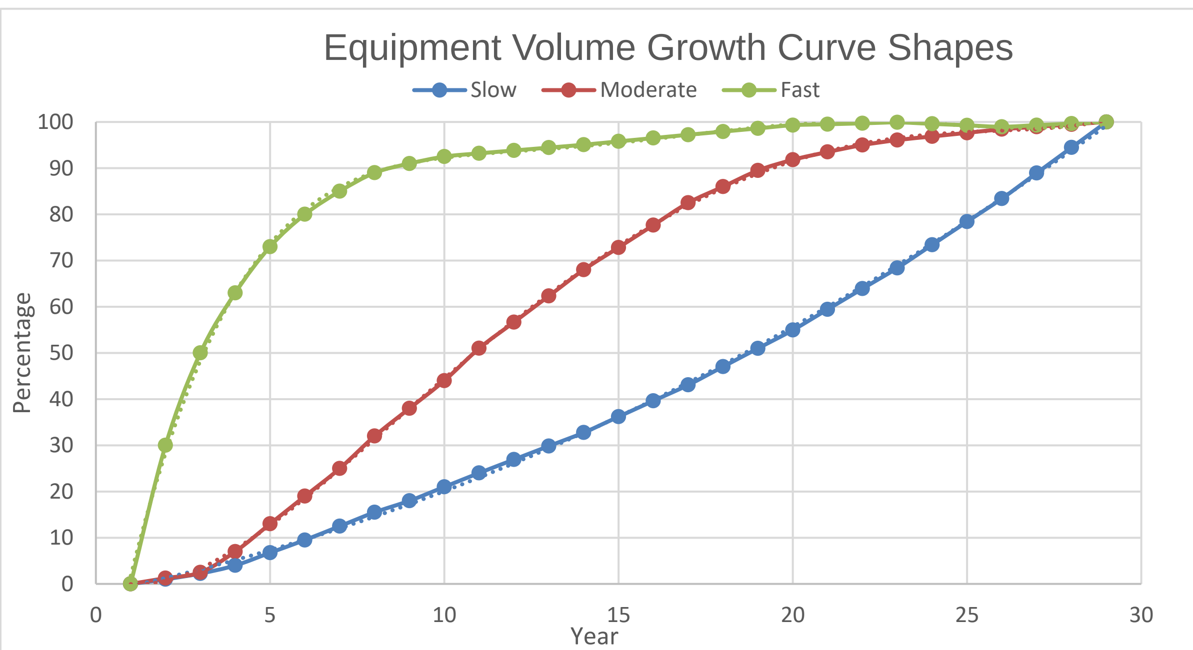


Figure 15: Growth Curve Shapes

In the Base Case, growth in hydrogen production is also subject to a stepwise function that represents the discrete size of an electrolysis facility producing hydrogen in Ontario. To meet the production volumes defined by the growth rate, electrolysis facilities can be sized at 1 MW (small), 10 MW (medium) or 100 MW (large). In other words, the model would not assume a production facility operating at 25 MW or 50 MW, even though these are technically possible. This choice of the study teams enables a more realistic calculation of capital costs and represents the way hydrogen production in a market would actually evolve.

SMR, as explained earlier, has two designations: SMR without any method of capturing by-product carbon dioxide, which is released as a GHG, and SMR that incorporates carbon capture (i.e., SMR+CC). Captured carbon is assumed to be permanently sequestered or used as valued product, so that it does not subsequently enter the atmosphere. Either way, the fate of the captured carbon does not affect the model calculations. However, the siting of SMR+CC facilities by the study team was considered an important factor in assessing the potential for carbon storage or use. Thus, SMR+CC sites are all proximate to industrial facilities, where the carbon could have value in the manufacture of new product, or to parts of the province where subsurface CO_2 injection and storage are possible, based on favourable geological factors (these are explored in the companion report by H2GO Canada, *Scoping the Commercial Potential for Carbon Capture, Utilization and Storage and Hydrogen Storage in Ontario to 2035*.

The study team noes that synthetic fuels and combustible products produced using captured carbon would not necessarily result in an elimination of CO_2 emissions. Instead, such synthetic fuel products would more likely defer emissions or have an offsetting impact. Future refinements to the production model could include a more customizable selection of captured carbon fates.

In the Base Case, SMR production of hydrogen begins in 2026 and follows a fast growth rate, while SMR+CC production does not initiate until 2028 and follows a moderate growth rate. Thus, SMR without carbon capture contributes significantly to hydrogen production volumes in the early years but reaches its maximum fairly soon. SMR with carbon capture enters the market later but continues to grow through 2050.

In this scenario, an attempt is made to balance the potential effects of increasing carbon pricing over time, the effect of which would blunt the uptake of SMR *without* CCUS, against the commercial maturity of existing SMR systems, around which hydrogen production could ramp quickly at comparatively low cost. Note that even hydrogen from SMR can be less carbon-intensive than many fuels it might displace, such as diesel in a vehicle. Furthermore, the scenario assumes sufficient capacity exists for captured carbon to be received and sequestered within Ontario or exported to other jurisdictions for permanent storage. The study team acknowledges the uncertainty in this assumption. It also recognizes that emerging hydrogen production technologies, such as methane pyrolysis, could possibly achieve commercial readiness much sooner than is currently reflected in the Base Case, and that this would obviate the need for logistically complex CO_2 capture and storage solutions. This underscores the benefit in running numerous scenarios to better understand the effects that broader system limitations can have on different types of hydrogen production, which is what makes the H2GrO-TEA Model such a useful tool.

4.6 Hydrogen Production Module Output – Base Case Scenario

Figure 16 below shows the Annual Hydrogen Production for the Base Case scenario by designated pathway. The dominant production pathway in this scenario is electrolysis powered by grid-supplied electricity, followed by SMR with and without carbon capture. These are the most readily available, large-scale hydrogen production methods identified today. SMR initiates without carbon capture. SMR with carbon capture does not scale up significantly until 2030. In the Base Case, by 2050 only 55 per cent of all SMR plants in Ontario are assumed to integrate some form of CCUS. This reflects an increasing availability of supporting infrastructure for the collection, transport and storage of carbon dioxide from SMR plants in Ontario, as well the introduction of methane pyrolysis in the market.

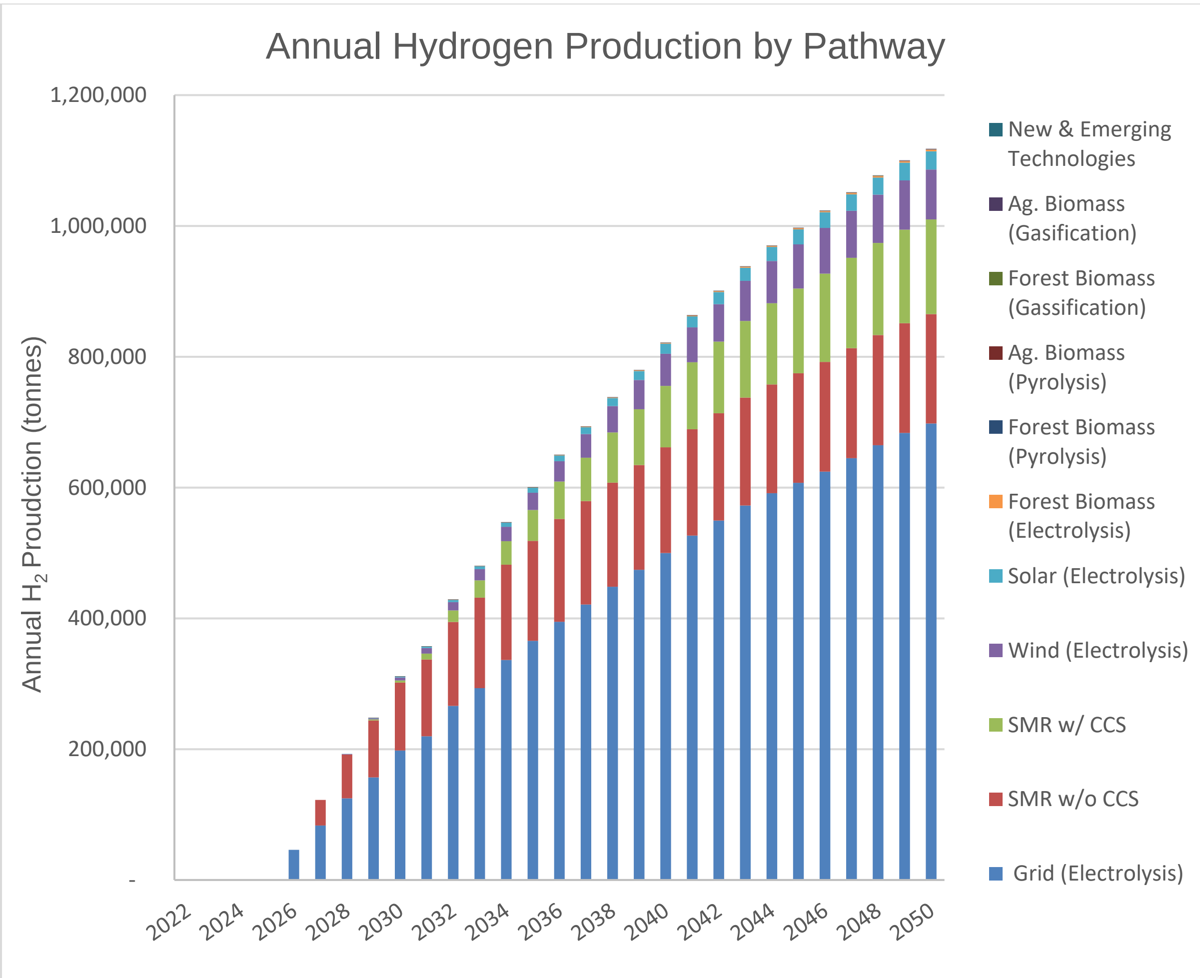


Figure 16: Annual Hydrogen Production by Pathway

The Base Case scenario projects total production of low-carbon hydrogen in Ontario are negligible until the late 2020s, and then rapidly increasing to roughly 600 megatonnes, annually, by the mid-2030s, relying mainly on grid-powered electrolysis and steam methane reforming. Grid-supplied electricity continues to drive production to 2050, but power supplied directly from wind and solar energy becomes a faster-growing feedstock for hydrogen production from the mid-2030s onward.

As the model does not currently make projections beyond 2050, the rate of growth begins to decline as that endpoint is approached. This simply reflects the throughput capacity of the low-carbon hydrogen supply system becoming fully utilized in the years following its initial build-out.

By 2050, the production of low-carbon hydrogen in Ontario reaches approximately 1.1 megatonnes (132 PJ) annually. For context, this is roughly equivalent to 4 per cent of current, total final energy use in Ontario (2019) [21]. The study team considers this a conservative estimate, but it served the purpose of building and calibrating the model, such that more aggressive scenarios can be simulated. This aligns to the Canada Energy Future report, which projects 130 petajoules of hydrogen demand in Ontario in 2050 (under an evolving policies scenario).

The following figures present the same projections for hydrogen production in Ontario but represented by producing region.

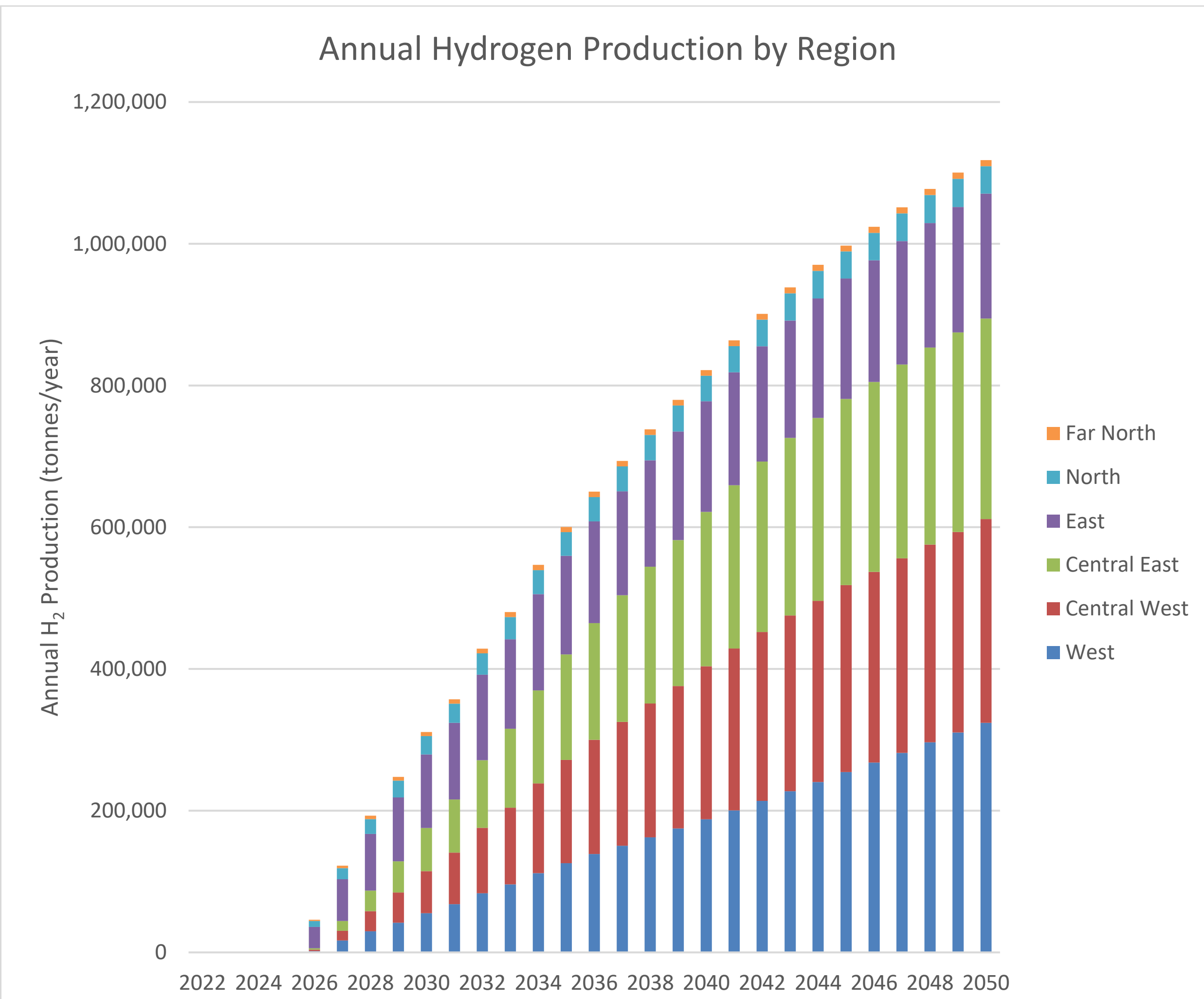


Figure 17: Annual Hydrogen Production by Region

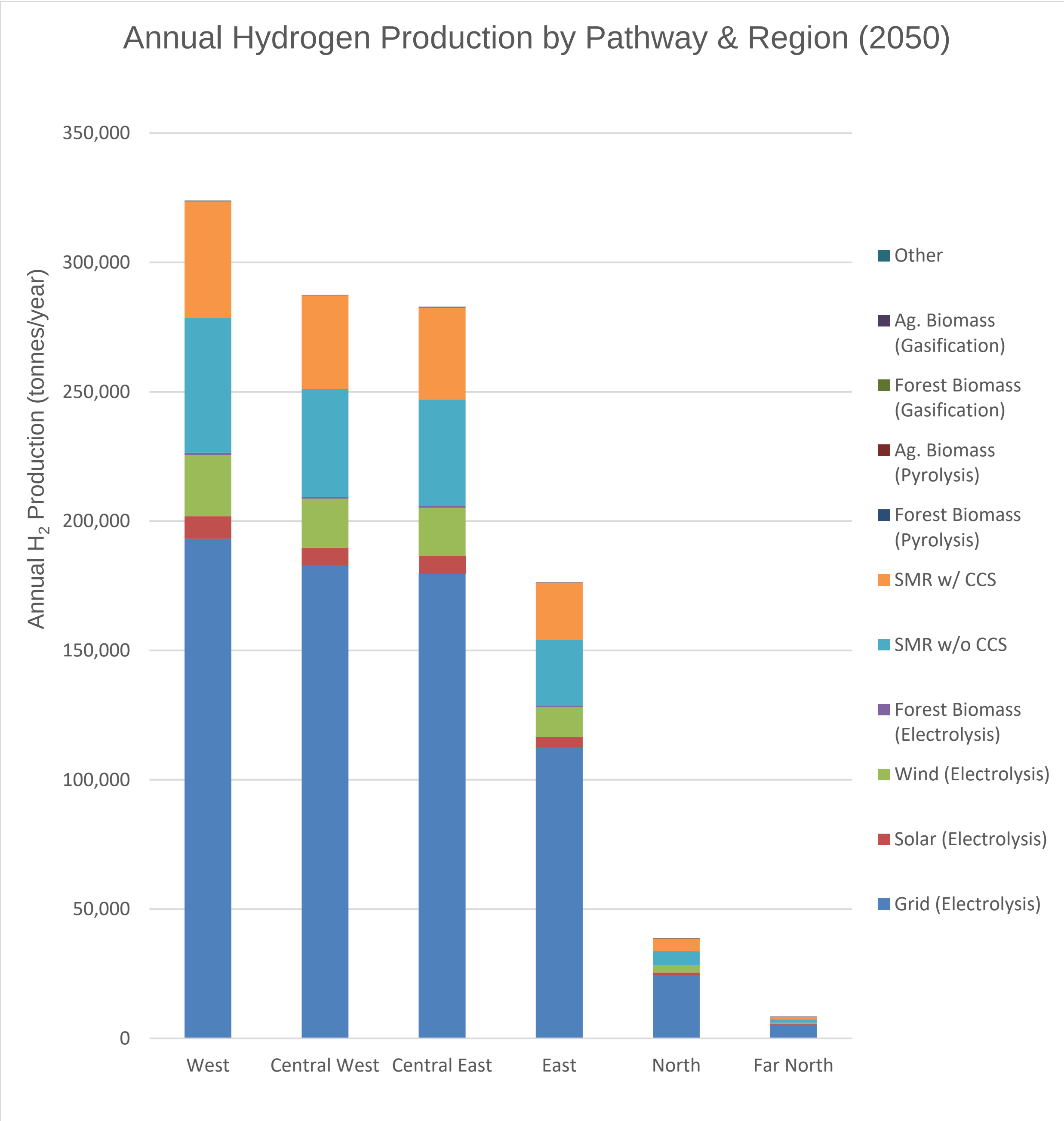


Figure 18: Annual Hydrogen Production by Pathway & Region (2050)

Ontario Opportunity: hydrogen production using new nuclear technologies

Terrestrial Energy is an Ontario-based nuclear technology company that is developing integral molten salt (IMS) reactor designs for producing power. These plants generate electricity and high-temperature heat for industrial use. By levering the heat energy from the reactor, water splitting can be achieved with much less electrical energy for producing hydrogen and oxygen.

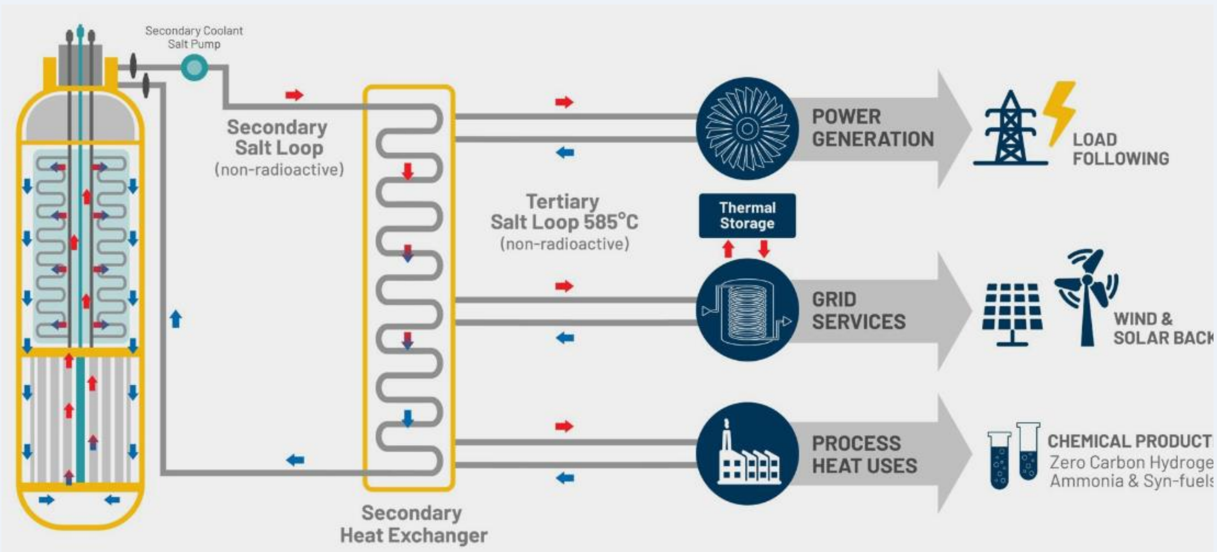


Figure 19: Flexible Industry Energy
Source: Terrestrial Energy [39]

Moltex Energy, a Canadian company based in New Brunswick (a province with a similar mix of power generation as Ontario), is developing a stable salt reactor and waste-burner (SSR-W) design. Its use could support hydrogen production while also reducing nuclear waste material from CANDU reactors.

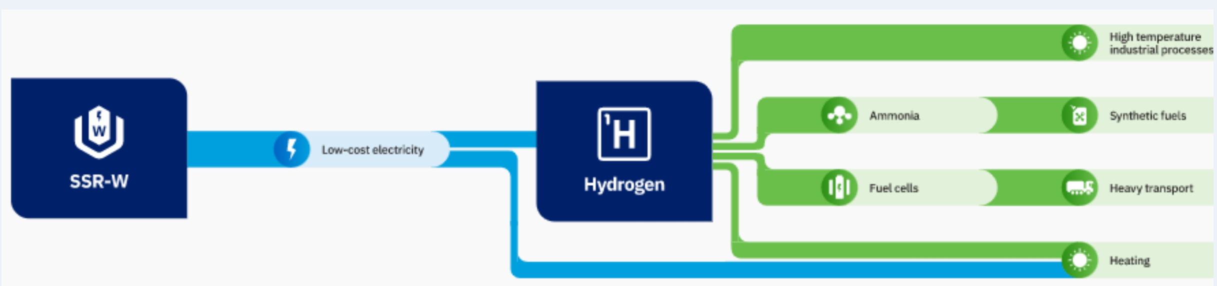


Figure 20: SSR-W role in hydrogen economy
Source: Moltex Energy [46].

5.0 HYDROGEN CONSUMPTION

Hydrogen consumption refers to the use of hydrogen as an energy commodity to power some form of energy service, such as space heating, electrical loads or transportation, or as a chemical feedstock for the manufacture of some material. In either case, the hydrogen undergoes molecular bonding and is thus "consumed." In many energy services the hydrogen bonds with oxygen to become water, through combustion or some electrochemical process.

Estimating the potential consumption of hydrogen is challenging, because it can be practically applied to many diverse end-uses. Most fuels are dominantly used in only two or three distinct applications. For example, diesel is used as a fuel in heavy-duty vehicles, portable power generators and, sometimes, for process heat in industry where more common fuels, such as natural gas, are not practically accessible. Hydrogen can be applied as a substitute fuel for diesel, but also for gasoline, natural gas, kerosene and so on. The lower the lifecycle carbon-intensity of the hydrogen compared to the conventional fuel it displaces, the greater the net reduction in GHG emissions and, thus, the more progress made in decarbonizing Ontario's economy.

The H2GrO-TEA Model's Hydrogen Consumption module can represent any end-use application for hydrogen the user chooses to define. The module provides a calculation of the potential annual hydrogen *consumption* (sometimes referred to as *demand* in this report) for each defined *end-use* (sometimes referred to as *application* in this report). Each application is based on data and analysis arising from the Regional Scan module. The module data can be continuously revised as better information is acquired over time. The balance between module outputs of hydrogen production and consumption directly shape the modeling carried out in the Hydrogen Ecosystem module (explained later in section 7.0 of this report).

In the Base Case scenario around which the model was built, 20 unique applications of hydrogen use were designated. Some of these exist in every region of the province, such as transportation, while some do not, such as steelmaking. Accordingly, the profile of hydrogen consumption differs for each of the regions defined in the model. Moreover, the module does not permit the use of hydrogen to exceed the energy-equivalent amount of demand for each application. For example, if the total litres of gasoline consumed by light-duty vehicle in 2030 represents a certain demand for transportation energy, then the total hydrogen consumed cannot exceed the demand in this application. Energy demand limits are set according to the reference case for 2050, *Canada's Energy Future*, or are interpolated from sector and fuel type forecasts published by the Canada Energy Regulator. These limits can be changed in the module to simulate scenarios other than the Base Case.

In identifying the applications where hydrogen would apply, the study team drew on guidance from its informal advisory group, as well its own experience. Hydrogen might be technically feasible in some applications, but not economically practical. Furthermore, the study team took stock of other decarbonization pathways that are more likely than hydrogen to be adopted by the market. Electrification through direct connection with the provincial grid or via battery-based energy storage would be favourable to a hydrogen solution, for example, unless hydrogen system offered some particular advantage. Duty-cycle assessment was thus an important part of the study team's assessment. For instance, in the case of passenger vehicles, some applications, such as commuter or personal convenience transportation, which are used for short periods of time (i.e., <4-6 hours/day) can easily be operated using energy stored in an onboard battery pack. In other cases, such as with taxi service or urban delivery vehicles, the longer duty cycle (i.e., >6 hours/day) and the need for quick refuelling (say, 5 to 15 minutes) may favour the use of a faster-dispensing, more energy-dense fuel, such as hydrogen.

The Hydrogen Consumption module represents the co-existence of numerous low-carbon solutions by defining the share of the market in which the use of hydrogen has significant, recognized advantages. In the Base Case, the share of passenger car energy demand met by hydrogen is marginal, as plug-in electric and hybrid-electric vehicles are expected to dominate this market. By contrast, heavier vehicle modes, including freight transport by truck and rail, rely more on hydrogen to achieve low-carbon, zero-emission operation in the Base Case scenario.

5.1 Defining Hydrogen-Using Markets in the Consumption Module

As mentioned earlier in Section 2, the geographic locations of prospective hydrogen markets in Ontario were scoped and a map was developed. This mapping work supported some foundational analyses presented in the companion report by H2GO Canada, *Scoping the Commercial Potential for Carbon Capture, Utilization and Storage and Hydrogen Storage in Ontario to 2035*. The maps also served an important function in the H2GrO-TEA Model; specifically, in the Hydrogen Delivery, where the physical siting of markets supports transport cost calculation, and in the Hydrogen Consumption module, where each market is uniquely characterized with its own profile of hydrogen demand. Indeed, the hydrogen consumption estimates generated by this module are a roll-up of the analyses conducted for each discrete market. The following explanation of how the hydrogen markets were defined for the H2GrO-TEA Model mirrors that presented in the companion report.

As described previously in Section 4, leading prospects for hydrogen production sites throughout the province were designated and characterized. Next the team developed a set of emerging hydrogen markets (also called hydrogen hubs) according to the following criteria.

- Large urban population centres in each region, including the ten most populous cities in Ontario, were selected to represent a multi-sector (i.e., commercial, residential, transportation), diverse range of hydrogen end-use applications.
- Presence and proximity of industrial end-use applications of hydrogen contributed to hub assignment.
- Urban areas close to one another were considered to represent a consolidation of demand that supported hub assignment.
- Where communities were too small or remote within a region to support an urban population-centred end-use market, a representative hub was assigned to the administrative region (this serves to ensure that the balance of Ontario's entire population outside of urban centres is considered in the hydrogen supply and demand modeling conducted for the companion report).
- As a corollary to the above criteria, each administrative region was ensured to have at least one market hydrogen hub to serve the population, regardless of distribution and density.

Based on this analysis, thirteen (13) market hubs were geographically assigned, as well as five representative hubs to serve the remaining, populations within the administrative regions (defined in the regional scan described in Section 2). The resulting list of all hydrogen markets is provided in the following table.

Table F: Prospective Hydrogen Market Hubs

Model ID	City	Region	Map ID
Market 1	Rep Far North	Far North	-
Market 2	Thunder bay	North	1
Market 3	Sault Ste. Marie	North	2
Market 4	North Bay & Sudbury	North	3
Market 5	Rep North	North	-
Market 6	Hamilton	West	4
Market 7	Niagara, Welland, St. Catherines	West	5
Market 8	Kitchener/ Waterloo	West	6
Market 9	London	West	7
Market 10	Windsor/Sarnia	West	8
Market 11	Rep West	West	-
Market 12	Central West (Peel, York)	Central West	9
Market 13	Barrie	Central West	10
Market 14	Rep Central West	Central West	-
Market 15	Central East (Toronto, Durham)	Central East	11
Market 16	Kingston	East	12
Market 17	Ottawa & Kanata	East	13
Market 18	Rep East	East	-

These hydrogen market designations are presented in the following map, where blue circles represent the urban markets served and the red circles represent the region served (having no population-centred hub). Timmins, for example, is proximate to a number of possible hydrogen production and end-use applications (e.g., mining, forestry, pulp & paper), and this potential is captured in the Rep North regional market.

It is important to note there are several major industrial facilities in Ontario that do not fall within one of the identified market hubs. Some are also large emitters of CO_2 that could be served by hydrogen as a pathway to decarbonize their operations. This is why prospective sites of low-carbon hydrogen production marked on the map can fall outside of the blue areas.

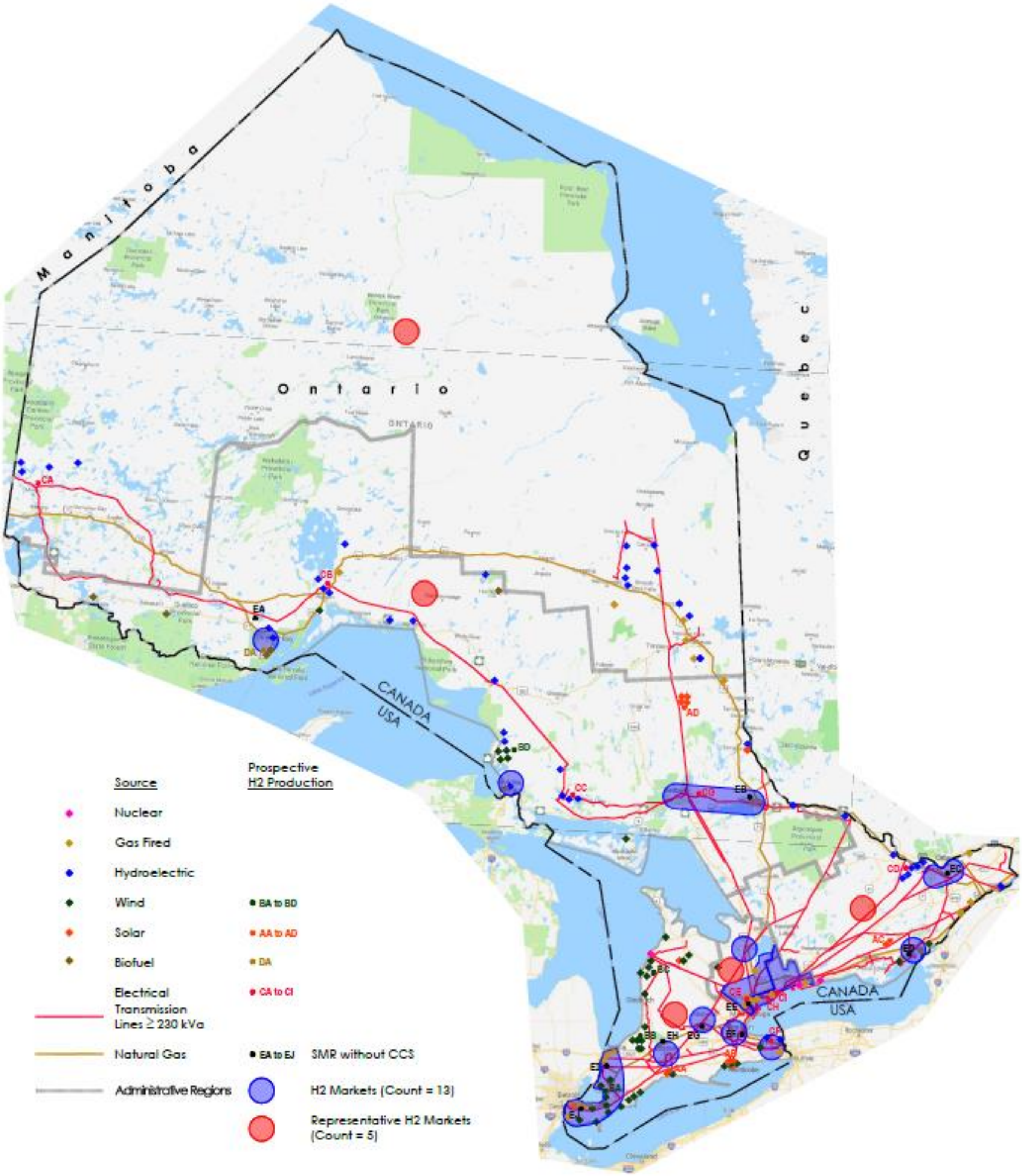


Figure 21: Prospective Hydrogen Production Points and Hydrogen Market Hubs
Source: Adapted from Government of Ontario [5], IESO [18], Canada Energy Regulator [19], OEB [20]

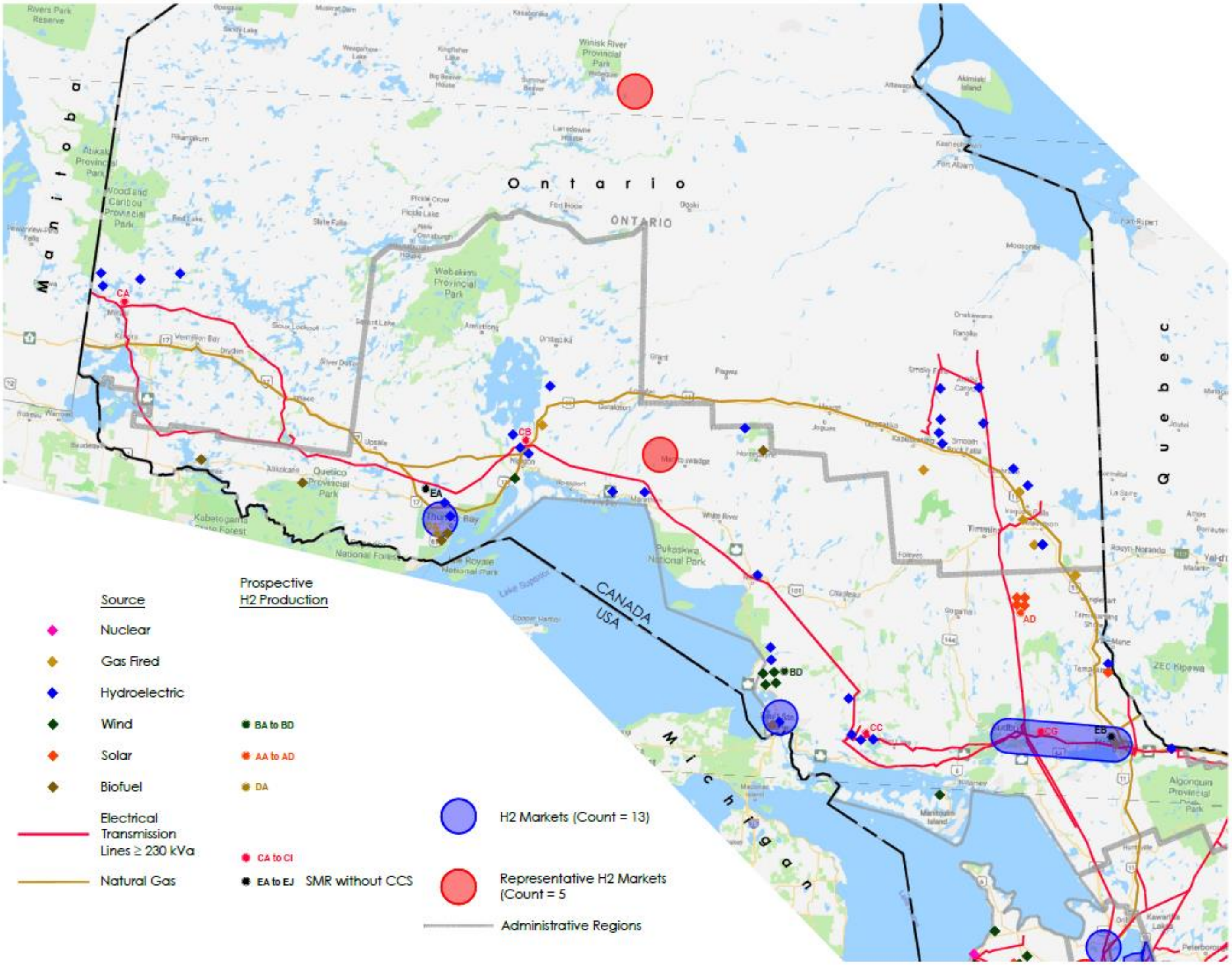


Figure 22: Prospective Hydrogen Production Points and Hydrogen Market Hubs: Northern Ontario
Source: Adapted from Government of Ontario [5], IESO [18], Canada Energy Regulator [19], OEB [20]

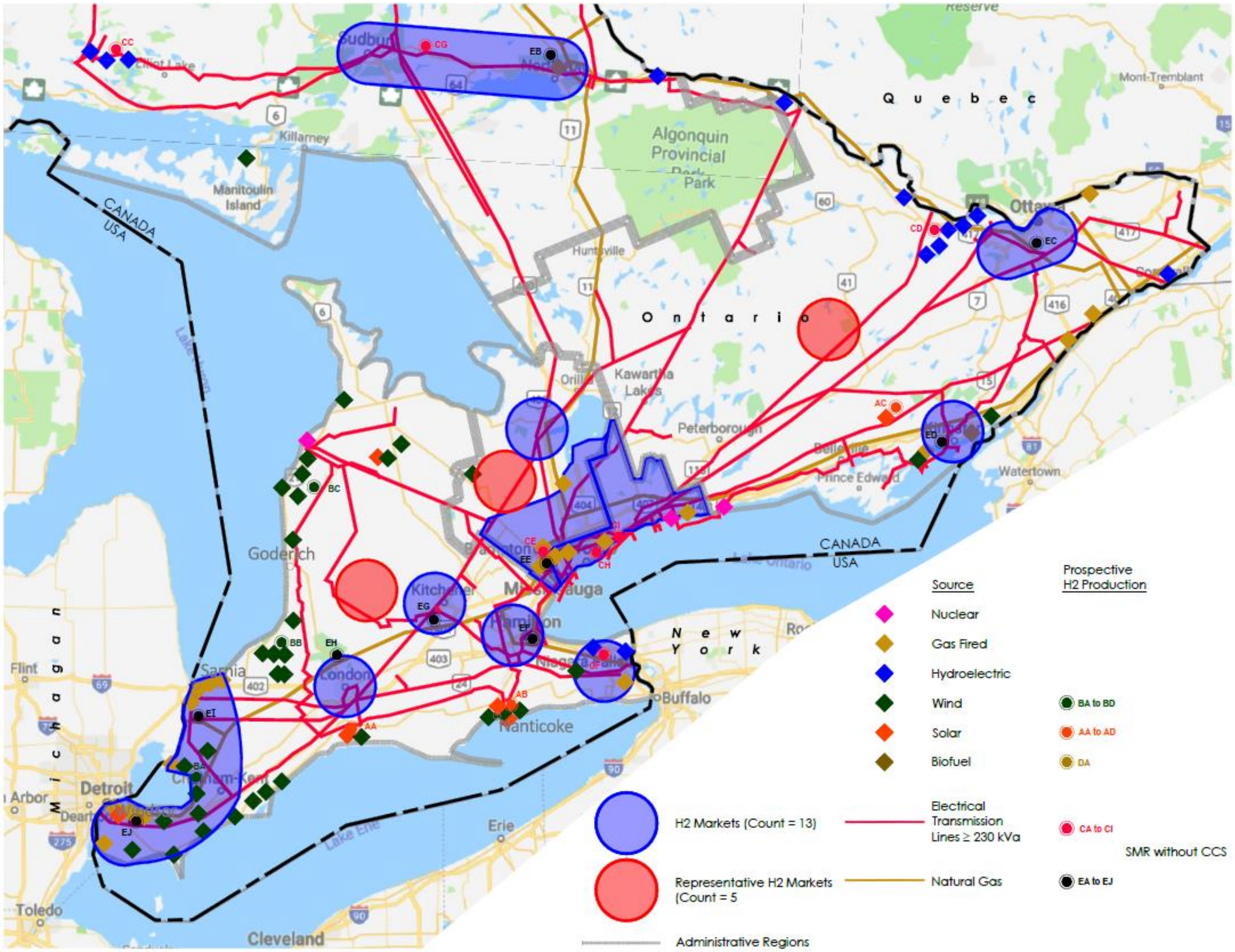


Figure 23: Prospective Hydrogen Production Points and Hydrogen Market Hubs: Southern Ontario
Source: Adapted from Government of Ontario [5], IESO [18], Canada Energy Regulator [19], OEB [20]

These 18 Ontario hydrogen hubs are briefly characterized as follows:

Market 1:	Representing the provincial population and remote communities in the Far North region to ensure inclusion in opportunity assessments. Further development potential in the Far North must also be considered as the scope of opportunities will continue to grow with the strong probability of large scale development and construction within the next decade.
Market 2:	Thunder Bay is one of the largest cities in northern Ontario, representing 17 per cent of the population in the north region. Thunder Bay also hosts one of the province's industrial heartlands in the North region.
Market 3:	Sault Ste. Marie is located very close to the U.S. border, making it well-connected to international markets and is also central to industrial supply chains. This market represents 11 per cent of the North region's population.
Market 4:	North Bay and Sudbury are combined to make up another 25 per cent of Ontario's population in the North region. Based on the proximity of these cities within the region, it reasons to consolidate them into a single hydrogen market, from which economic efficiencies can be leveraged.
Market 5:	Representing the population in the North region outsides of markets 2, 3 and 4, thus accounting for the service of smaller and remote communities with hydrogen opportunities.
Market 6:	Hamilton is a major industrial centre in Ontario and represents 16 per cent of the population in the West region.
Market 7:	Niagara, Welland and St. Catharines are cities in close proximity and near the U.S. border. Also having major transportation corridors, this market hosts 11 per cent of the West region's population.
Market 8:	Kitchener and Waterloo are major cities outside of the GTHA that are near each other and represent 12 per cent of the population in the West region. Kitchener is also a city with significant industrial activity and is a centre of technology innovation.
Market 9:	London is another major city outside of the GTHA representing 11 per cent of the population in the West region.
Market 10:	Windsor and Sarnia are both cities bordering U.S. and its substantial markets. Notably, Sarnia hosts one of Ontario's heaviest concentrations of industrial facilities.
Market 11:	Representing the remaining West region outside of markets 6 through 10.
Market 12:	Peel and York are regions within the GTHA that include some of the largest cities in Ontario. Pearson International Airport also falls within this region. 82 per cent of the population of the Central West region are within Peel and York.
Market 13:	Barrie is the ninth-largest city in Ontario, and is expected to generate significant demand for hydrogen.
Market 14:	Representing the remaining 14 per cent of the population within the Central West region.
Market 15:	Includes the City of Toronto and Durham region, representing 100 per cent of the population of the Central East region. This is the largest of the six administrative regions defined and the most populated city in Canada.

Market 16: Kingston represents 24 per cent of the population in the East region and is critically well-positioned between Toronto and Ottawa, geographically, enabling hydrogen fuelling between the two hubs.

Market 17: Ottawa and Kanata are the most populated cities in the East region, representing 64 per cent of the population. Ottawa is the capital of Canada and borders Quebec, which is expected to have thriving hydrogen markets.

Market 18: Represents the remaining communities in the East region.

The markets described above form the Base Case scenario; however, model users can add new hydrogen markets to support the simulations of new scenarios.

First Nations administrative locations are included in this map, recognizing that Indigenous enterprises could develop hydrogen production, distribution and exporting operations within and beyond the borders of the urban hydrogen markets.

5.2 Projecting Hydrogen Demand by End-Use Application

The H2GrO-TEA Model's Hydrogen Consumption module organizes applications into traditional energy end-use sectors:

- Transportation, relating to the use of hydrogen as a fuel to power vehicles;
- Industrial, relating to the use of hydrogen as a fuel for process heat or as material feedstock for manufacturing, energy storage and portable power generation;
- Buildings & facilities, relating to space heating in commercial, institutional and residential structures, as well as facility back-up power systems

Within each of these sectors, discrete applications are defined and assigned mathematical relationships that equate demand for the relevant service (e.g. personal mobility, freight movement, home heating) to demand for hydrogen. A profile for growth in hydrogen demand is also needed to simulate market adoption of hydrogen-using technologies. By combining these two aspects of hydrogen demand, the capacity to define scenarios is established in the consumption module. The following logical steps were applied by the study team.

1) Each hydrogen-using application is designated in the module and a particular duty-cycle is applied. An application may be used under different duty-cycles. For example, the duty-cycle for personal vehicle use is not the same as taxi service, yet the application is the same (i.e., a light-duty vehicle). Therefore, each designation in the consumption module is a unique combination of application and duty-cycle. This combination also yields an annual hydrogen consumption estimate, which maps to each designation.
2) Drawing on the hydrogen markets analyses (see previous subsection) the population of designated applications can be estimated (i.e., the number of hydrogen-using devices). Each market has a particular profile of potential hydrogen applications, which aligns with the distribution of energy end-use sectors (i.e., transportation, industrial, buildings & facilities). The product of the estimates for annual hydrogen consumption and market population for each designated application can then be summed to determine total annual hydrogen demand. The change from year to year is determined by the growth rate applied, as described next.

3) A series of growth rates are applied to designated applications:
   - a general population growth rate for each of the identified hydrogen-using markets;
   - a rate of growth in market adoption of the hydrogen-using device; and
   - a rate of hydrogen consumption for each application, which can be positive or negative to represent changes in end-use efficiency and duty-cycle over time.

   The growth rate for market adoption uses curve functions such as those shown previously in Section 4.5, Figure 15, to represent slow, medium, and fast paces. Also required are a starting year, which could represent the introduction of a new application, the maximum level of market share achieved and the year in which that peak occurs. Market share can be chosen to reflect the availability of competing, non-hydrogen applications. For example, low-carbon home heating may be achieved using a hydrogen furnace or an electric heat pump. Local factors within a hydrogen market can influence the choice of market split among the identified alternatives.

The study team drew on published data and external, expert advice to inform the selection of input variables in the Base Case scenario. Where authoritative references were not available, the study team relied on their own experience and judgement. Variables were further adjusted during calibrating runs to produce output calculations that seemed consistent with a conservatively biased forecast of hydrogen consumption in Ontario. Alternative scenarios can be defined and simulated in the H2GrO-TEA Model's Hydrogen Consumption module to test different conditions that effect of certain variables on future market demand.

In addition to hydrogen demand by application, sector and market, the Hydrogen Consumption module also generates the following outputs:

- the associated distribution infrastructure required, based on standard size increments;
- capital cost of the distribution infrastructure;
- operating and maintenance costs;
- jobs created, relating to the distribution infrastructure; and
- GHG emissions reductions, in comparison to that from the use of the incumbent fuel.

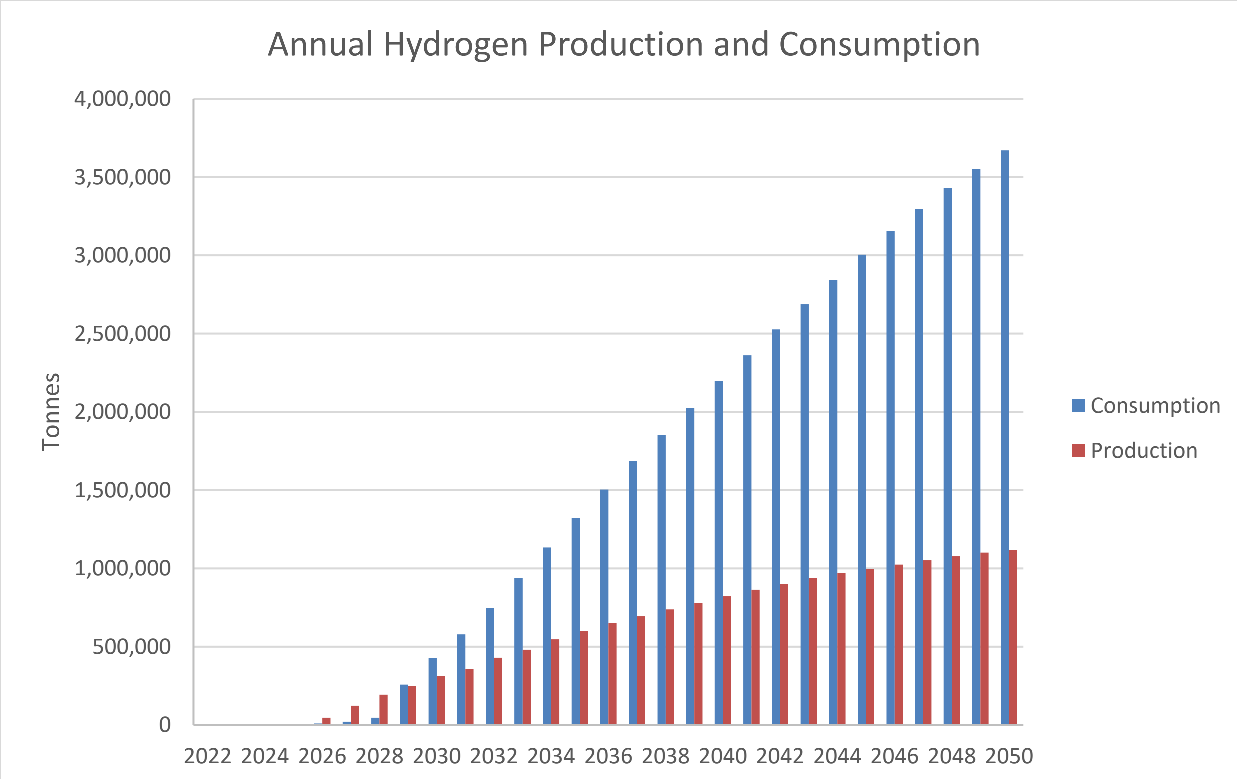


Figure 24 below presents the total consumption of low-carbon hydrogen in Ontario, each year to 2050, in the Base Case scenario. For comparison, the output of the hydrogen production module for the Base Case is also shown (see section 4.6). Evident in this scenario is that demand for hydrogen has the potential to far outpace the production within the province.

The gap between production and consumption raises questions. For instance, how might Ontario produce all the hydrogen that it uses? Could this be achieved through a change in production technology, or simply a scale-up of feedstock use? Alternatively, could the needed hydrogen be imported to Ontario? What would it cost? Later in this report, section 7.5, two alternative Base Case scenarios are described, the outputs of which help to illustrate how the H2GrO-TEA Model can be used to compare and contrast different strategic approaches to hydrogen systems development in Ontario.

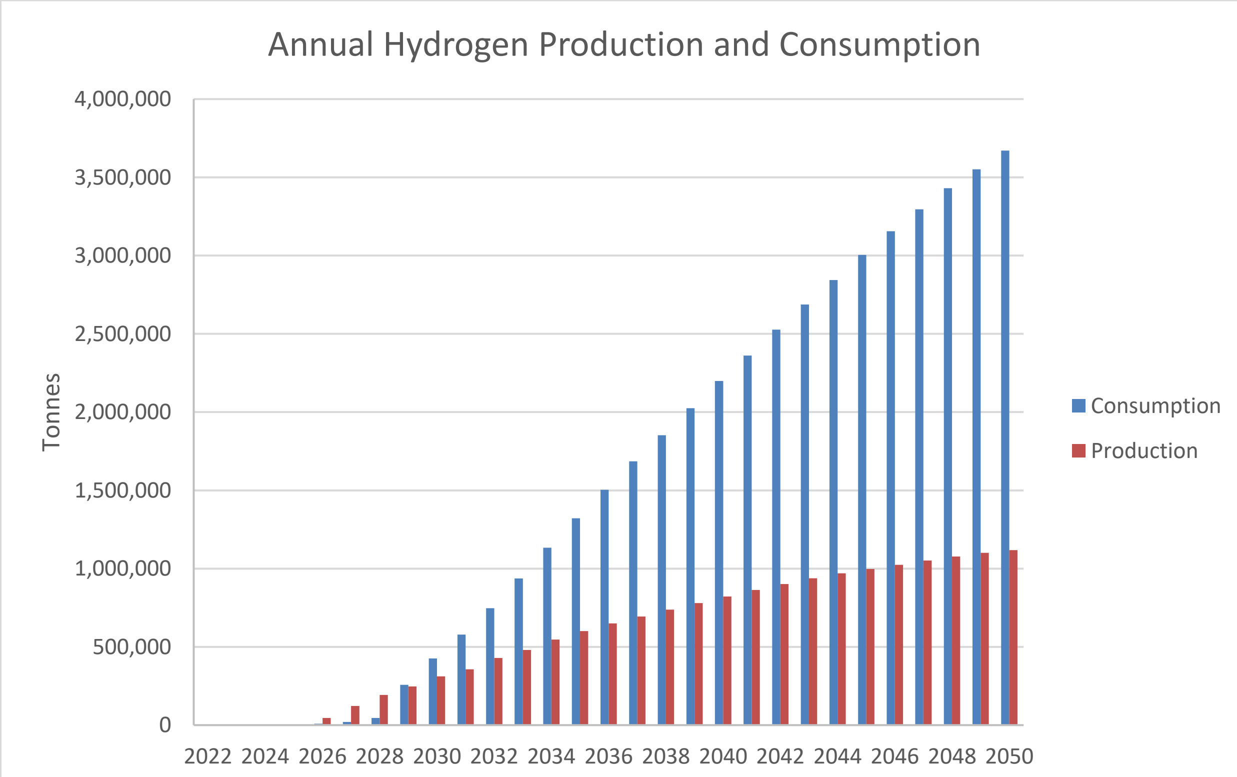


Figure 24: Ontario Hydrogen Production and Consumption

In the following subsections, notable characteristics of the hydrogen applications comprising the Hydrogen Consumption module are described. This reporting is not exhaustive, so not every aspect of the module design is addressed, but the highlights are presented to help illustrate the logic and assumptions applied by the study team. As asserted the introduction (section 1.0), the model inputs and outputs should be refined through a series of workshops with sector stakeholders, through which a broadly accepted scenario can be developed. In the meantime, the study team considers the Base Case to be an acceptable starting point for hydrogen systems planning in Ontario.

5.3 Transportation Sector Applications

Hydrogen has long been considered to have potential as a low-carbon fuel for many transportation fuel applications. Hydrogen fuel can be converted into mechanical and electrical energy needed to power vehicles using internal combustion engines or fuel cells. Spark-ignited combustion engines can be designed to run on pure hydrogen gas, while compression-ignited engines can operate on a blend of diesel and hydrogen. Fuel cells generate electrical energy from hydrogen through an electrochemical reactions, and tend to be more efficient at generating power than combustion engines. Both emit water as the main emission, although combustion engines will also emit some oxides of nitrogen, as typical of combustion processes.

The Hydrogen Consumption module is a tool to explore how hydrogen demand might evolve within these various applications in Ontario. The Base Case scenario uses the following applications (i.e., designated by both the technology *and* a duty cycle) but more can be incorporated.

- *Long range personal passenger vehicles* – These are light-duty vehicles operating on a high up-time duty-cycle, and is a good representative of taxi and limousine service. The study team assumes that most passenger vehicles used in household service (e.g., commuting for work, shopping, leisure) are more likely to rely on plug-in electric vehicle powertrains than hydrogen, at least until 2050.

- *Medium-duty personal passenger vehicles* – These are light truck and medium-duty vehicles used primarily for personal transport as opposed to freight. These are separated form light-duty passenger vehicles because their size and mass can favour hydrogen fuel regardless of the intensity of the duty-cycle. Examples include full size SUVs and pickup trucks. Nonetheless, plug-in EVs have potential to occupy a significant share of this class.

- *Medium-duty vehicles in commercial service* – These are vehicles in the medium-duty size classes (i.e., Class 3 to 6) operating mainly on a local delivery and return-to-base duty-cycle, as typical of local delivery trucks. Stop-and-go service for 10 hours or more each day favour hydrogen for infrequent and fast refueling.

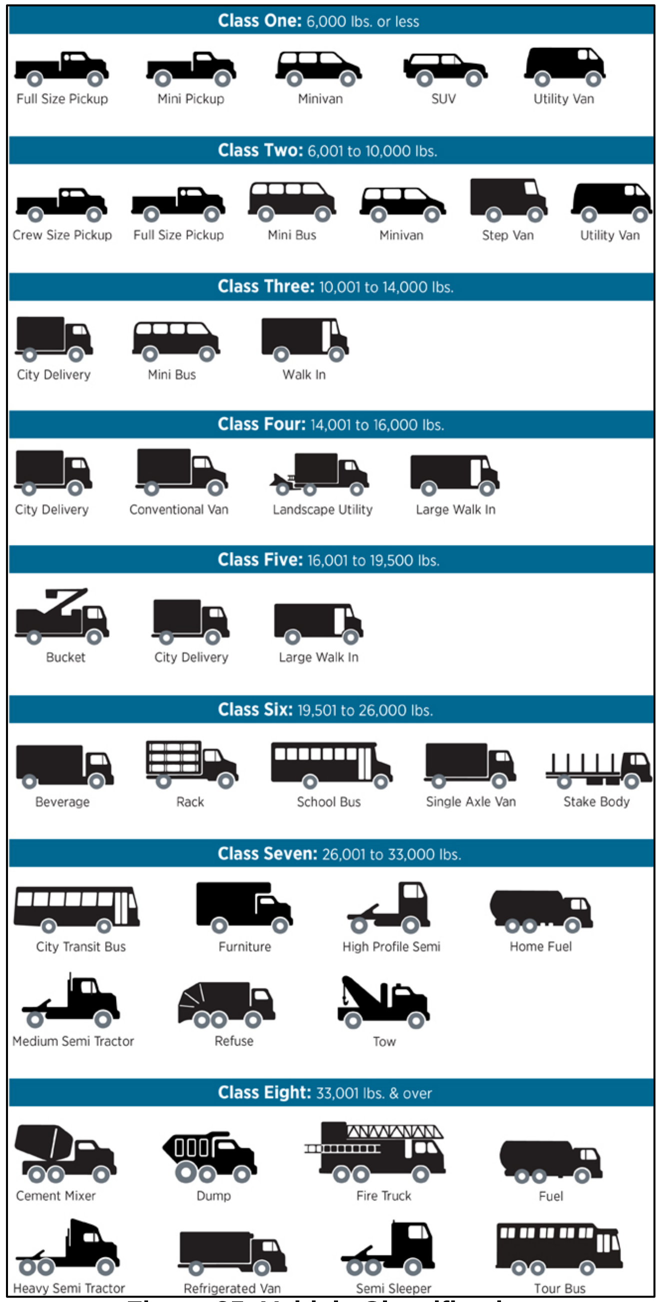


Figure 25: Vehicle Classification
Source: Alternative Fuels Data Center (U.S. DOE) [36]

- *Medium- and Heavy-duty vehicles* – These include on- and off-road vehicles and vehicular equipment operating in heavy payload or long-range transport service, such as Class 7 to 8 semi tractors and refuse haulers. Duty cycles often include at least 8 hours of continuous operation, daily, requiring large onboard stores of fuel.

- *Vocational vehicles* – The vehicles and duty-cycles in this application can vary from small to large and usually have highly specific duty-cycles. The Base Case includes transit buses and forklifts only, but street sweepers, bucket trucks and mobile cranes are all potential candidates for addition, given further research of the duty-cycles.

- *Rail* – This application refers to locomotives in freight transport service. To develop options for low-carbon, zero-emissions service, freight rail companies are currently piloting fuel cell-electric locomotives. There is interest in the longer range and fast refuelling characteristics of hydrogen compared to plug-in alternatives.

As described earlier, the H2GrO-TEA Model's Hydrogen Consumption module applies growth functions to each according to user-defined parameters for each hydrogen market; namely:

- the year of initial deployment or the initial level of penetration if the year of initial deployment is prior to year one;
- the estimated maximum level of market share;
- the year by which the maximum is reached; and
- the choice of a slow, medium or fast growth profile.

For example, the input used in the Base Case scenario for Medium- and Heavy-duty vehicles in the *Ontario Central East* regional market are:

- initial deployment in 2029;
- maximum market share of 40 per cent;
- peak market share reached just past 2050; and
- market adoption rate follows a fast growth curve.

Note that the market share references the projected population of the application expected in the year 2050. Therefore, the model also includes a growth rate projection for the total number of vehicles in the market. The remaining share of the market demand (i.e., 60 per cent in this example) is not expected to be met with low-carbon hydrogen, but with some other low-carbon solution, such as plug-in rechargeable battery pack, renewable fuels or synthetic fuels of non-biogenic origin (i.e., electrofuels).

Selected output calculations of the hydrogen consumption module are presented in Figure 26 and Figure 27 below, respectively representing the demand for low-carbon hydrogen in each transportation sector application by year *to* 2050, and by administrative region *in* 2050. Also presented is the approximate number of hydrogen refuelling stations required to support the projected level of consumption by on-road vehicle application, in Figure 29.

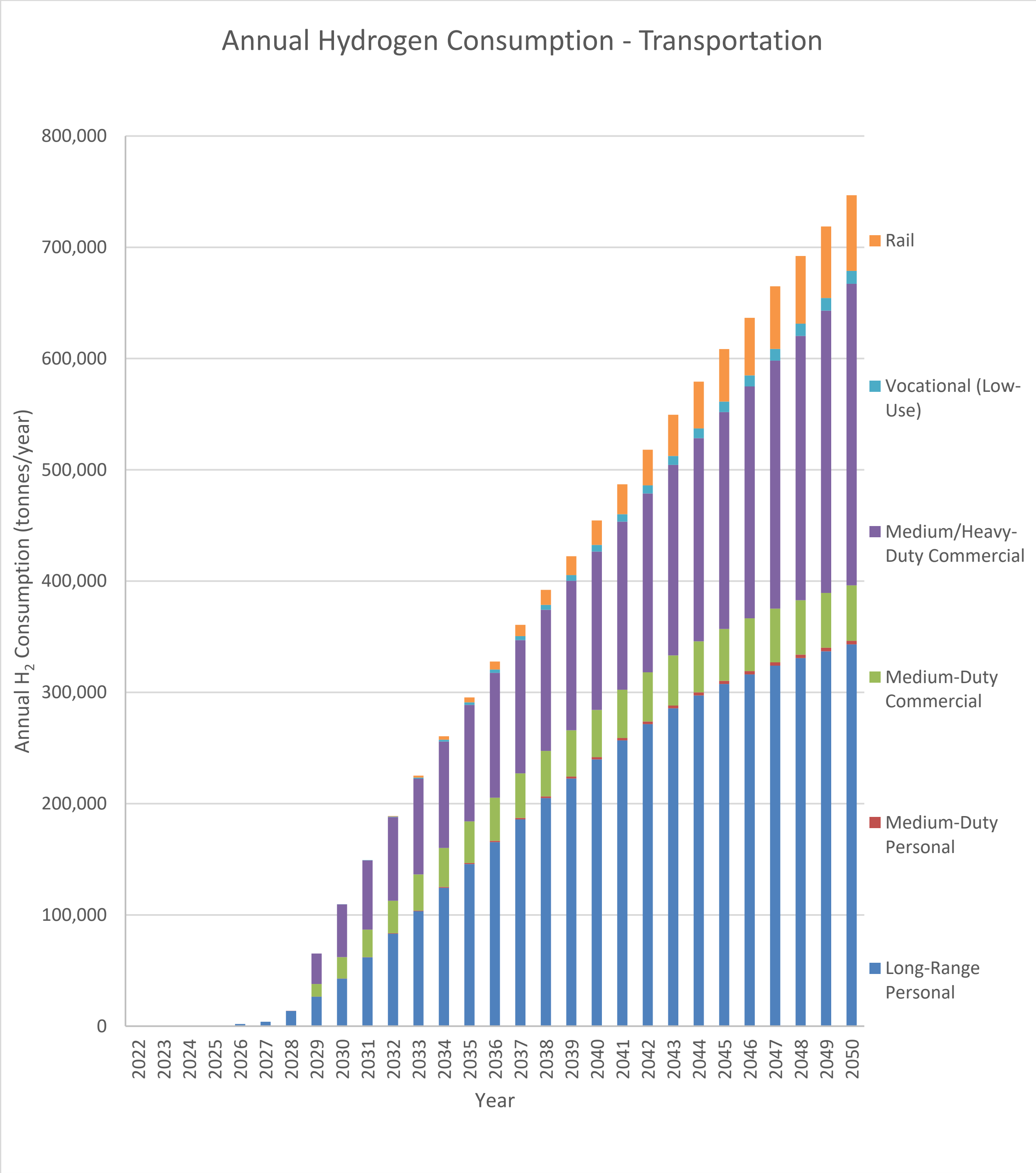


Figure 26: Projected Annual Hydrogen Consumption – Transportation

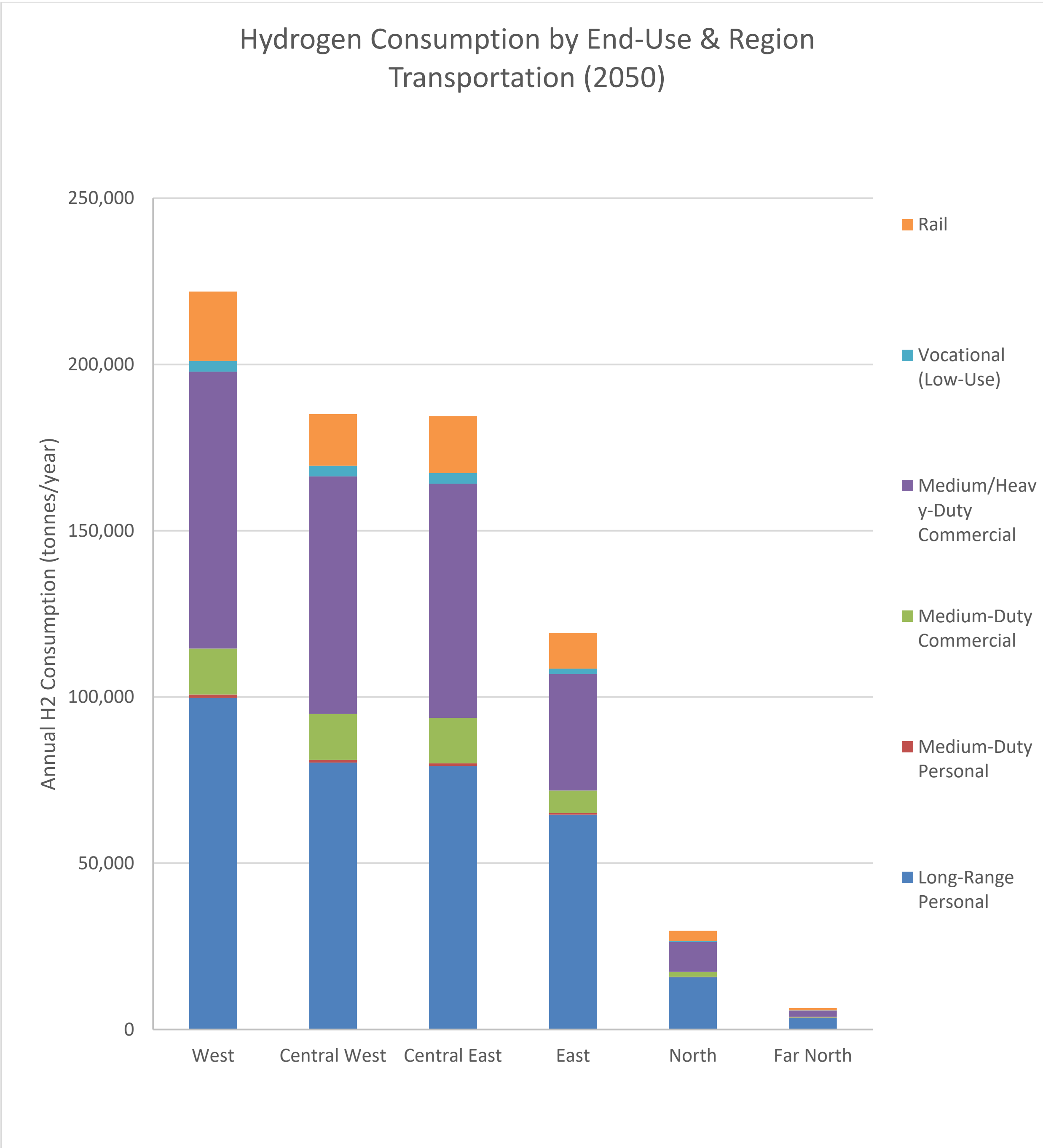


Figure 27: Projected Annual Hydrogen Consumption by End-Use & Region Transportation (in 2050)

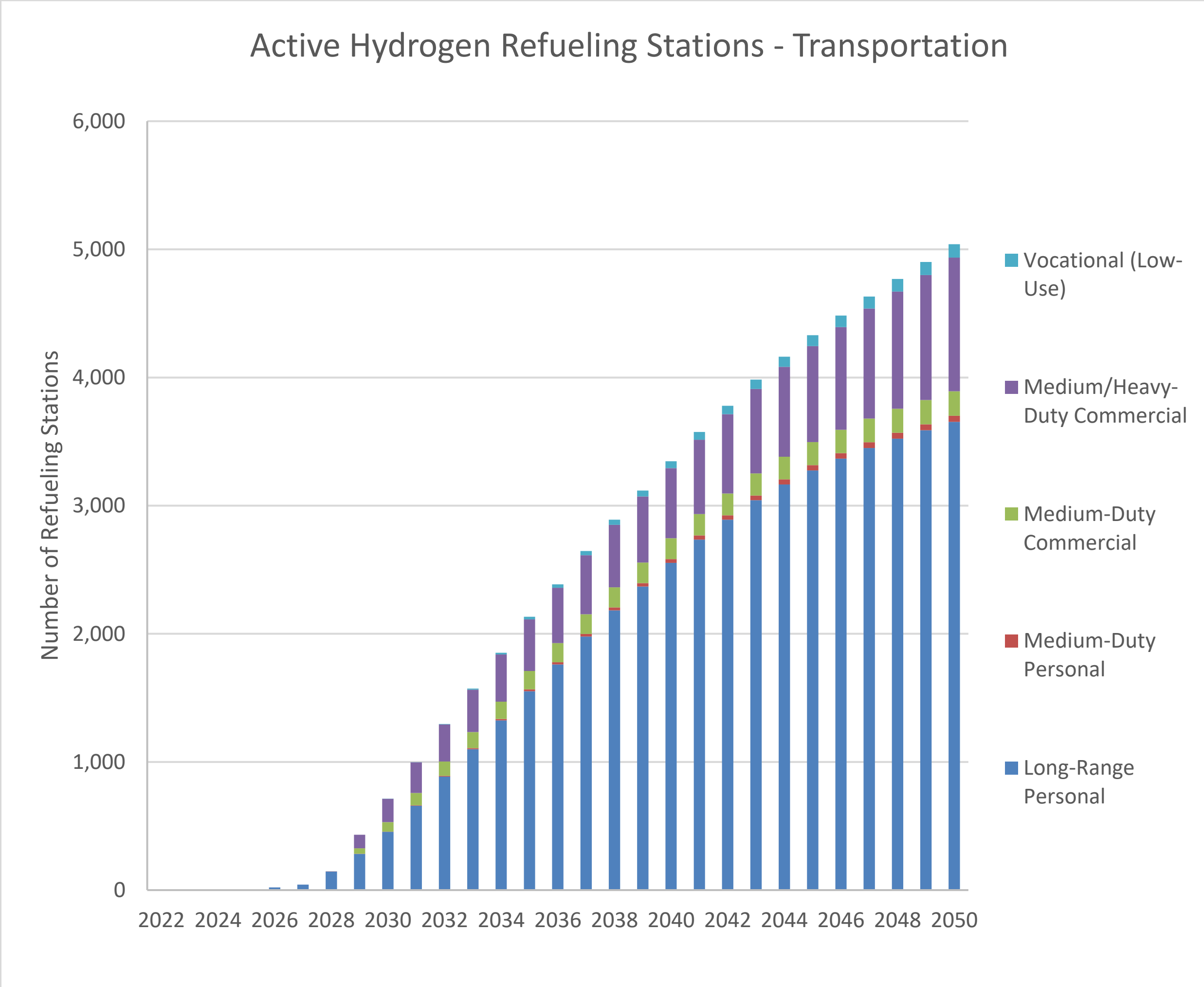


Figure 28: Number of Hydrogen Refueling Stations Required – Transportation

As evident in the above charts, low-carbon hydrogen as a transportation fuel grows to more than 700,000 tonnes annually by 2050. The long-range personal passenger vehicle application and medium- and heavy-duty vehicle applications make the largest contribution to this total. By the 2040s, locomotives in this scenario are making an out-sized contribution to hydrogen demand relative to the overall share of transportation energy use. The distribution of hydrogen applications appears fairly consistent in each of the administrative regions except for the Far North, where larger vehicles for personal use are more prevalent.

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Ontario Opportunity: hydrogen-fueled vehicles on-road and off-road

The Toyota Mirai is a hydrogen fuel cell-electric vehicle (FCEV) a zero-emission, **on-road personal passenger vehicle**. The 2022 model has an estimated driving range of nearly 650 km on a full fill of about 5.7 kilograms of hydrogen. Nearly 15,000 personal FCEVs have been sold or leased in the U.S. at the end of 2022, by automakers Toyota, Hyundai and Honda. Most of these vehicles are used in California, where 55 retail refueling stations make hydrogen available. A small number of FCEV are on the roads in British Columbia and Quebec, where a few stations have been established. [41] [39] [40]

Snowmobiles – a feature of life in northern and remote communities – are being trialed in Austria using hydrogen fuel cells instead gasoline combustion engines for all-electric propulsion. [42]

The CP Hydrogen Locomotive Program is deploying a series of **freight locomotives** into revenue service. These locomotives are powered exclusively by hydrogen fuel carried onboard, which is used by the fuel cells to generate electric traction power to haul trains. The first of these vehicles – a road switcher – was demonstrated in revenue service in Calgary in late-2022 [43].

5.4 Industrial Sector Applications

Many industrial processes can be decarbonized using hydrogen, either as an alternative to traditional, more carbon-intense fuels or as a material feedstock. The Base Case scenario uses the following industry sector applications, although a more refined array of end-uses can be defined and added:

- *Fuel for process heat* – The heat generated in the combustion of natural gas (and, occasionally, fuel oils or biomass) for various manufacturing processes can be provided through hydrogen combustion. Here, process heat is for manufacturing processes in Ontario that are *not* part of the following applications.
- *Steelmaking* – Coal is traditionally used to reduce iron ore (Fe_2O_3) into pure iron (i.e., Direct Reduced Iron, DRI), which is then used to make steel. Carbon from the coal bonds with the oxygen in the iron ore, releasing CO_2 to atmosphere. Hydrogen can also serve as a DRI agent, which eliminates the CO_2 emissions from the consumed coal, leaving only water emissions in its place. Heat from the combustion of hydrogen can also be used in parts of the steelmaking process to further displace coal and, in some cases, use of natural gas (e.g., integrated steel mill blast furnaces).
- *Cement manufacturing* – Cement plants are established around supplies of water and electricity, and the cement-making process also generates a significant amount of waste heat. These are resources that can power water electrolysis, which yields pure oxygen and hydrogen. The pure oxygen can be used in an oxy-fuel combustion process to generate additional heat that improves the efficacy of carbon capture from the plant flue gases, which can reduce the overall cost of decarbonizing cement production. Potentially, the use of pure oxygen instead of air (which is only one-fifth oxygen) for fuel combustion could also reduce the volume of gas flow through the system, further reducing cost of cement production. The hydrogen from electrolysis can be used to displace other fuels on-site, such as in diesel-using equipment, as well as vehicles that routinely visit the site, which contributes to the overall decarbonization of plant operations.
- *Petrochemical production* – Petrochemical refineries use a great deal of hydrogen in refining crude oil and other oil feedstocks into fuels and lubricants of the desired quality and volumes, including gasoline, diesel and aviation fuel. This hydrogen is usually produced via SMR, either in-situ or delivered. Access to less carbon-intense supplies of hydrogen can help reduce the carbon-intensity of the refining process and thus the finished fuels.
- *Ammonia and fertilizer production* – Ammonia (NH_3) is a key feedstock in fertilizer production. Hydrogen (usually produced via an SMR process) and nitrogen separated from air are reacted to form ammonia. Less carbon-intense supplies of hydrogen, such as electrolysis using low-carbon electricity or SMR+CCUS, can help decarbonize the fertilizer manufacturing process.
- Methanol and synthetic fuel production – A supply of low-carbon hydrogen can be combined with the carbon dioxide emitted at an industrial facility to form methanol (via a methanation process), or to synthesize a range of hydrocarbon fuels. Similarly, carbon dioxide extracted directly from the atmosphere (i.e., via Direct Air Capture systems) can be reacted with low-carbon hydrogen to produce synthetic fuels. Sustainable aviation fuel (SAF) is one such output, the market value of which may be high enough to justify

the cost of its production involving DAC. Conceptually, if the carbon dioxide released in the combustion of the synthetic liquid fuel is recovered from the atmosphere and re-used, then a net-zero carbon balance is achieved, and the fuel may be considered low-carbon.

- Other chemicals or materials production, and process feedstock – These is a wide range of chemical production processes that require hydrogen. Each of these would become inherently lower in carbon-intensity using low-carbon hydrogen. Hydrogen also serves:
  - as a hydrogenating agent in the food industry to produce saturated fats and oils;
  - in atomic hydrogen welding to weld refractory metals and tungsten;
  - in manufacturing hydrogen peroxide;
  - in place of Chlorofluorocarbon refrigerants for large electrical generators or for safety and lower environmental impact as a searching gas for leaks in manufacturing plants.
- *Portable power generation* – A smaller, lighter version of station electricity generators, portables generators can be easily moved to wherever electricity is needed, but no grid connections are available, such as during temporary events, power outages and disaster relief operations, or in the following important applications:
  - *in the motion picture industry* – A surprising number of diesel-fueled portable power generators are used to deliver on-site power during motion picture productions for cameras and recording equipment, lighting, trailers and other equipment. Production sets are usually active for a matter of days only, making it difficult to tap into local power services, even in urban environments. Hydrogen can displace diesel to reduce emissions and, if fuel cells are used, then power can be generated at very low noise levels, which is valued in this application.
  - *in the construction industry* – Most major construction projects rely on portable power generators for all manner of on-site equipment. Switching from diesel to low-carbon hydrogen can contribute to decarbonizing the construction industry.
- *Stationary electricity generation* – Remote communities that are not serviced with grid-supplied electricity, or only partly so, are often reliant on large diesel-fueled power generators. Hydrogen-fueled combustion engines or fuel cells can provide a low-carbon alternative, especially if local renewable power is used to produce the hydrogen. Stationary generators are also used to supply back-up power for critical facilities, such as hospitals and data centres.
- *Electricity storage* - This hydrogen is stored for future use as electricity and for grid management services. Additionally, electrolytic hydrogen is blended with natural gas for use in existing natural gas-fired electricity generators.

As in the transportation sector, each designated application in the Industrial sector is assigned a growth profile that the user defines by setting parameters for initial year of market entry, share of market uptake potential, year of market saturation, and rate of uptake *for each region*. For example, the application of low-carbon hydrogen to cement-making in the Central West administrative region was set to initialize in 2029, achieve peak market share of 50 per cent shortly after 2050, and follow a fast growth curve.

The parameters selected in the Base Case scenario were based on the population, active industries and resources available in each administrative region. Consistent with conservative assumption, the scenario limits uptake of hydrogen to not more than 50 per cent in any industrial application and only where relevant opportunities are known to exist. As recommended elsewhere in this report, a series of consultative workshops should be held with experts and stakeholders to refine the assumptions and model parameters in each application to deliver more precision in the model's projections of different scenarios.

Selected output calculations of the hydrogen consumption module are presented in the figures Figure 29 and Figure 30 below, respectively representing the demand for low-carbon hydrogen in each industrial sector application by year to 2050, and by administrative region in 2050.

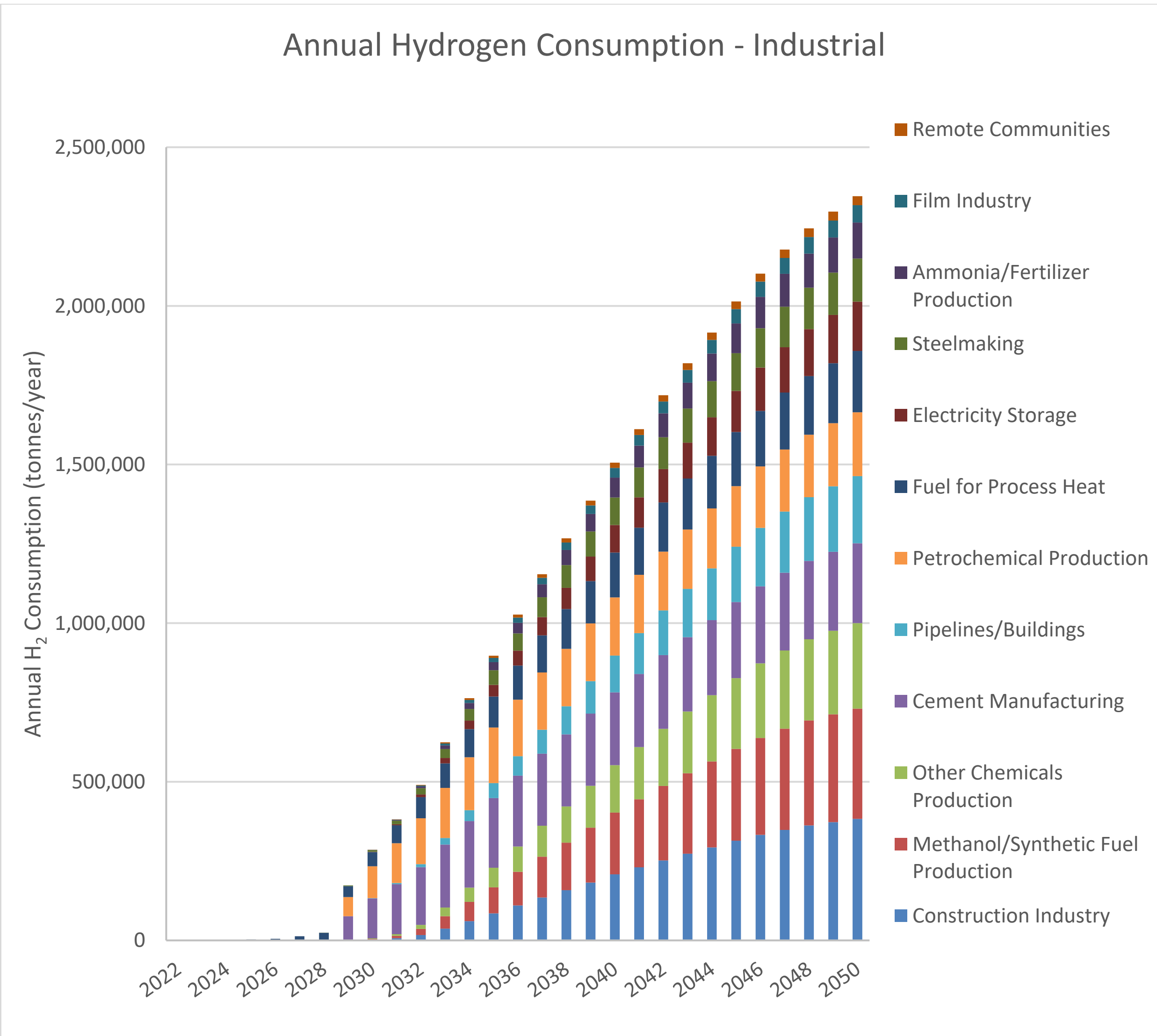


Figure 29: Annual Hydrogen Consumption by End-Use – Industrial

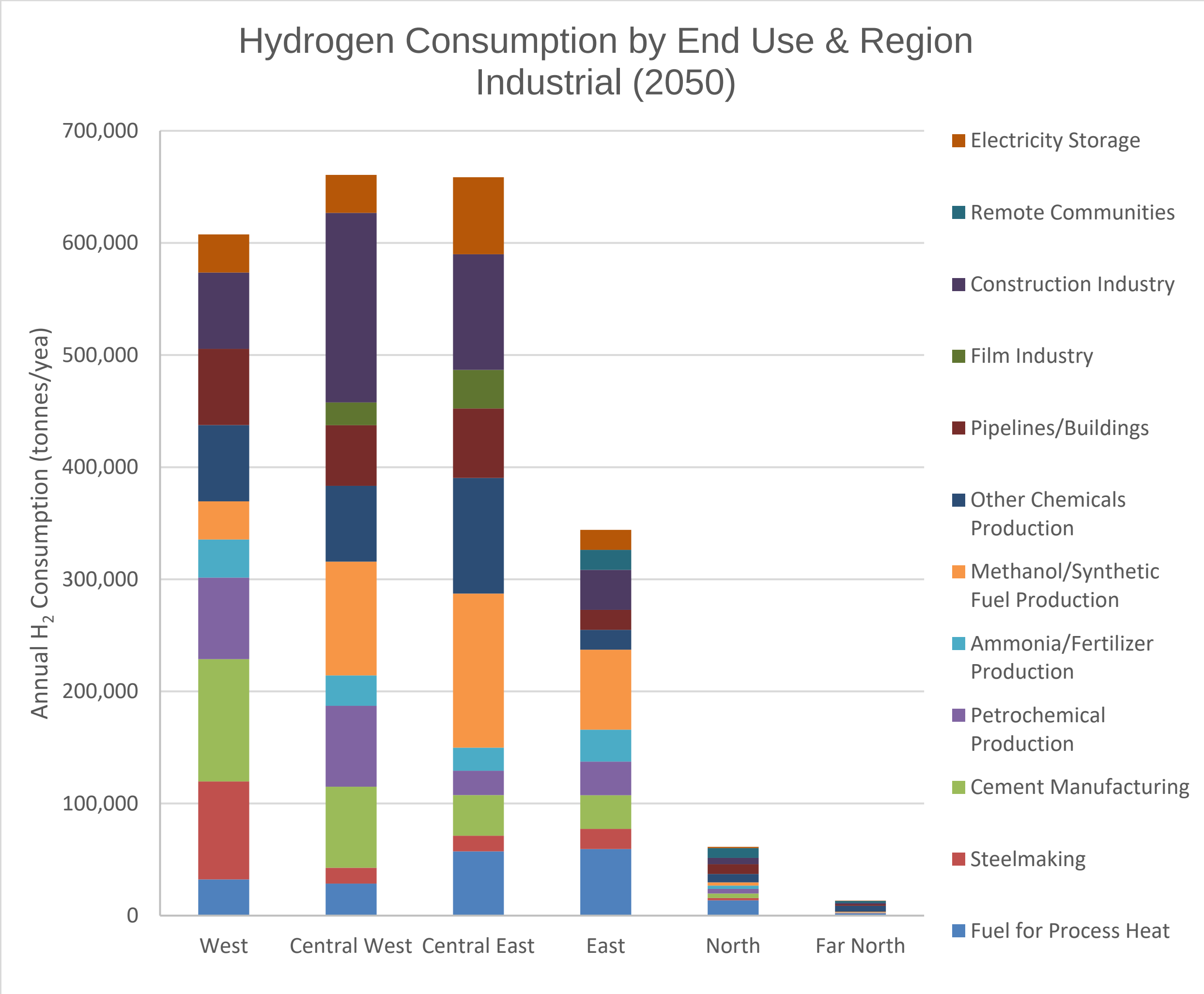


Figure 30: Annual Hydrogen Consumption by End-Use & Region – Industrial (in 2050)

The charts show that low-carbon hydrogen use at industrial and alternative application sites throughout Ontario grows to roughly 2,300,000 tonnes annually. Exclusively industrial applications make up about 1,500,000 tonnes of the 2,300,000 tonnes annually by 2050. In this projection, a comparatively even distribution of hydrogen across different types of manufacturing processes occurs. Cement and petrochemical producers are the earliest adopters of low-carbon hydrogen, with steelmaking, synthetic fuels and hydrogen for industrial process heat driving most of the growth from the mid-2030s onward. The regional breakdown for industrial sector hydrogen applications is similar even compared to the transportation sector, as each region has a distinct cluster of industrial activity.

According to these Base Case projections, at least twice as much hydrogen could be consumed in industrial applications than in transportation in Ontario. It is important to note these charts refer to private industrial pipelines and buildings applications. The next section will break down residential and commercial hydrogen demand.

Ontario Opportunity: hydrogen-fueled combined space and water heating

Gradient Thermal, a manufacturer of furnaces and boilers based in Calgary, recently received support from the Natural Gas Innovation Fund for the development of its new H2 syncFURNACE™, a combined furnace and water heater fueled by pure hydrogen. Ideally suited for homes and small commercial building spaces, hydrogen-ready space and water heating appliances and equipment can support a transition to low-carbon heating fuel. Some equipment may suitable for blends of hydrogen in natural gas, which could enable a smooth transition to non-fossil space and water heating [44].

Ontario Opportunity: Greening motion picture productions with hydrogen portable power

"Hollywood North" is big business in Ontario. Film and TV productions are a common sight on the streets of our cities, parks and shorelines. But the recording equipment and trailers require power, which is supplied by diesel-fueled portable power generators. Suppose these generators used fuel cells instead to supply power – quietly and free of emissions – fueled with hydrogen that is delivered on-site? This would enable studios to eliminate a major contributor to the industry's carbon footprint, while providing another attractive reason to produce content in Ontario. Recently, this concept has been trialed in Motion Picture sets in France, proving the feasibility of the concept [45].

5.5 Buildings and Facilities

Low-carbon hydrogen can serve as an alternative fuel for space heating in buildings, thereby displacing the combustion of fossil fuels and integrating into efficient, multicyclic thermal systems. Additionally, hydrogen can be used in systems of power generation and to store electricity. The Base Case scenario includes the following hydrogen applications in the buildings and facilities sector.

- *Pipeline blending* – Hydrogen can be blended into natural gas and transported in natural pipelines without the need for retrofits so long as the blend rate is moderate (e.g., not exceeding 15 per cent [22]). Beyond a moderate blend level, pipeline systems may require changes to tolerate hydrogen-material interactions. Hydrogen blended into natural gas enables some of the end-use application potential in the Base Case.
- *Residential buildings* – Displacing natural gas with low-carbon hydrogen as a fuel burned in residential furnaces can help to decarbonize home heating. Notably, natural gas can be used with very high efficiency and is among the least carbon-intense fossil fuels. Displacing it with hydrogen is technically feasible, but yields less reduction in GHG emissions than, say, diesel fuel.
- *Commercial buildings* – Hydrogen can be used in place of fossil fuel-fired furnaces and boilers for commercial building heating systems.

The parameters of market entry and growth are set following the same methods described previously for the transportation and industrial sector applications. For example, the residential buildings application enters the market in 2030 and by 2050 achieves a maximum market share of 10 per cent and follows a slow growth profile. This is to simulate the effect of a 10 per cent blending of low-carbon hydrogen in natural gas and combusted in home furnaces.

Selected output calculations of the hydrogen consumption module are presented in Figure 31 and Figure 32 below, respectively representing the demand for low-carbon hydrogen in each buildings & facilities sector application by year to 2050, and by administrative region in 2050.

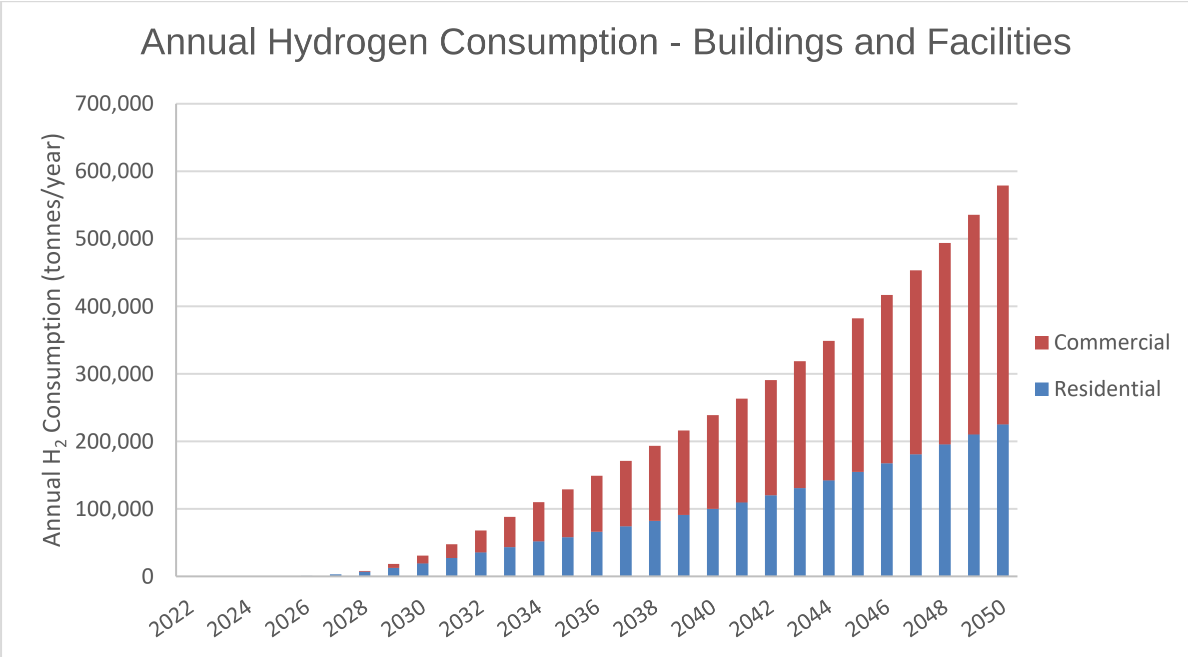


Figure 31: Annual Hydrogen Consumption – Buildings and Facilities

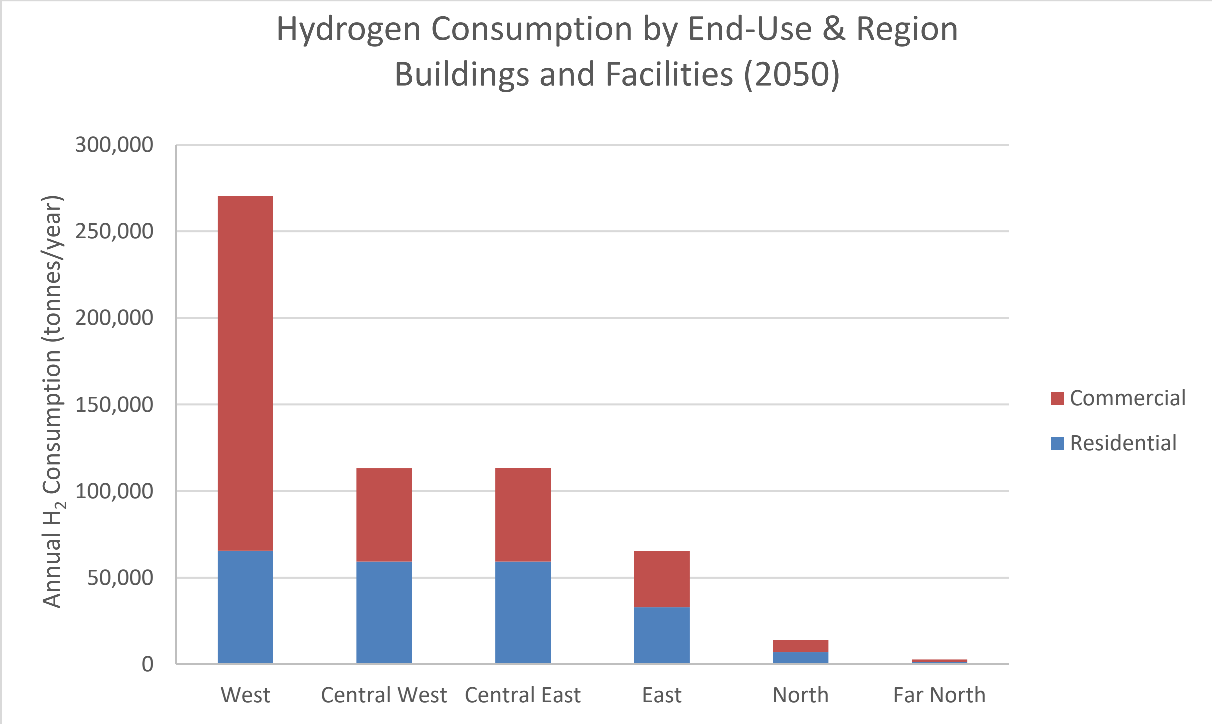


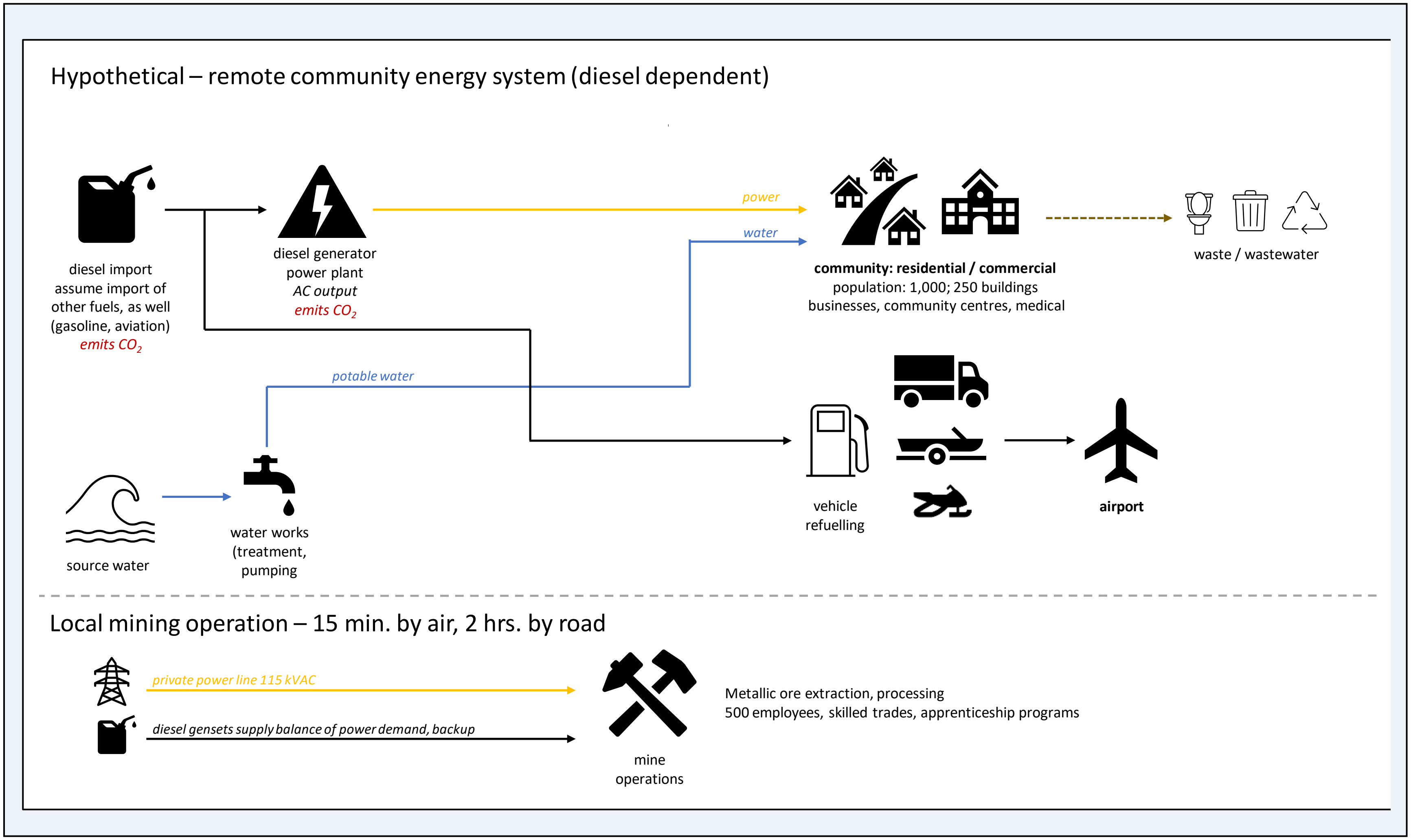
Figure 32: Annual Hydrogen Consumption – Buildings & Facilities (in 2050)

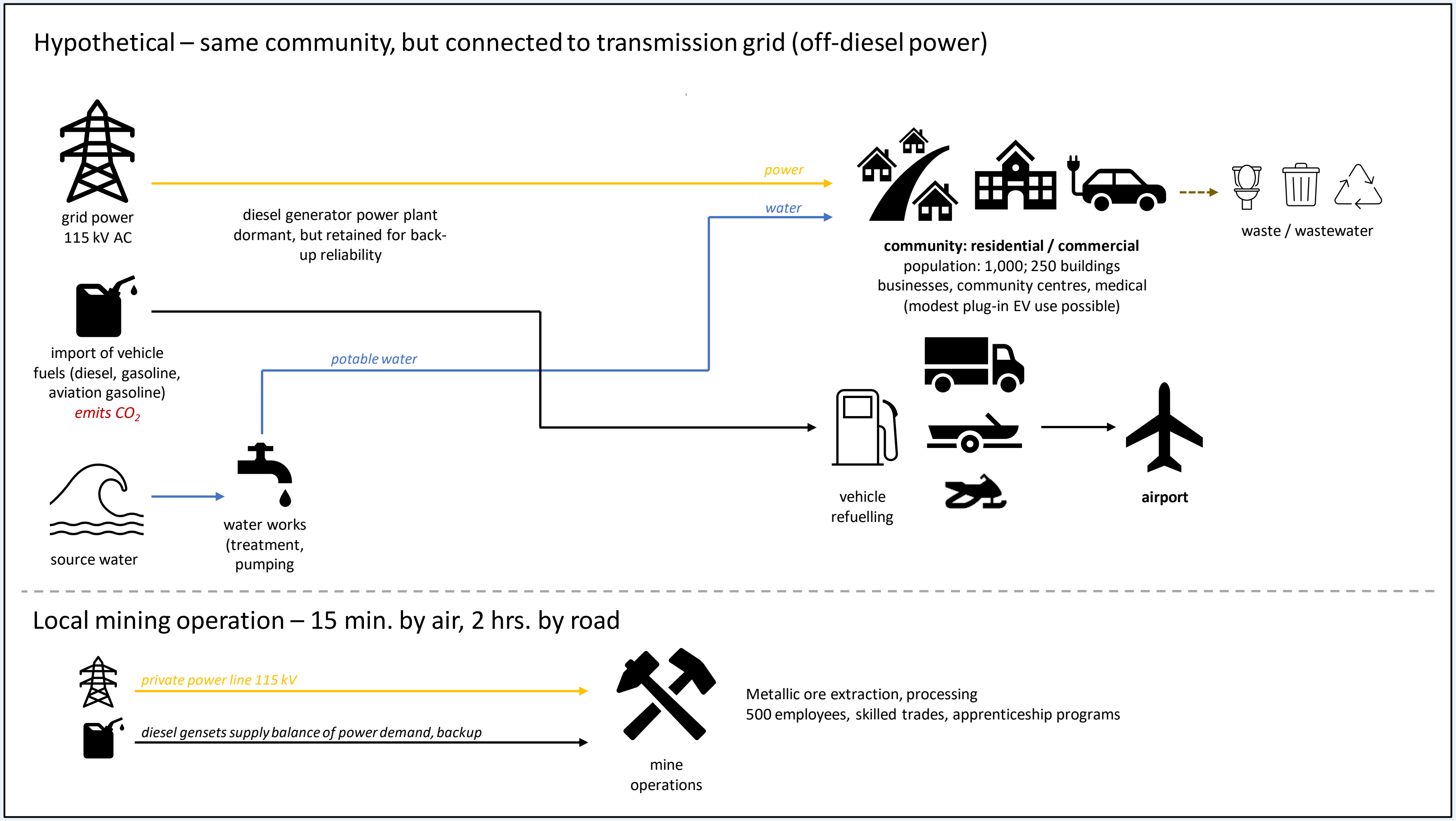
Uptake of low-carbon hydrogen by application varies significantly across the administrative regions of the province. This is mainly due to residential and commercial spaces being a function of population.

Ontario Opportunity: hydrogen energy independence in remote and Indigenous communities

Remote and Indigenous communities that are isolated from power transmission grid, pipeline and highway infrastructure (or partly so) are often reliant on imports of diesel to fuel power generators for electrical loads, such as lighting, space heating and electronics. Delivering fuel to these communities is expensive, creating economic burden, and limits options to improve energy prosperity. In some instances, hydrogen produced using local energy resources can yield new opportunities for remote communities to reduce reliance on diesel, as well as commercial development.

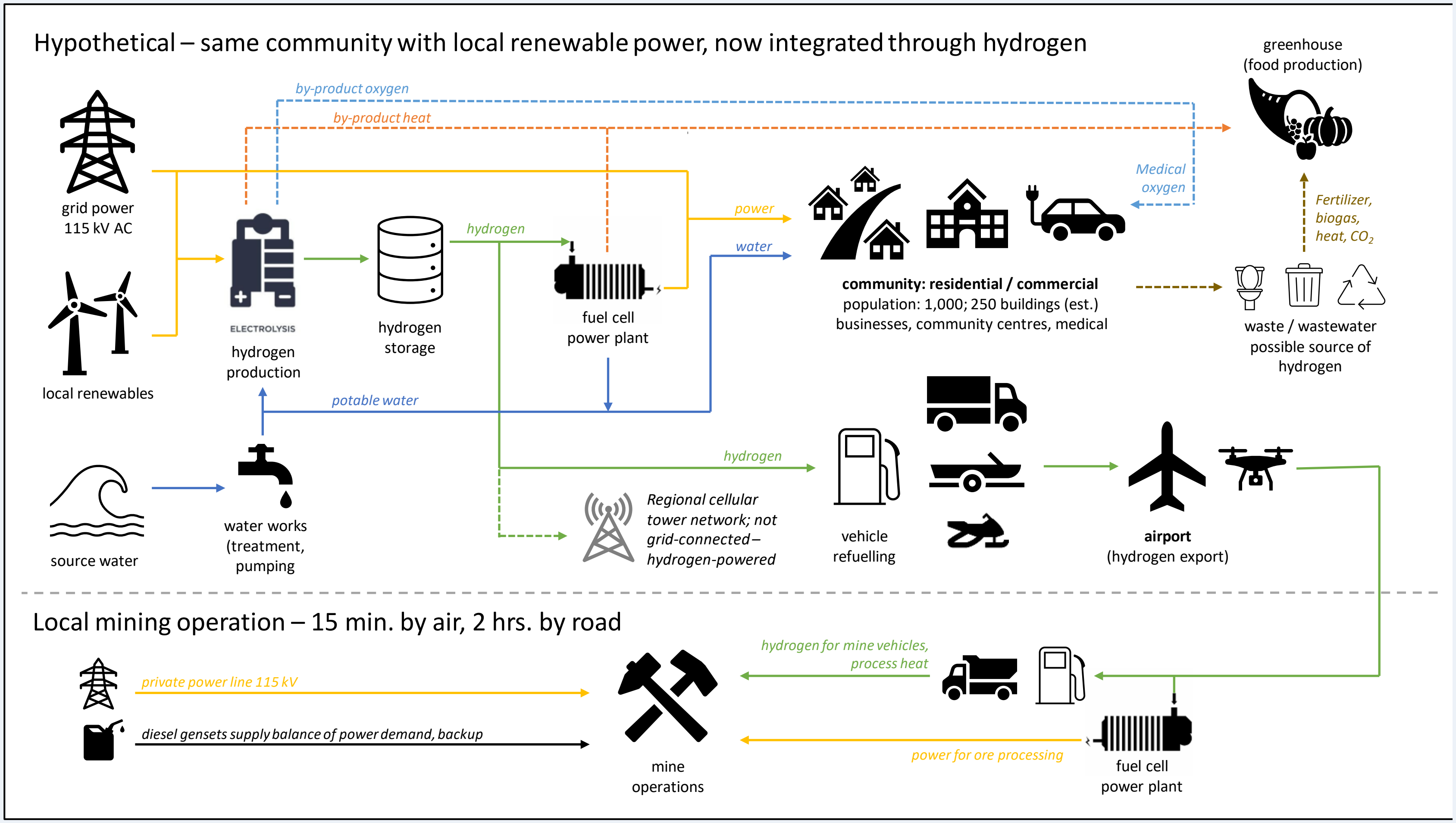
Consider the following example as a hypothetical First Nations community, having a population of approximately 1,000 individuals and a small airfield. The community is wholly reliant on diesel as its source of energy, which it must import (along with fresh produce). However, there is potential for renewable power generation, and a new transmission line is planned to connect the community to the regional grid. This is a welcome development, but the diesel power plant remains on back-up duty when grid power is interrupted. There is also a mine nearby, which is a source of employment for the community. Below is representation of the main energy and material flows through the community; first as it is, and then how it would be after becoming grid-connected.


Hypothetical – remote community energy system (diesel dependent)
diesel import
assume import of other fuels, as well (gasoline, aviation)
emits CO_2
diesel generator power plant
AC output
emits CO_2
power
water
community: residential / commercial
population: 1,000; 250 buildings
businesses, community centres, medical
waste / wastewater
potable water
source water
water works (treatment, pumping
vehicle refuelling
airport
Local mining operation – 15 min. by air, 2 hrs. by road
private power line 115 kVAC
diesel gensets supply balance of power demand, backup
mine operations
Metallic ore extraction, processing
500 employees, skilled trades, apprenticeship programs



This First Nations community is now much less reliant on diesel, but it still requires fuel imports for vehicles and airfield operations. How might the picture change with the incorporation of hydrogen systems?

The introduction of hydrogen production on-site changes the picture significantly. It enables maximum productivity of local renewable power resources, supplements grid power and enables a transition to hydrogen-powered vehicles. By-product heat and oxygen from the hydrogen plant can serve local greenhouse and medical needs. Importantly, the community can over-produce hydrogen and deliver the surplus to the local mine (potentially by air), where it can help to green their operations, and reduce their reliance on diesel, too, as illustrated below. Note also the use of hydrogen to power local cellular transmission towers, which are not grid-connected, enabling greater connectivity and data bandwidth for the community.



5.6 All Sector Applications Combined – Low-Carbon Hydrogen Consumption

The charts below consolidate the sector-specific hydrogen consumption projections produced by the model, with transportation, industrial and buildings & facilities, combined. The first shows the growth in total hydrogen consumption by region to 2050. Next the breakdown of sector applications by region is shown in the year 2050. Lastly, growth is shown again but broken out by sector.

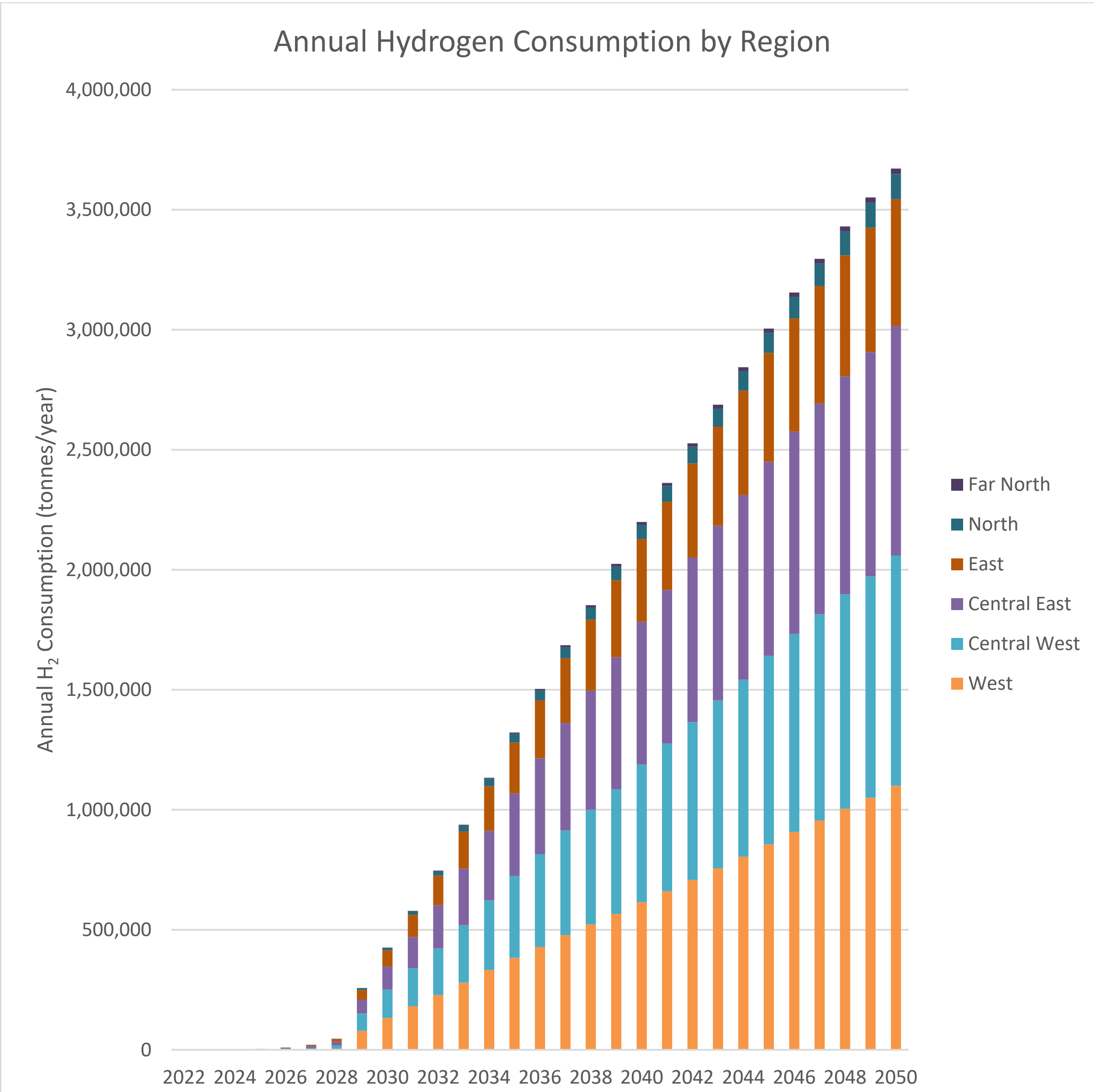


Figure 33: Ontario Annual Hydrogen Consumption by Region

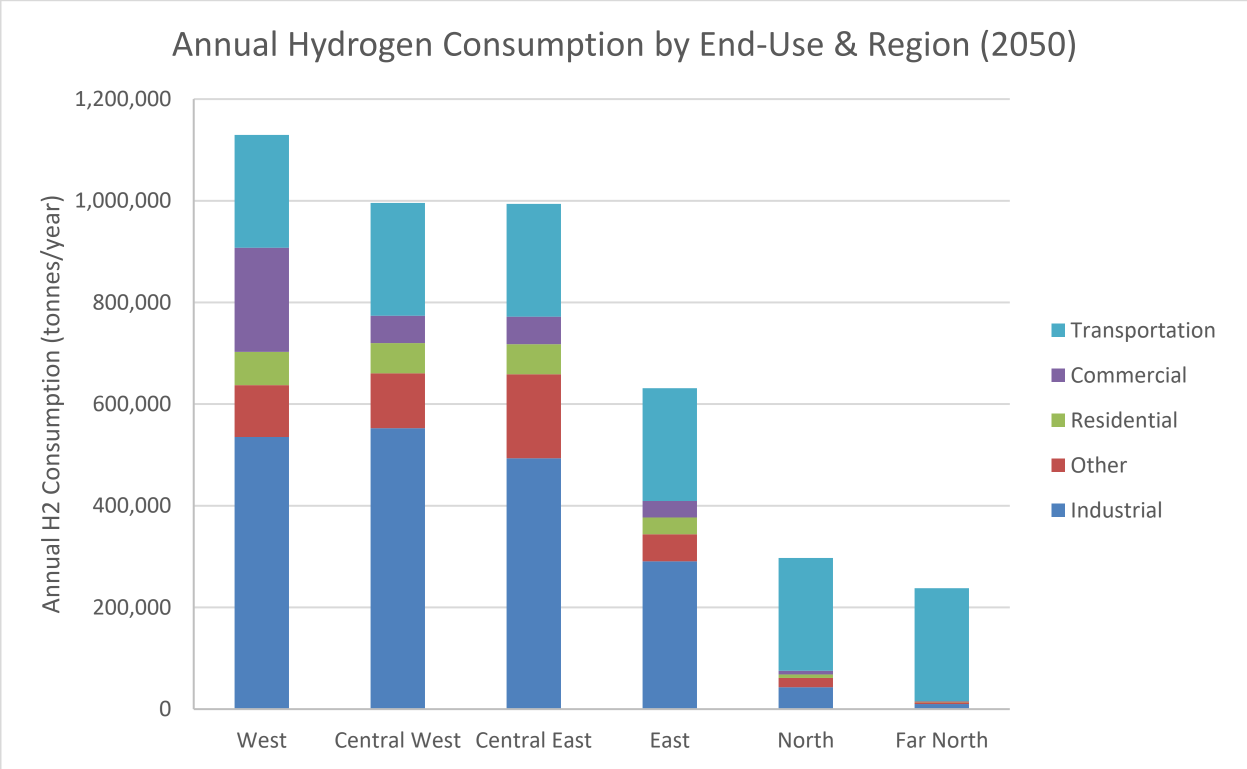


Figure 34: Ontario Annual Hydrogen Consumption by End-Use & Region 2050

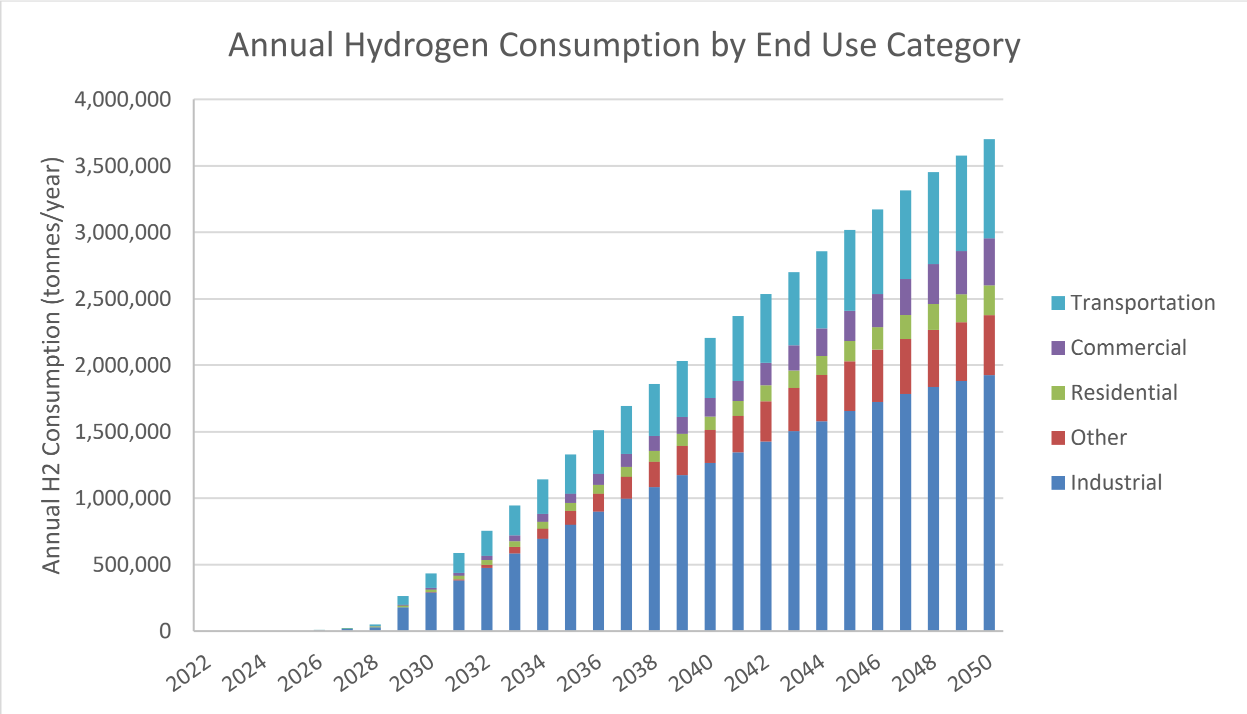


Figure 35: Ontario Annual Hydrogen Consumption by End-Use

6.0 HYDROGEN DELIVERY

The H2GrO-TEA Model's Hydrogen Delivery module knits together the Production and Demand modules, using the outputs of each to calculate the amount of hydrogen needing to be transported from the various points of production to the markets where hydrogen is consumed. It also computes the modes and costs of delivery by administrative region (defined in Section 3 relating to the regional scan), based on the identified transportation corridors shown in Figure 36, which includes highway, railway and pipeline networks. This map was developed for this study and for the companion report by H2GO Canada, *Scoping the Commercial Potential for Carbon Capture, Utilization and Storage and Hydrogen Storage in Ontario to 2035*. Two information layers of this map are shown in Figure 36 and Figure 37 further below, respectively highlighting the transportation modal corridors in Ontario and the locations of the identified hydrogen markets.

The Hydrogen Delivery Module works the data it receives in the following ways.

1) The distances between each hydrogen market and hydrogen production site are input to a master table, representing the Base Case scenario. More locations can be added by users, but the distances must be recalculated and added to the master table, accordingly. The distances are then ranked by proximity, such that hydrogen produced can be directed to the closest markets first.
2) In the Base Case, it is assumed that hydrogen produced at specific sites is not entirely consumed in the closest market. Rather, some of that hydrogen arrives in other markets nearby. This is to simulate the costs of hydrogen transport as they are more likely to occur in a dynamic, competitive marketplace. The module is set such that 50 per cent of hydrogen produced is received at the closest market, geographically, 30 per cent in the second closest and 20 per cent to the third closest. To simulate different scenarios, the user can set different distribution patterns.
3) The hydrogen demand in each market is an output of the hydrogen consumption module. The difference between the hydrogen volume delivered to a market and that market's total hydrogen demand is calculated to determine (1) if there is hydrogen available for broader distribution, and (2) if additional hydrogen must be brought in from more distant production sites.
4) The volume of hydrogen that is delivered to market is assigned a method of delivery based on quantity and distance between the production site and market. In the Base Case, the following parameters were used.
    a. <u>Speciality</u> delivery methods are assumed if the volume delivered is less than 10 kg/day *and* the delivery distance is less than 50 km. The methods encompass a wide range of boutique delivery solutions tailored to the needs of the application.
    b. Delivery by <u>truck-and-tube trailer</u> is assumed if the volume ranges from 10 kg/day to less than 10,000 kg/day (roughly equating to a maximum of 10 truckloads) *and* if the distance is less than 200 km. Tube trailers are a common means of hydrogen transport, as well as other gases.
    c. Delivery by <u>railway (tank car)</u> is assumed if the delivery volume is greater than 10,000 kg/day but less than 1,500,000 kg (based on an assumption of 15,000 kg per tank car, up to a maximum of 100 tank cars per day).

   d. Delivery by pipeline if delivered volumes exceed the 100 tank car railway capacity.

5) A delivery cost is applied to the volume of hydrogen delivered, using a factor for the mode of delivery used.
6) The above steps are repeated for each administrative region and for every five-year increment starting in 2025 to 2050. Prior to 2025, the amount of low-carbon hydrogen produced and delivered over longer distances is expected to be insignificant at a provincial scale. Between the five-year increments, the delivery costs are estimated by interpolation.
7) For each year, the module calculates the cumulative difference between the amount of hydrogen produced and the amount of hydrogen consumed across all markets. This allows the overall amount hydrogen available for export from the province to be determined or, depending on the scenario, the hydrogen import requirements needed to meet overall provincial demand. Respectively, the module then calculates a total hydrogen import delivery cost or a hydrogen export-generated revenue estimate.

The location of administrative centres for First Nations lands are represented in companion report and in Figure 37 below. Métis Nation of Ontario Community Councils have offices in many cities and towns. A full list of all administrative offices can be found in Appendix 1 of *Scoping the Commercial Potential for Carbon Capture, Utilization and Storage and Hydrogen Storage in Ontario to 2035* by H2GO Canada.

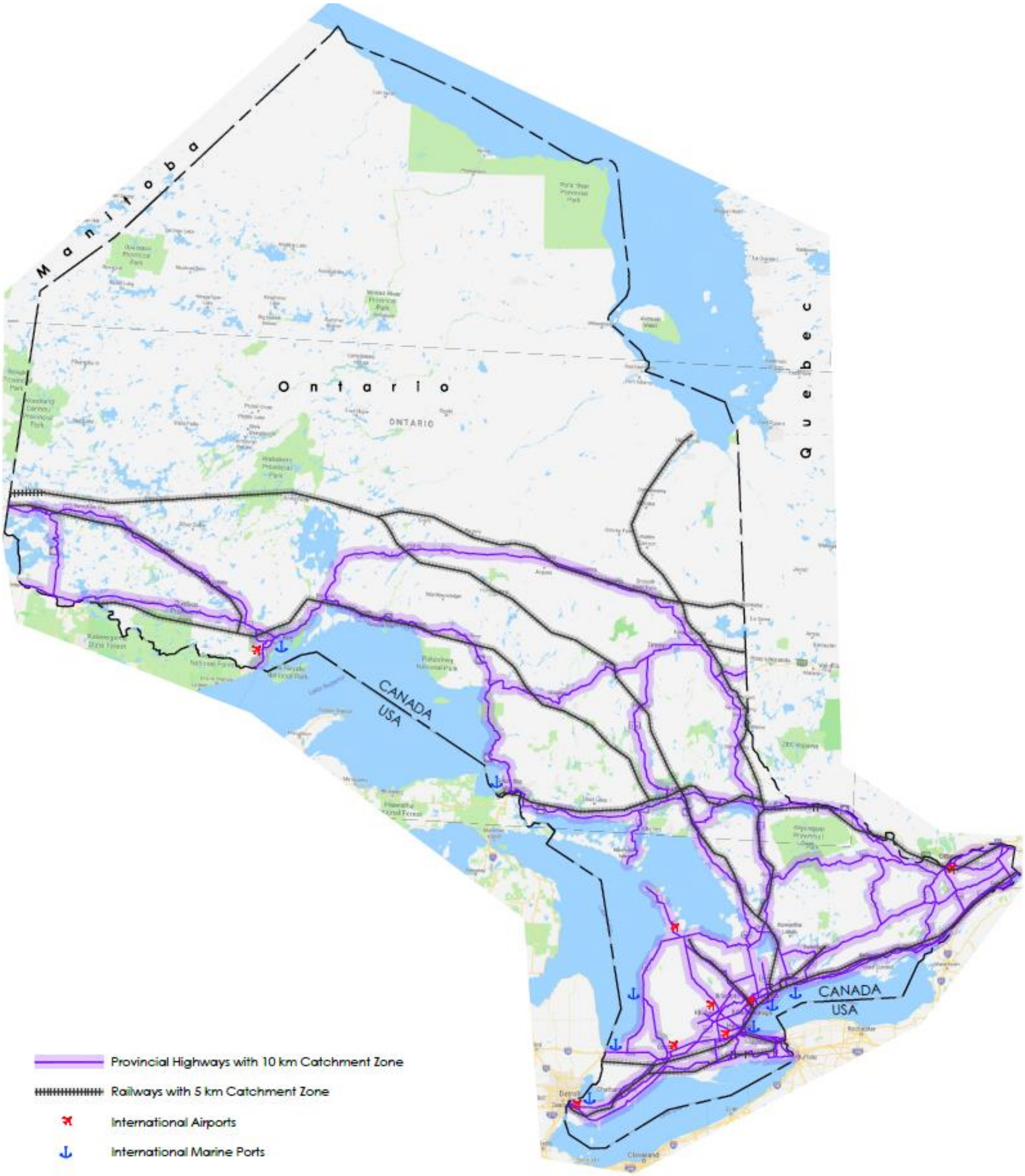


Figure 36: Ontario Transportation Corridors
Source: Adapted from Government of Ontario [23], Railway Association of Canada [24]

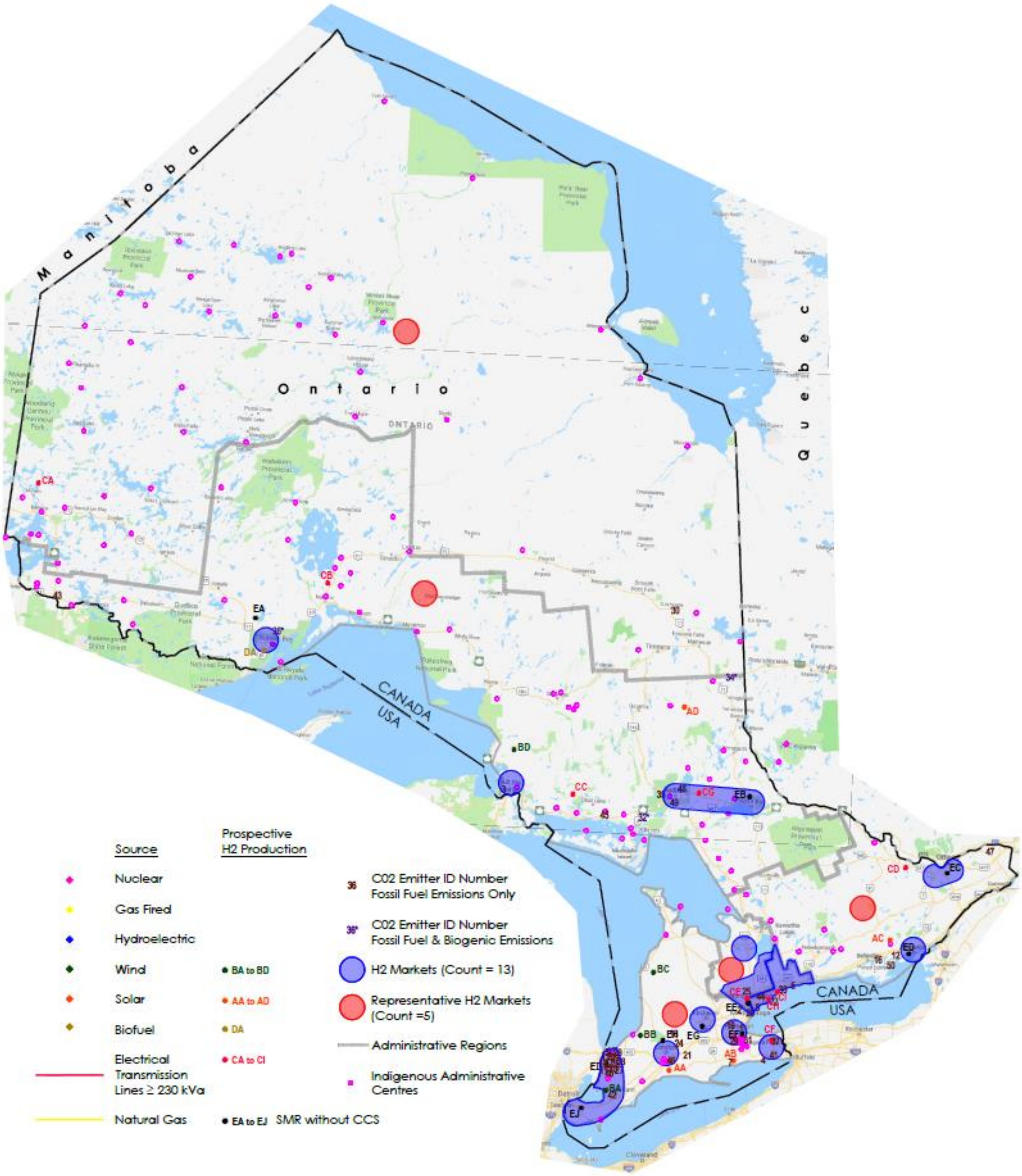


Figure 37: H_2 Market Hubs, CCUS Intersections, and Indigenous Administrative Centers
Source: Adapted from Government of Ontario [5], IESO [18], Canada Energy Regulator [19], OEB [20], Indigenous Services Canada [25], Hughes [26]

7.0 HYDROGEN ECOSYSTEM

H2GrO-TEA Model's Hydrogen Ecosystem module receives output data from the Hydrogen Production, Consumption and Delivery modules. These data are used to calculate total hydrogen system capital costs and operating costs, which includes facility construction, feedstock delivery, labour and maintenance, as well as supporting infrastructure. It also deducts the value of fuel avoided (displaced by hydrogen) to yield a more holistic estimate of net costs for the benefits generated. The benefits calculated in the module include GHG emissions associated with hydrogen production *and* the emissions reductions resulting from use of that hydrogen, yielding a net change. Also included are estimates of new jobs derived from the construction of the hydrogen system and its ongoing operation and maintenance.

These outputs help to paint a bigger picture of how hydrogen systems and markets might evolve in Ontario over the next few decades, and the potential impacts and implications. The module also normalizes the outputs to variables of interest. For example, costs can be presented as a function hydrogen flows or GHG emissions reductions, in a levelized manner. Analyzing the outputs in this way facilitates comparison of different scenarios. What if? scenarios, in which certain outcomes are held constant to see how inputs would have to change, are also possible. Examining how these metrics change as the inputs are modified, allows the model user to discover and quantitatively evaluate Ontario's hydrogen challenges and opportunities.

The following subsections present some outputs of the Hydrogen Ecosystem module under the Base Case scenario, and explore some scenario-play options to illustrate how the H2GrO-TEA Model can be used.

7.1 Cost of Hydrogen Delivered to End-Use Applications

The H2GrO-TEA Model's Hydrogen Ecosystem module generates four key outputs used in calculating the total levelized cost of hydrogen:

- capital cost of all hydrogen production and supporting infrastructure;
- maintenance cost of all hydrogen production facilities;
- operating costs for all hydrogen production facilities; and
- cost of delivering hydrogen to market, including hydrogen imported from outside the province to meet market demand.

Cost factors are sourced mainly from Change Energy's proprietary database, with cost factors that represent real, current market pricing. Additional factors were sourced from peer reviewed and published studies.

The figure below illustrates the timing of the capital outlays needed to support the production and distribution of hydrogen forecasted in the Base Case. The model times the construction of low-carbon hydrogen production facilities and distribution systems to occur in advance of a rise in market demand. This is to ensure that capital equipment does not sit idle awaiting for hydrogen throughput to increase. At the same time, facilities and infrastructure are built in large increments. For example, roads and hospitals are built to accommodate a future level of use – not the current level of demand. As demand saturates the capacity, the systems are expanded to higher levels of throughput (i.e., a new lane is added to a highway, or a new wing to a hospital).

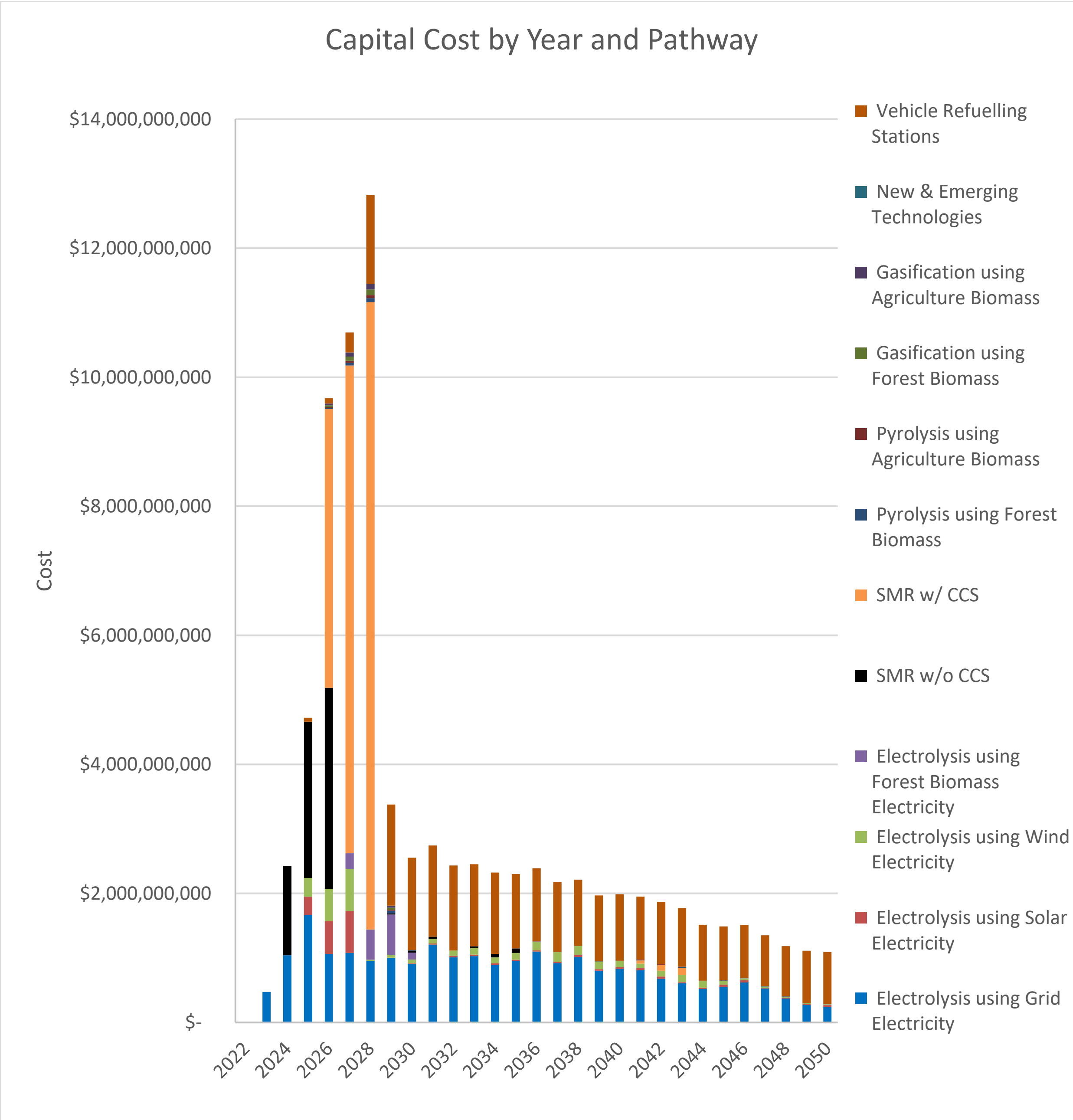


Figure 38: Capital Cost by Year and Pathway

The model optimizes for efficiency of system build-out but is realistically constrained by increments that are practical. Distribution will be supported by over-the-road delivery until the growth in volume approaches a threshold that supports pipeline construction. Prior to this point, the model will trigger the required investment. The result is an estimate for annual capital costs characterized by many peaks and valleys.

In summary, cumulative expenditures to 2050 in the Base Case sum to:

- capital costs including refueling infrastructure: $85,192,092,891
- maintenance costs: $22,799,260,036
- operating costs: $77,606,841,951
- delivery costs within Ontario: $1,348,282,035
- hydrogen import cost: $406,245,838,178

The following charts visualize the breakdown of expenditures by administrative region, by accumulation and by hydrogen production pathway. These are provided as examples of how the model outputs can be used to focus on different aspects of hydrogen scenarios.

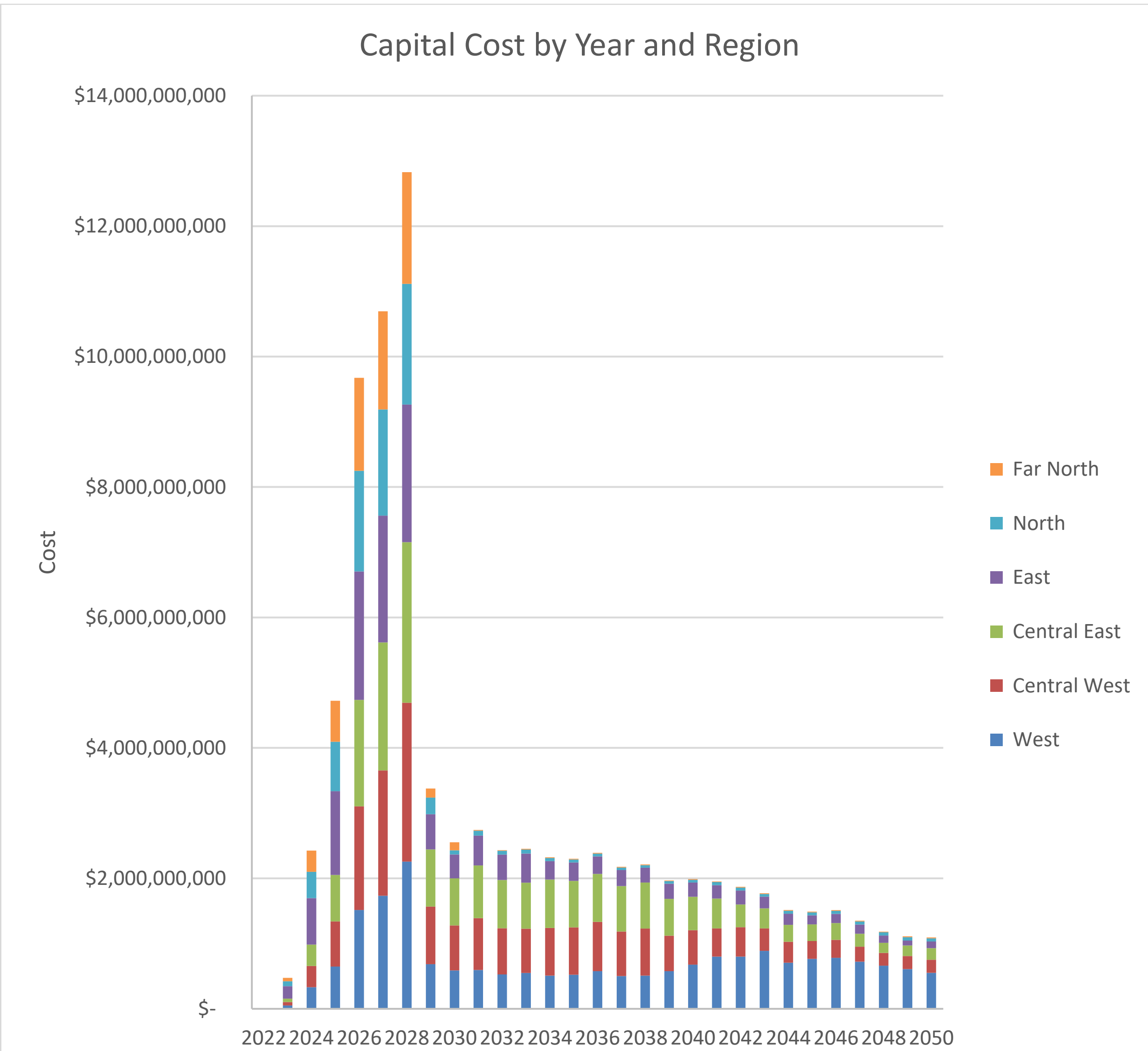


Figure 39: Capital Cost by Year and Region

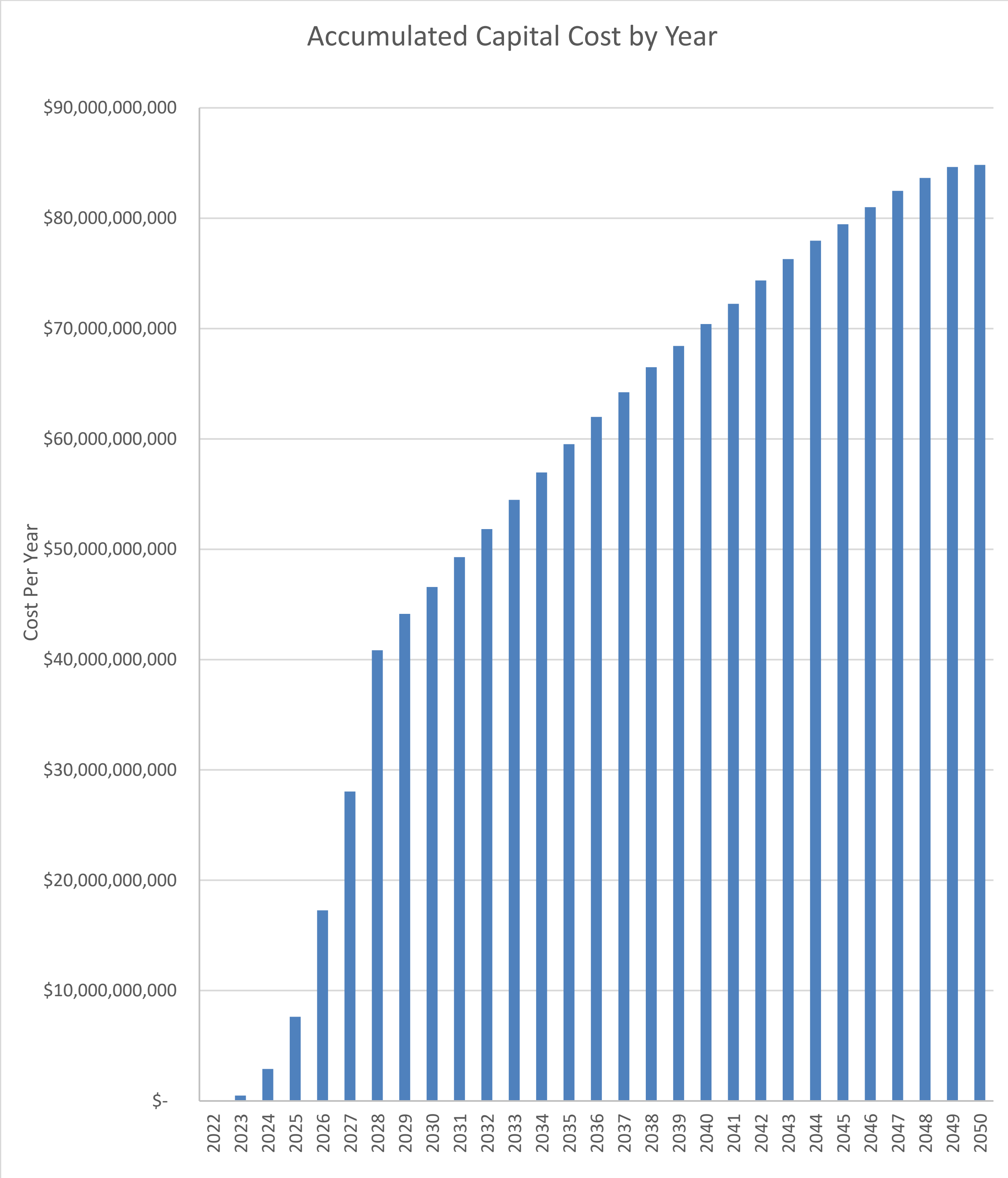


Figure 40: Accumulated Capital Cost

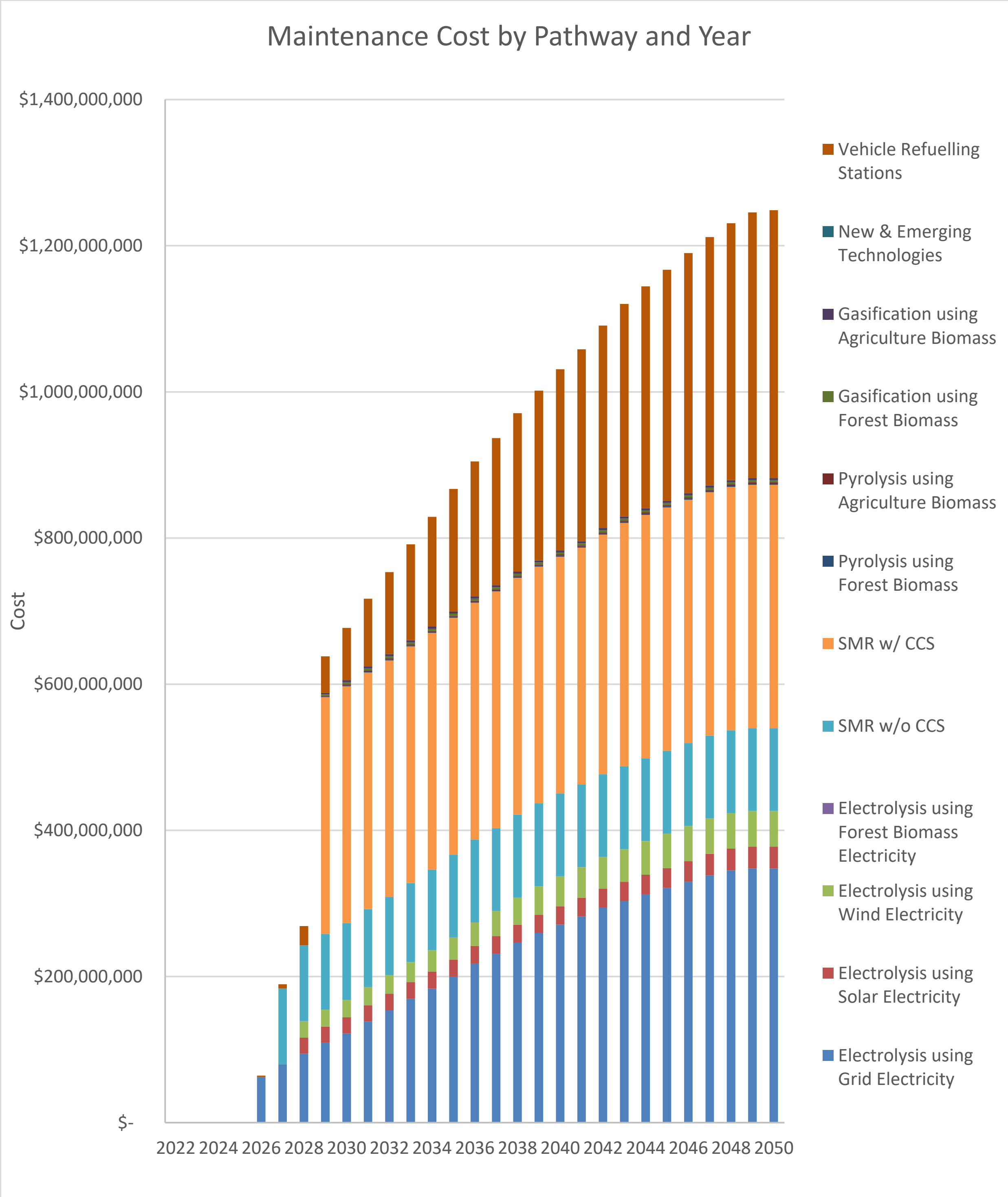


Figure 41: Maintenance Cost by Pathway and Year

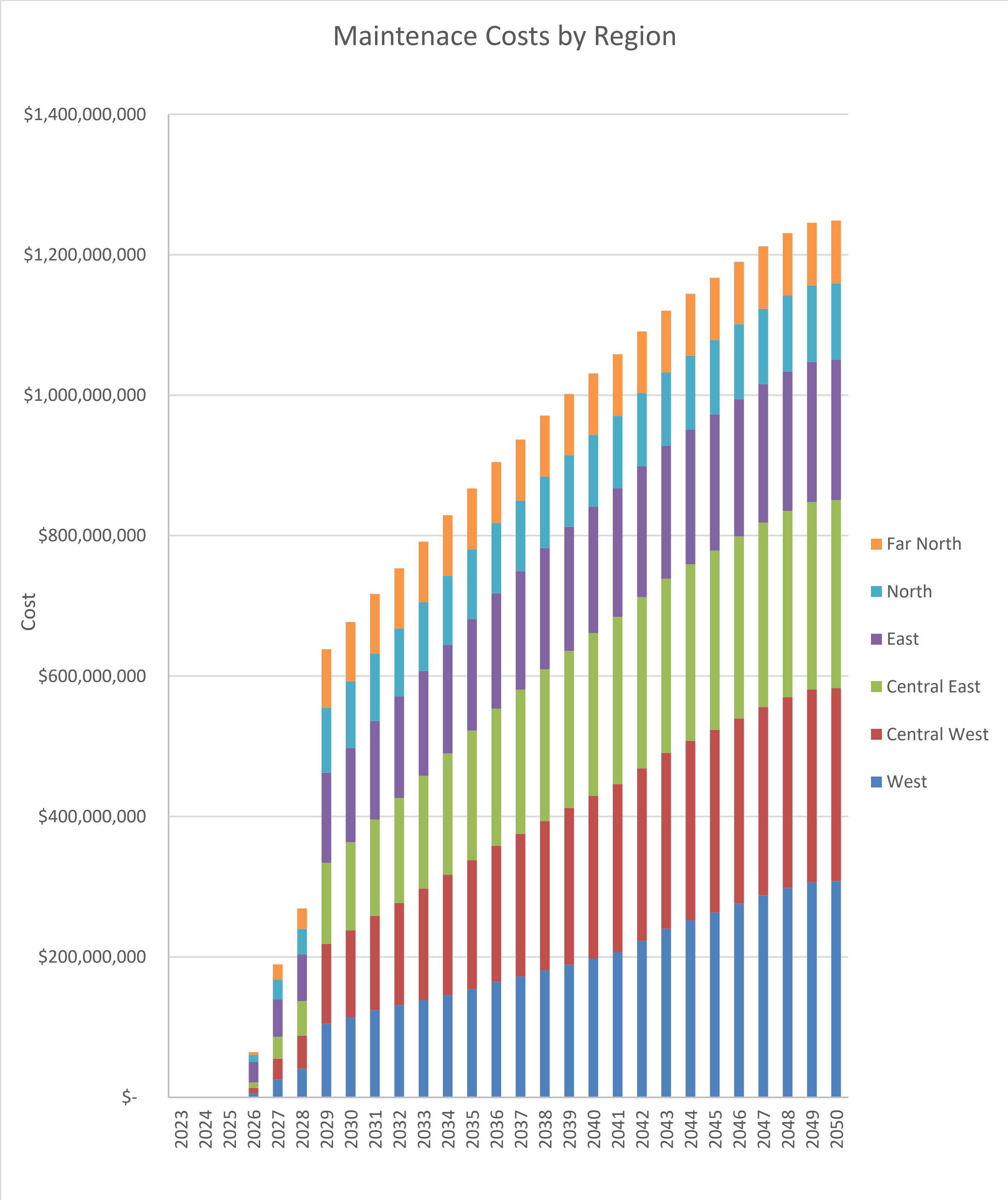


Figure 42: Maintenance Cost by Region and Year

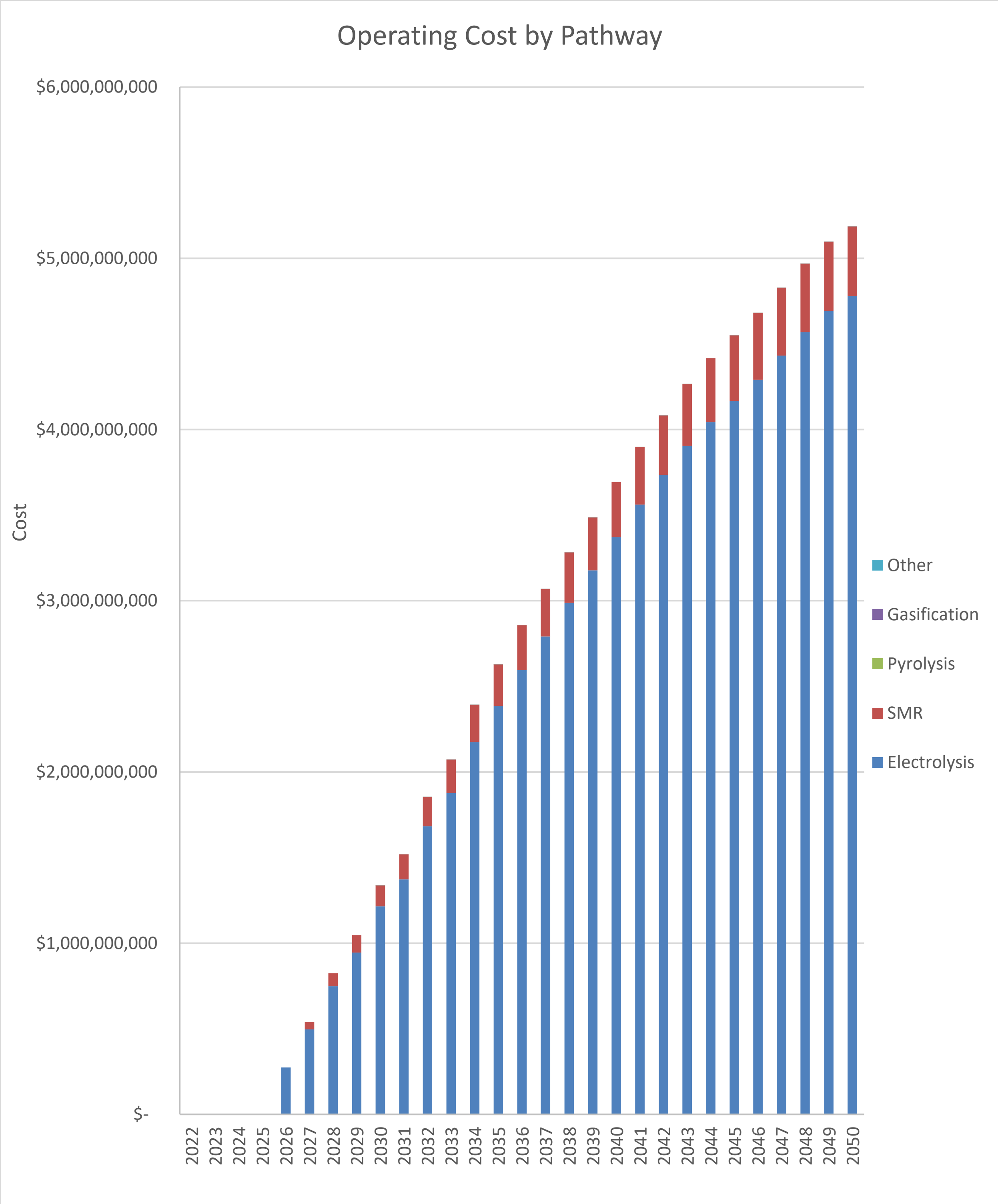


Figure 43: Operating Cost by Pathway

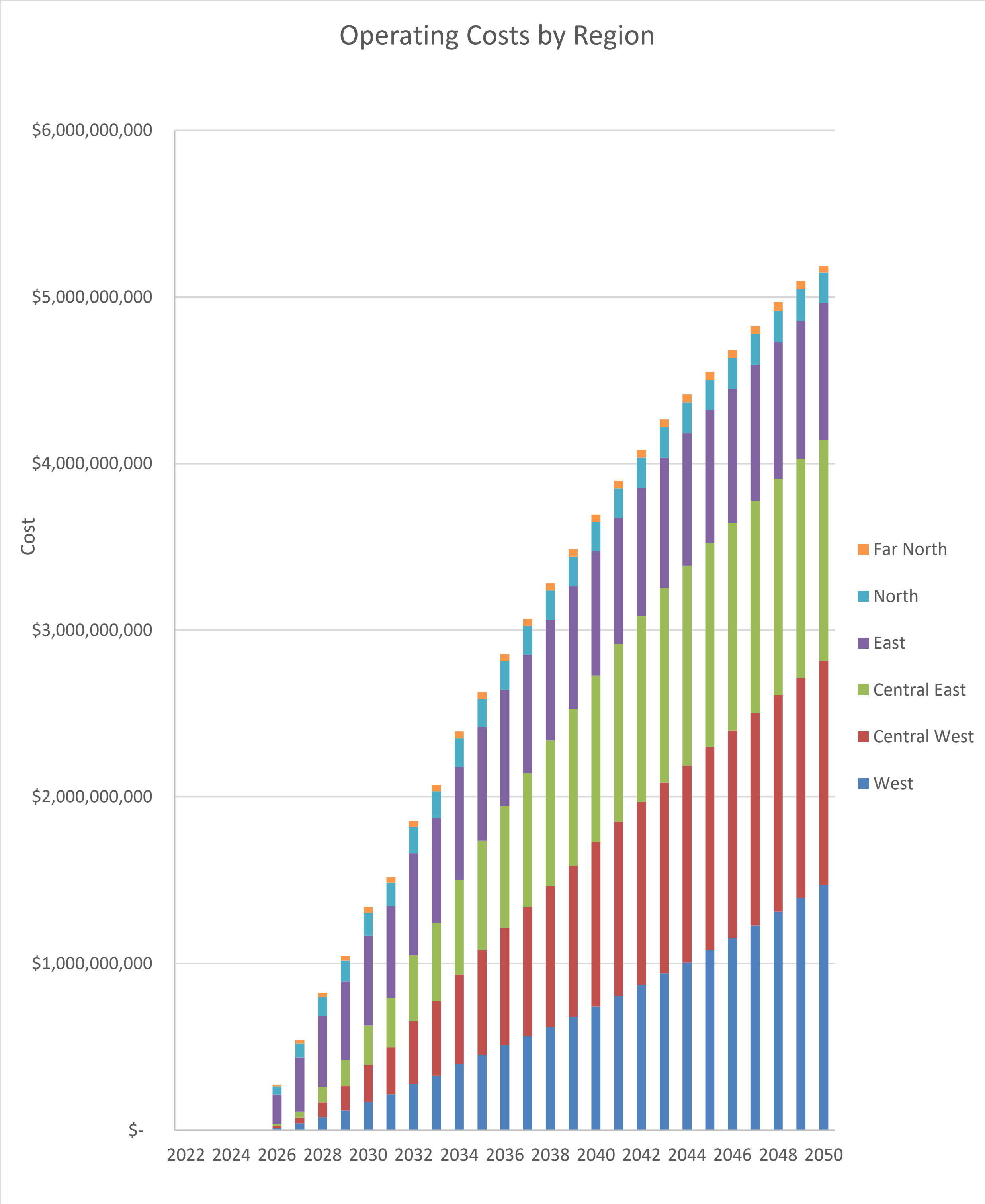


Figure 44: Operating Costs by Region

7.2 Changes in Greenhouse Gas Emissions

The Hydrogen Ecosystem module receives GHG emissions data from the production and consumption modules and uses these to calculate new emissions associated with the production of hydrogen, which adds to the provincial inventory, and emissions reductions due to low-carbon hydrogen displacing fossil fuels (as well as improvements to the carbon-intensity of some industrial applications). Recall that the production of hydrogen generates GHG emissions, according the carbon-intensity of the feedstock supply chains, but produces negligible emissions at the application (i.e., point of use). There are thus local air quality benefits that could be considered in further version of H2GrO-TEA Model.

The following chart shows the annual change in GHG emissions in the Base Case for years 2030 to 2050 in five-year increments. The increase in emissions from hydrogen production is minor compared to the reductions resulting from its use.

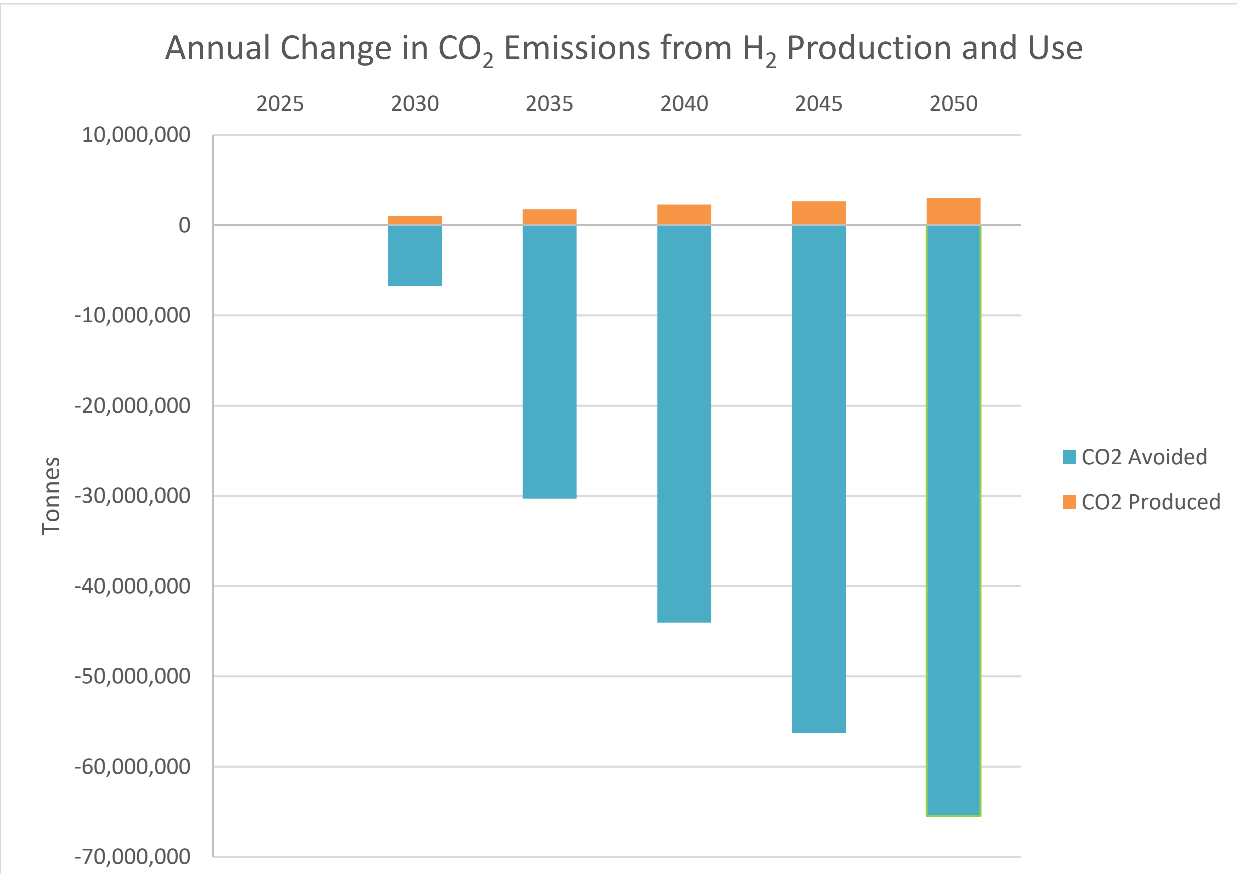


Figure 45: Ontario Projected CO_2 Emissions – Net Change

The net change in GHG emissions in the Base Case scenario in 2050 is reduction of 62 Mt of CO_2. For comparison, Ontario's GHG emissions inventory in 2020 is reported as 150 Mt [27]. The cumulative change in emissions by 2050 is 874 Mt. The Figure below shows the rate of accumulated reductions overlaid in comparison to the CO_2 from the different hydrogen production pathways.

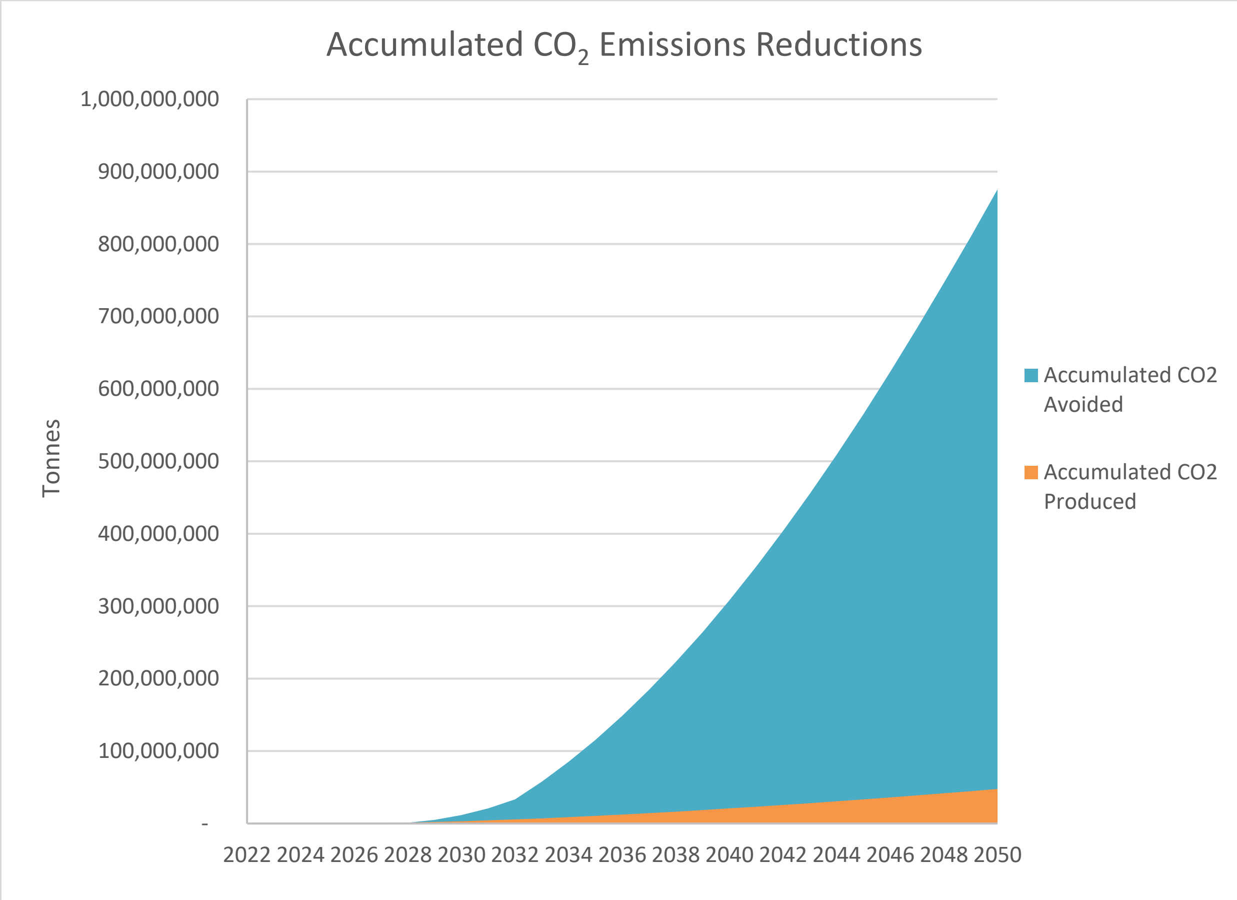


Figure 46: Comparing Accumulated CO_2 Emissions Reductions and Increases

7.3 Jobs Created

The H2GrO-TEA Model's Hydrogen Ecosystem module calculates job creation under three broad categories:

- jobs related to capital project execution, including construction;
- jobs related to ongoing facility and infrastructure operations and maintenance; and
- indirect jobs.

Indirect jobs are the largest category. They refer to jobs that support the industry or support the workers engaged in the industry. The number of indirect jobs is typically determined by applying a factor (e.g., 10) to the number of direct jobs; however, this factor will require refinement as the nature of the direct jobs becomes better understood. For the Base Case, the module generates the job creation profile shown in Figure 47 and Figure 48 below, according to low-carbon production pathway and by administrative region.

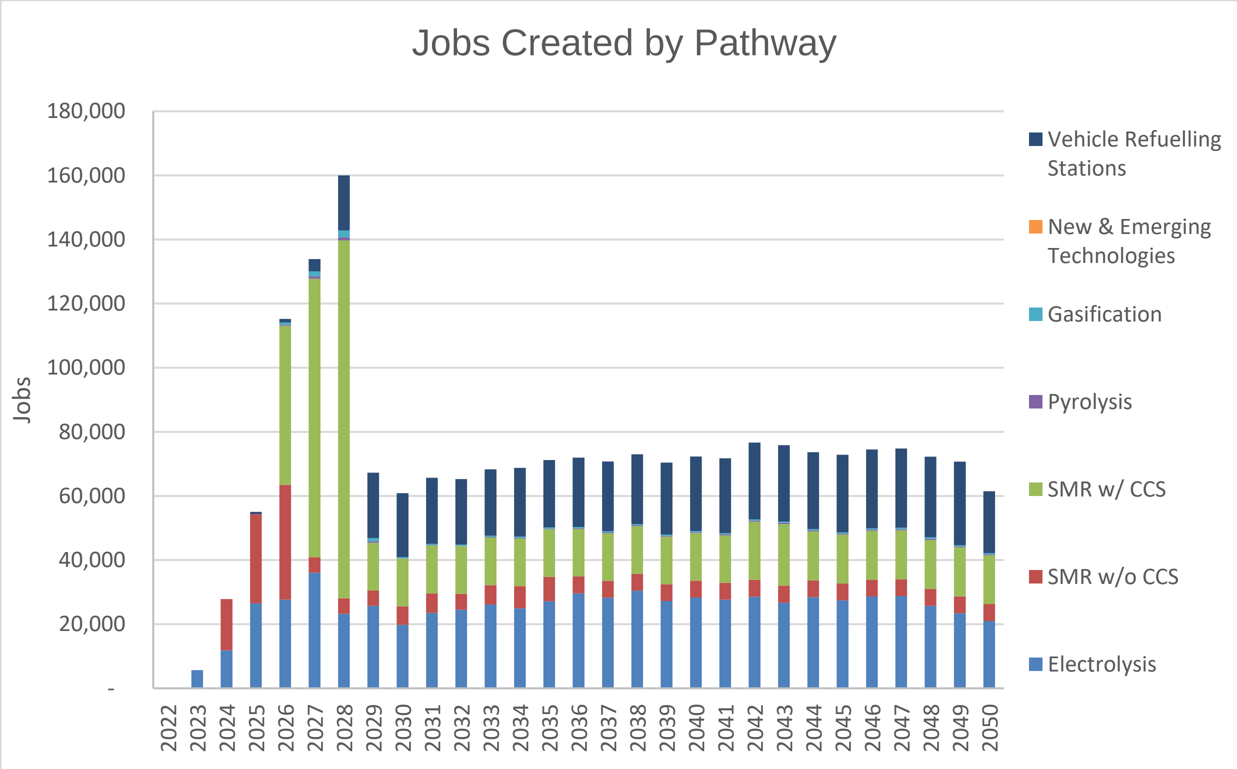


Figure 47: Jobs Created by Production Pathway

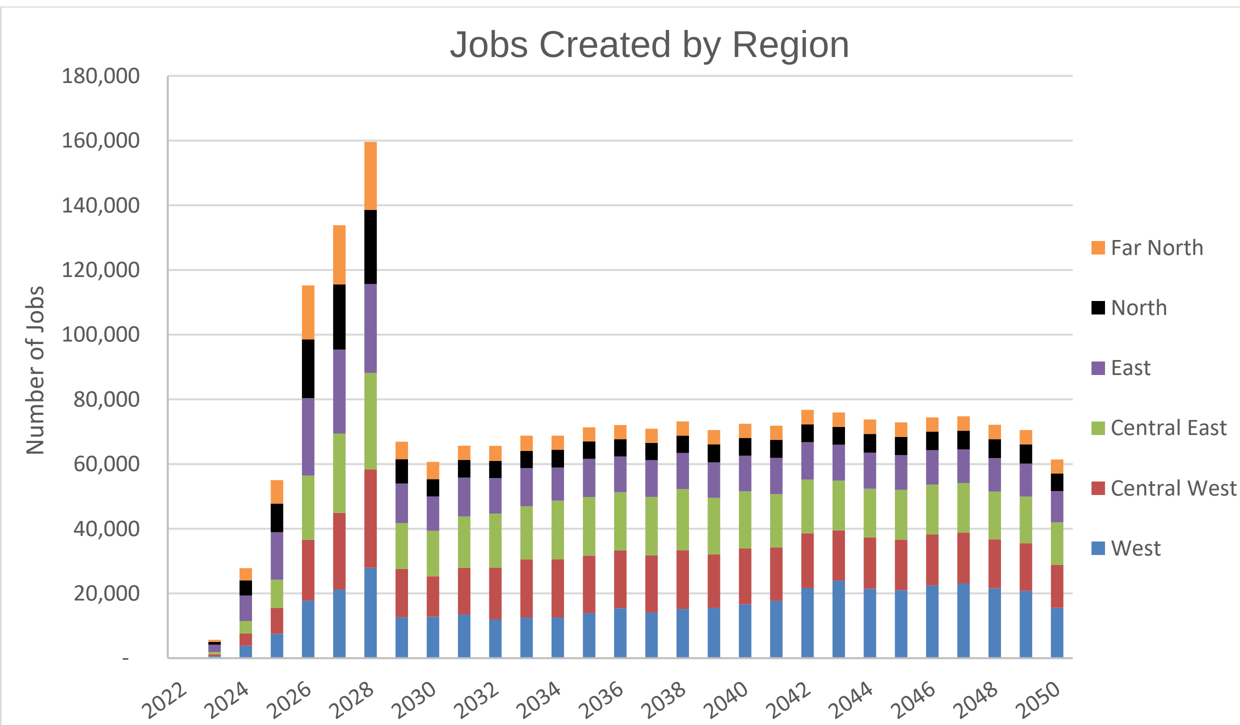


Figure 48: Jobs Created by Region

The Base Case generates steady job growth, reaching a peak of more than 160,000 jobs by 2029, after which it drops back to around 70,000. Jobs drop off in this manner as the first rush of labour related to infrastructure development begins to taper off, and jobs associated with capital projects are no longer required.

Note that module does not take into account the impact to jobs associated with the incumbent industries that will be affected by the expansion of hydrogen markets in Ontario. It may be that some jobs are lost, but hydrogen draws significantly on knowledge and experience common in fossil fuel industries (e.g., gaseous and fluidic distribution and storage systems), so the prospect of a just transition of employment opportunity is considered high.

7.4 Levelized Costs of Hydrogen

The levelized cost of energy is a method of comparing the total costs and benefits of two or more scenarios. It is usually represented with total system costs in the numerator and the total system benefits in the denominator. A seminal guide produced in 1995 by the U.S. Department of Energy, *A manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies*, provides the following guidance [28].

$$Levelized\ Cost\ of\ Energy = \frac{total\ lifecycle\ cost\ of\ energy}{\sum_{n=1}^{N} \frac{Q_n}{(1+d)^n}}$$

$$Q_n = energy\ output\ in\ year\ n$$
$$d = discount\ rate$$
$$N = analysis\ period$$

The H2GrO-TEA Model's Hydrogen Ecosystem module adapts this approach to calculate levelized cost of hydrogen in three ways:

1) sum of annual costs / sum of annual hydrogen produced in the year in question.
2) sum of costs over lifetime / sum of hydrogen produced over modeling period [$/kg-$H_2$]
3) sum of costs over lifetime / sum of net GHG emissions reduced over modeling period [$/t-$CO_2$e]

Approaches 2 and 3 above result in weighted average costs over the full modeling period. Approach 1 requires that capital investments be amortized over a defined period and applied as appropriate. The Base Case amortizes capital over a 20-year period, applying a cost of money of 10 per cent. Since little hydrogen is produced in the early years, this creates an initial spike in the apparent annual levelized cost. The spike settles out as production increases and the utilization of capital assets improves. The model retires capital investments after the 20-year period, reducing the level on ongoing capital costs for the overall system.

There is a known inaccuracy in the levelized cost calculations. Namely, that the model assumes a slow-down in new facility and infrastructure construction as 2050 approaches. This slowdown is not realistic; rather, it is an artefact of the Base Case timeline, which supposes that no *new* demand for low-carbon hydrogen will occur past 2050. Of greater concern to the study team is that the effects of carbon pricing, carbon-intensity rules on fuels and other policy measures are disregarded in the current version of the model.

Regardless of these confounding factors, the study team elected to keep levelized cost calculations simplified in the current version of the model because it make cause-and-effect analyses of different scenarios easier to conduct, and this aids in further refining and calibrating the model inputs and outputs. Also, economic sophistications are unlikely to change the results significantly.

Summarizing the outputs of the module:

1) The weighted average **levelized cost of hydrogen delivered** is estimated at **$13.88/kg**. This is the all-in cost of hydrogen delivered to the point of its application. This includes the cost of vehicle refuelling infrastructure as applicable. However, it does not include the cost of the hydrogen using technology. Importantly, this estimate incorporates the cost of the specific fuel that is displaced, or avoided, as a consequence of using low-carbon hydrogen instead. While this approach is analytically correct, it is also useful to know the cost of hydrogen delivered in isolation of related fuel savings. In the Base Case, this cost is $19.87/kg. To put the cost of hydrogen delivered into a more familiar context, $14 per kilogram would have a cost-equivalence, adjusted for efficiency of fuel use, of roughly $1.75 per litre of gasoline.
2) The **levelized cost of GHG emissions reduced** is estimated at **$437/tonne-$CO_2$e**. This is based on the levelized cost of hydrogen delivered, as reported above, and reflects the cost of fuel avoided. Ignoring the savings from the specific fuel avoided yields an estimate of $760/tonne-$CO_2$e. Note (again) that this approach truncates the GHG emissions reduced past 2050, as installed equipment continues to run through its remaining useful life.

These cost estimates may appear high at first glance. Published estimates of marginal abatement costs and levelized costs of GHG emissions reductions often reference estimates of $50 to $300 per tonne for many decarbonizing technologies. The above calculations, however, include the cost of making hydrogen available in every identified market, which requires significant distribution systems that enable transport of bulk hydrogen, as well as significant imports of hydrogen to the province. That, combined with the other conservative assumptions, push the levelized cost estimates upward in the Base Case scenario. In the next section, some alternative scenarios are presented. These were developed by the study team to illustrate how the levelized costs of hydrogen in Ontario are sensitive to the mismatch of production capacity within the province and demand.

In addition to the analysis presented above, the H2GrO-TEA Model can also generate levelized cost estimates by specific production pathway [and by application??]. The range of targeted analyses is numerous. Readers are encouraged to reach out to the authors to discuss their needs for any particular sets of analyses and estimations.

7.5 Scenario-Play – What if? Analysis

In Figure 24 in Section 5.2, the comparison of the low-carbon hydrogen produced in Ontario to that consumed is shown. Clearly, in the Base Case scenario, demand exceeds the capacity of the province's hydrogen producers to supply, by as early as 2030. Thus, hydrogen imports from neighbouring jurisdictions is required. This section explores alternative scenarios that mitigate the need for hydrogen imports by either increasing domestic hydrogen production capacity, or by dampening demand and the effect this has on the Ontario hydrogen ecosystem

The import/export disposition of the Base Case scenario is visualized in Figure 49, below. Note that in this scenario, the energy feedstock required to produce low-carbon hydrogen via electrolysis is given by the conversion factor, 60 kWh/kg-H_2. Electrolysis is the production pathway that yields the most hydrogen in the Base Case, and 60 kWh of electrical energy are needed to produce a kilogram of hydrogen. This is yet another conservative assumption, as some manufacturers will assert 50 kWh or less, but the study team assumes production occurs over a wider range of efficiencies. The relevance of this productivity factor will become clear in the following paragraph.

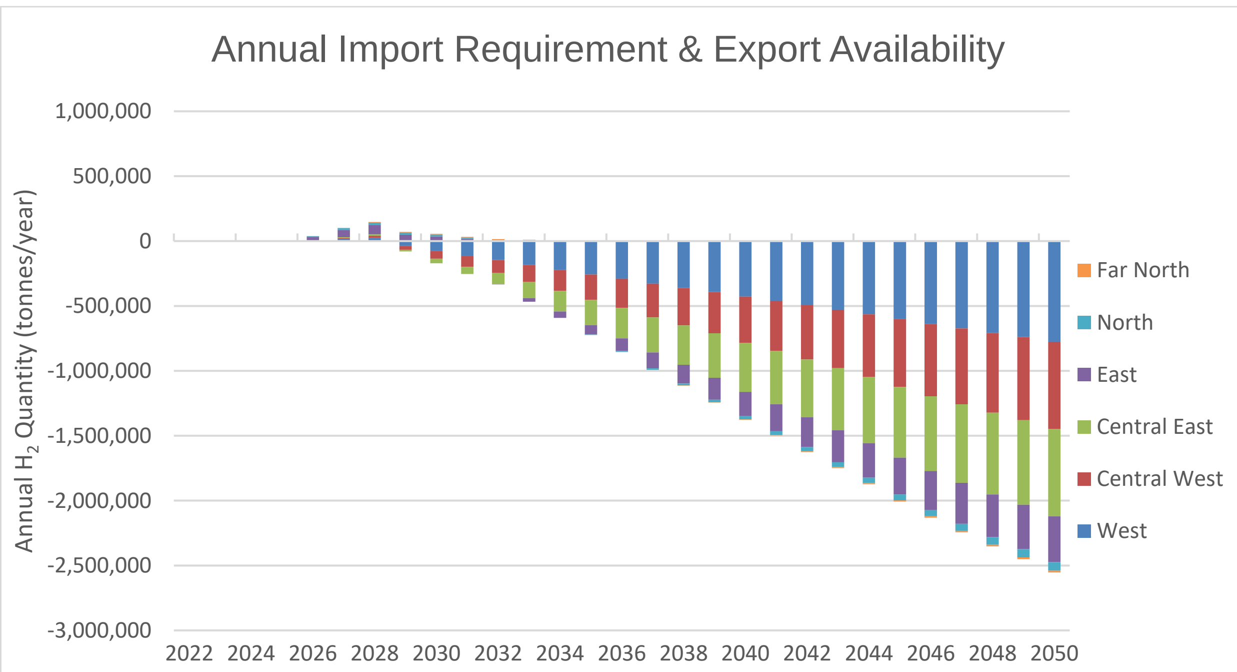


Figure 49: Annual Import Requirement and Export Availability - 60 kWh/kg H_2

What if Ontarians decided they wanted to be less reliant on imported hydrogen, or build capacity to be a net exporter? One way would be to aggressively develop and deploy more efficient technology for hydrogen production, thus making more hydrogen on the same input of electrical energy. This is technologically feasible *if* a thermochemical water splitting production pathway is assumed. Such a production system was explored in Section 4.2 (i.e., Copper-Chlorine cycle for hydrogen production). The performance of this pathway is approximated by reducing the electrical energy input from 60 kWh to 20 kWh to produce a kilogram of hydrogen, with the remaining 40 kWh needed to produce hydrogen provided by high-temperature heat. Effectively, this triples the amount of low-carbon hydrogen production potential supported by the available supply of electricity, which is constrained in Ontario (per the Base Case assumptions described in Section 4). The balance of the heat energy needed is much less constrained; waste heat can be sourced from power plants and industrial facilities where hydrogen is produced nearby, or natural gas can be burned. In either case, the costs will be less than traditional electrolysis.

The effect of moving to 20 kWh/kg-H_2 productivity in Ontario is shown in Figure 50 below.

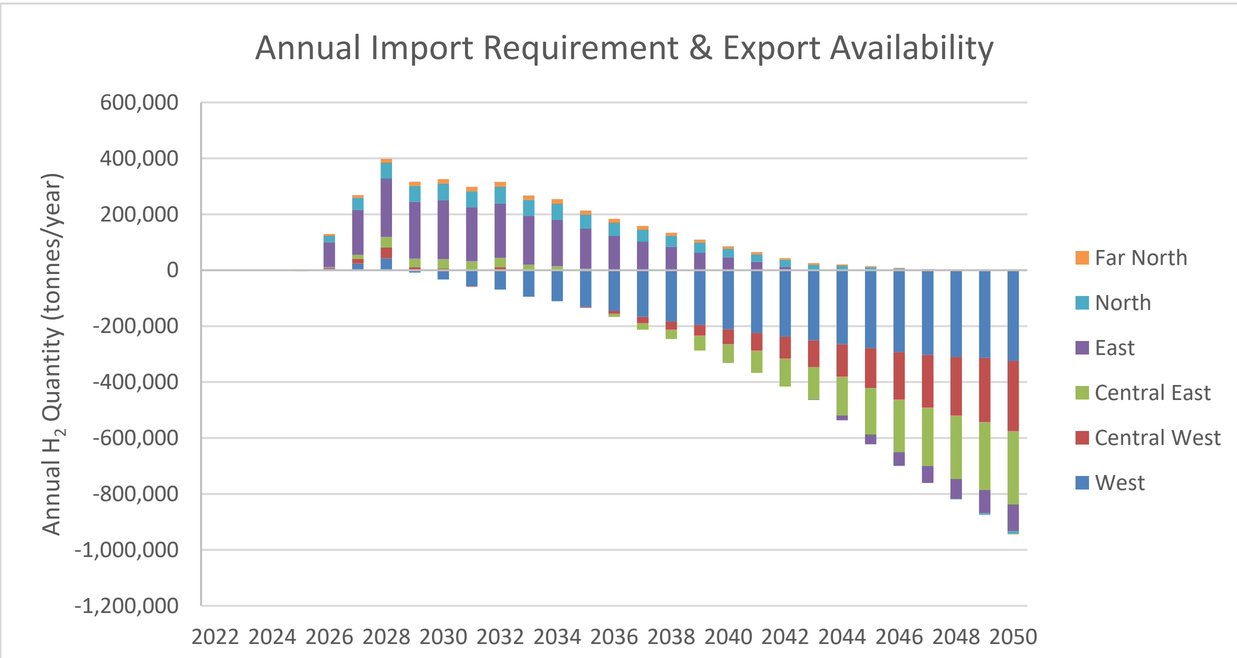


Figure 50: Annual Import Requirement and Export Availability - 20 kWh/kg H_2

The chart above illustrates the potential of technology to move Ontario into a net exporter disposition through the late-2030s in the Base Case. Note that the charts above also show the disposition of intra-province imports and exports between the administration regions in Ontario. Some regions have a shortfall (requiring import), whereas others have a surplus (enabling export). The model assesses the opportunity for intra-provincial movement of hydrogen to optimize overall self sufficiency.

What if hydrogen demand in the Base Case scenario was somehow satisfied by Ontario-produced hydrogen *only*, thus eliminating the need for hydrogen imports? The study team modified the Base Case in two ways to explore this condition:

1) *Base Case Mod-1*, in which hydrogen production capacity is inflated through augmented efficiency to approximately meet demand in the province. This is simulated by reducing the input electricity needed to produce hydrogen via electrolysis to 35 kWh/kg-H_2 (selected because it demonstrates the efficiency of high temperature copper chloride electrolysis). As described above, this can rely on more energy efficient pathways. As well, the Base Case condition that not more than 50 per cent of available feedstocks will be used for low-carbon hydrogen production is removed, allowing 100 per cent of feedstock availability to be leveraged. As well, production pathway growth rates are reset from slow or moderate to the fast growth profile.

2) *Base Case Mod-2*, in which hydrogen demand (i.e., consumption) is artificially constrained to remain with the production capacity of the Base Case conditions for the province. To simulate this scenario, the market adoption rates of all hydrogen end-use applications are reset to follow a slow growth profile, and maximum market share is reduced by an average of half or more (e.g., residential and commercial applications are decreased from 10 per cent market share to 2 per cent).

The results are shown in Figure 51 and Figure 52 below.

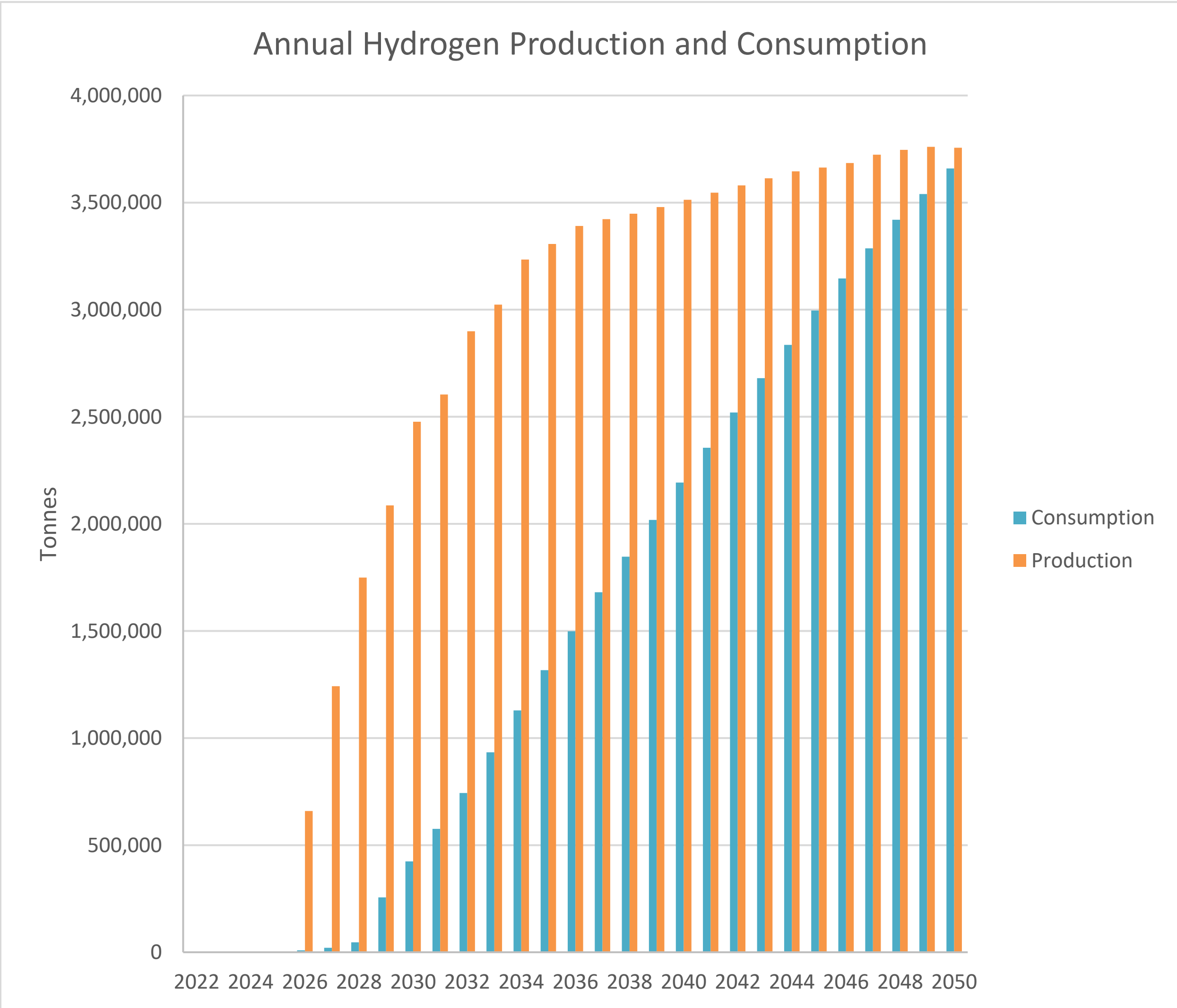


Figure 51: Base Case Mod-1

In the Mod-1 scenario, production remains greater that consumption for most the period, but begin to converge approaching 2050 at more than 3,500,000 tonnes. This effectively eliminates the need to import of low-carbon hydrogen to meet in-province demand, and allow for an export trade in Ontario-produced hydrogen to be established.

Mod-1 is possible as explained earlier by lowering the energy required for electrolysis 35 kWh/kg-H_2 along with the other changes to the input parameters. Another option explored if the energy for electrolysis could not be lowered, and Ontario were to supply all its own hydrogen, up to an additional 22,500 MW of low-carbon electricity generating capacity (i.e., using wind, solar, hydro, biomass or nuclear power) is required. For simplicity and the limits of the model, the lowered energy of electrolysis for Mod-1 will be used for comparison to other model scenarios.

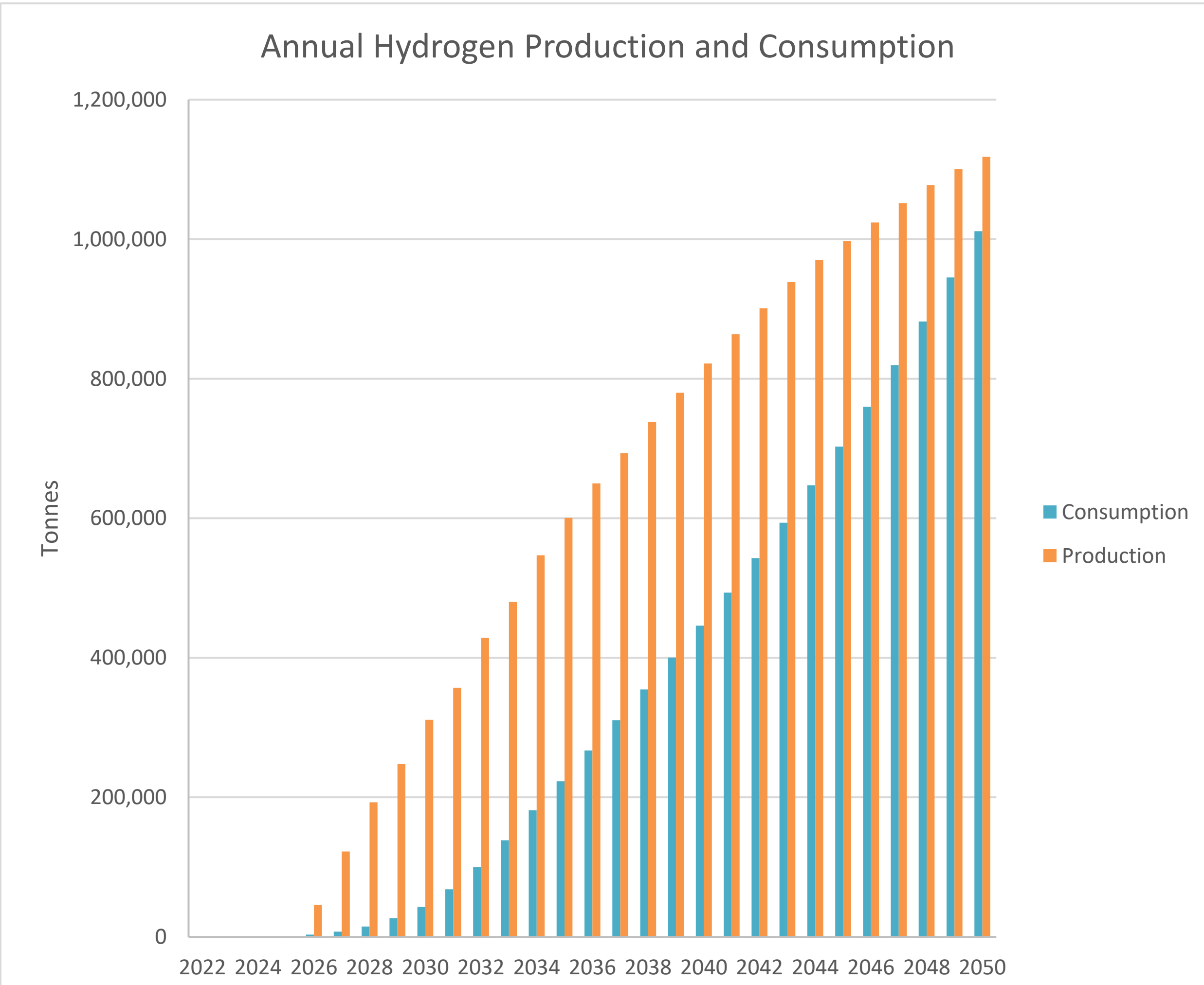


Figure 52: Base Case Mod-2

In the Mod-2 scenario, consumption of low-carbon hydrogen is severely cut back from roughly 3.5 megatonnes to 1 megatonne (1,000,000 tonnes). While this ensures that demand can be met with the provincial supply defined in Base Case 1, it also results in fewer GHG emissions reductions and fewer jobs created.

The following table compares some of the key outputs of the H2GrO-TEA Model's Hydrogen Ecosystem module for the Base Case and its variants, Mod-1 and Mod-2.

Table G: Comparing Outputs of Base Case and its Modified Scenarios

Parameter	Base Case	Base Case Mod-1	Base Case Mod-2
Total hydrogen produced in 2050	1,117,943 tonnes	3,756,144 tonnes	1,117,943 tonnes
Total hydrogen consumption in 2050	3,701,161 tonnes		1,011,364 tonnes
Total GHG emissions avoided	874,283,674 tonnes		316,904,393 tonnes
Weighted average $/kg H_2 consumed (savings of avoided fuel disregarded)	$19.77/kg	$11.10/kg	$22.50/kg
Weighted average $/kg H_2 consumed	$13.88/kg	$5.14/kg	$16.41/kg
Weighted average $/tonne CO_2 avoided (savings of avoided fuel disregarded)	$760.18/tonne	$217.73/tonne	$407.85/tonne
Weighted average $/tonne CO_2 avoided	$437.62/tonne	-$34.94/tonne	$256.63/tonne
Jobs created (maximum in one year)	160,598	230,634	144,375
Total capital invested in infrastructure	$85,192,092,891	$131,632,795,205	$67,362,355,774

The chart above highlights some important learnings about a potential hydrogen ecosystem in Ontario. The key finding is that investing in Ontario's productive capacity for low-carbon hydrogen vastly improves the economic performance its hydrogen markets and increases the societal benefits, in terms of GHG emissions reduction and job creation. Relative to the Base Case, Mod-1, in which hydrogen production is forcibly scaled up by three times, <u>reduces</u> the levelized cost of hydrogen delivered by 50 per cent or more. Moreover, the levelized cost of GHG emission reduction reduces to levels that are well within published estimates for most low-carbon pathways (i.e., less than $200/tonne). Indeed, when incorporating the avoided cost of the incumbent fuel, the Mod-1 scenario dips to a negative abatement cost. Importantly, the capital costs under the Mod-1 scenario are only 55 per cent higher than in the Base Case.

By contrast, restricting the growth of low-carbon hydrogen end-use applications within the province to levels that do not exceed regional productive capacity, as in Mod-2, increases levelized costs and yields fewer GHG emissions reductions and job creation.

Regarding the levelized cost of hydrogen for Base Case Mod-1, the module estimated it at $5.14/kg. This value is comparable to the levelized cost of hydrogen recently published in the Ontario's Hydrogen Hub in Sarnia-Lambton Strategic Plan [29]. The difference may be attributed to the province-wide nature of this study. In Base Case Mod-1, production infrastructure is developed in advance of demand and a 20-year capital cost recovery period is assumed. The Sarnia-Lambton Strategic Plan applied a 30-year economic life for all levelized cost estimates, the demand was continuous and was assumed to match production in each year. The strategic plan also focused on a singular locality with relatively high demand for industrial and commercial uses, in which fewer regional distribution costs would be accumulated.

8.0 DISCUSSION AND RECOMMENDATIONS

As demonstrated in the preceding Section 7, the H2GrO-TEA Model can be used to assess different scenarios of how low-carbon hydrogen markets in Ontario may evolve and function. Through scenario-play, the characteristics of hydrogen production, distribution and use in Ontario begin to emerge, including the challenges and opportunities faced. By examining how the model outputs are sensitive to user-defined inputs, it is possible to inform hydrogen system planning, policy development and project prioritization, with an eye toward optimizing the desired ecosystem benefits in the future.

This section describes some of the key findings that the study team observed when simulating the Base Case scenario. These findings may serve as persistent themes in future hydrogen system planning in Ontario. Also included in this section are points of reflection by the study team on enhancements that could be prioritized for follow-on versions and releases of the model.

Lastly, recommended next steps are presented herein for consideration by low-carbon hydrogen sector stakeholders in Ontario, informed by the experience of developing and using the H2GrO-TEA Model.

8.1 Key Findings Based On Model Dynamics

The H2GrO-TEA Model has been developed to accomplish two general tasks:

1) To evaluate the outcome of a specified scenario. A specific scenario is first characterized by suitable adjustment of the model inputs, upon which the various outcomes can be evaluated. This is not prediction, but predictive analysis (i.e., forecasting).
2) To determine the conditions that are necessary to achieve a defined outcome. By adjusting inputs, a scenario can be developed that achieves the goals of the model user. The resulting set of input parameters can then be evaluated for practicality, likelihood, and feasibility so that policy objectives can be developed accordingly.

The model uses several hundred discreet input variables that allow the user to define specific scenarios. This provides an opportunity for businesses and individuals in Ontario to use the tool to inform their decisions related to decarbonization, new ventures and utilizing hydrogen as a more sustainable energy or chemical commodity.

Ensuring that production keeps pace with demand appears to maximize benefits for Ontario

The Base Case scenario inputs produce a forecast of Ontario having limited capacity to export its low-carbon hydrogen. However, as shown in Base Case Mod-1, if the commercialization of emerging technologies is prioritized to accelerate market deployment (possibly assisted through government policy and programs), then an export orientation can be maintained for most of the period leading to 2050. Low-carbon hydrogen would also be available for export if local markets in Ontario develop more slowly that the Base Case estimates. The economic benefits appear to favour a strategy of intensifying hydrogen production.

> *Finding: Ontario can be self-sufficient in low-carbon hydrogen and be a net exporter by prioritizing its productive capacity. Simultaneous support of market adoption of hydrogen end-use applications in Ontario results in greater job creation and GHG emissions reductions. Increasing production hinges on new technology development for efficient conversion of available feedstocks to hydrogen.*

Least cost hydrogen pathways rely on low-carbon electricity

In the Base Case, electrolysis emerges as the dominant low-carbon hydrogen production pathway in Ontario due to the comparatively lower capital cost, lower carbon-intensity levels and ready access to water and grid-supplied power as feedstocks. Therefore, the greater the availability of renewable, hydroelectric and nuclear power within the province, then the more low-carbon hydrogen can be produced at less cost.

Methane reforming coupled with CCUS is the next most significant pathway with very low GHG emissions. It is more cost-effective and less carbon-intensive to produce hydrogen from natural gas using methane reforming than it would be for natural gas-fired power plants to supply electricity to electrolysis facilities. Thus, natural gas as a hydrogen feedstock generates more benefits through the methane reforming pathways.

> *Finding: Increasing renewable and nuclear power capacity will feed into (and support) least-cost hydrogen pathways in Ontario. Natural gas also feeds into lower-cost hydrogen pathways via methane reforming (i.e., using SMR or ATR systems with CCUS). Optimizing the economic and environmental benefits of low-carbon hydrogen production in Ontario is synergistic with its strengths in renewable and nuclear power, as well as its natural gas distribution system and carbon capture, use and storage potential.*

In the Base Case, the pathway for producing hydrogen using SMR with CCUS is projected to require roughly 11 megatonnes of CO_2 of storage potential, cumulatively, to 2050. This pathway thus depends on an evolving CCUS potential in Ontario.

Some hydrogen applications can scale with less capital cost, supporting market development

Some hydrogen end-use applications require greater infrastructure support. For example, the capital expense associated with 700-bar refuelling networks needed to support light-duty FCEV use is high. By comparison, the infrastructure needed to support a return-to-base refueling solution for medium- and heavy-duty FCEVs in urban commercial service is less expensive, yet the decarbonization benefits are comparable. Similarly, other applications, such as industrial facilities or portable power generators, can contribute significantly to increased demand for hydrogen within the province, but at comparatively lower capital cost since less support infrastructure is needed.

> *Finding: By focusing on applications that can consume higher volumes of hydrogen with less reliance on capital-intensive infrastructure, demand can scale up faster at lower costs of delivered hydrogen. The effect is to keep levelized costs low in the early years of market scale-up.*

8.2 Continuing Improvements to the H2GrO-TEA Model

The H2GrO-TEA Model can be expanded with new simulation capabilities and enhanced with more accurate and comprehensive data. The study team notes the following limits and opportunities that should be addressed in future versions of the model.

Developing a small, remote communities module – administrative region #7

The H2GrO-TEA Model is designed to simulate large, regional flows of low-carbon hydrogen in Ontario. It does model the effects of hydrogen produced and used in remote communities that may be off-grid or partially grid-supported. Yet, hydrogen systems could be instrumental to energy independence and energy prosperity within such circumstances. While these may not add significantly to the total, stacked hydrogen volumes generated by the model, the application of low-carbon hydrogen systems in smaller, more remote communities forms a crucial part of the value proposition underlying a provincial hydrogen strategy.

> *Proposal: Adapt the H2GrO-TEA Model principles to a smaller-scale community level and develop a user interface to facilitate scenario definition – based on population, local resources, regional offtake opportunities, etc. – to generate techno-economic assessments on a community-by-community basis. The sum of these simulations can be rolled up into an overall model representing a seventh administrative region for the province.*

Automating assessment of hydrogen pathway market share

The H2GrO-TEA Model is built assuming that other low-carbon solutions are being adopted in the market, and that hydrogen will be applied where it best meets the needs of users. However, markets and technologies are in a constant state of evolution. So, the model should be regularly updated to represent best-available knowledge and insights, thereby facilitating meaningful comparisons between hydrogen and other decarbonization pathways.

When framing such comparisons, the value proposition to the end-use is important to understand. For example, a plug-in electric passenger car may fit well with the driving patterns of the typical commuter, and thus be the optimal solution for zero-emissions, low-carbon mobility. By contrast, the same vehicle may be poorly suited to use in 24-hour taxi or limousine service, because of the cost of taking the asset out of service to recharge. Here, a fuel cell-electric vehicle may the better option.

The consequence of technology innovation and market adoption is shown by the model to significantly influence the throughput of low-carbon hydrogen within Ontario's markets. However, the current version of the model does not conduct a comparative evaluation of competing technologies. Instead, it relies on the user to define the levels of market share and pace of adoption. There is an opportunity, therefore, to build a comparative analysis module and integrate it into a future version of the H2GrO-TEA Model.

> *Proposal: A module can be developed and added to the H2GrO-TEA Model that performs a value assessment of alternative low-carbon pathways based on economic, social and environmental value sets (i.e., a triple-bottom line evaluation) to automatically adjust the market share likely to be achieved by hydrogen.*

Evolution of pipeline transmission

The H2GrO-TEA Model calculates the cost of transporting hydrogen by pipeline, within and across provincial boundaries, but it does not calculate the capital costs of building new, dedicated hydrogen pipelines or service corridors. At scale, pipelines are a highly cost-effective way to transmit gases, but challenges related to permitting and approval can be significant.

> *Proposal: The delivery module could be enhanced with new capacity to evaluate when the geographic and throughput conditions are met to develop new hydrogen corridors to serve Ontario and neighbouring jurisdictions.*

Incumbent fuel displacements

The H2GrO-TEA Model calculates the net GHG emissions change by deducting the emissions of the incumbent fuel from that of the hydrogen that displaces its use. However, a clear line-of-sight on the incumbent fuel does not always exist, especially in industrial applications. Canada's Energy Future forecast produced by the Canada Energy Regulator broadly categorizes some end-uses as "refined petroleum products" (RPP). RPP can refer to fuels like propane or petroleum coke, the carbon-intensity of which can differ greatly. In their specific applications, not all of these fuels have consistently-reported GHG emissions factors or carbon-intensity values/ The study team thus considered all RPP fuels as if they were diesel.

> *Proposal: Consultation with sector analysts and industry should be undertaken to establish more detailed factors for change in GHG emissions arising from the displacement of an incumbent fuel by the applicable low-carbon hydrogen pathways. The ecosystem module database should be enhanced using the findings.*

Expanded levelized cost estimation

The H2GrO-TEA Model calculates the elements spanning the full supply chain, but not all of these are necessarily of interest when determining a specific levelized cost factor. For instance, a levelized cost can be determined for a fuel from the point-of-production to the point-of-delivery to the end-user only, or it can also include the costs related to the deployment and maintenance of the end-use equipment as well. The costs of maintenance may include the fully-loaded cost of personnel, or they may only include the costs associated with additional training of that personnel. In some cases, the fully-loaded cost may be of interest, whereas in others only the incremental costs are important.

Furthermore, the cost of energy delivered in the form of hydrogen cannot be directly compared to that of the incumbent fuel displaced by hydrogen, due to possible differences in the efficiency with which the fuels are put to work. For example, to power a vehicle a given distance, more energy in the form of gasoline may be needed than energy as hydrogen. This assumes the vehicle's powertrain can make more efficient use of the hydrogen, as in the case of a fuel cell-electric vehicle that uses a combination of fuel cell and battery systems.

> *Proposal: Expand the range of default levelized cost outputs generated by the hydrogen ecosystem module.*

<u>Job creation</u>

The H2GrO-TEA Model estimates jobs created relating to hydrogen project construction, operations, maintenance and indirect jobs. It does not assess the potential for job loss associated with transitions to low-carbon hydrogen systems. This is expected to be minor compared to the employment opportunities gained. Nonetheless, it should be researched and incorporated into the model.

> *Proposal: Develop a just transition assessment tool to quantify the negative impact potential to employment levels among the modeled hydrogen pathways.*

8.3 Recommended Next Steps

The following actions are recommended for Ontario to enable the province to realize the full potential of the H2GrO-TEA Model and the value of this report for Ontario's citizens.

1. A workshop series should be planned and implemented that engages members of all sectors of society having an interest in the development of low-carbon hydrogen markets in Ontario. The purpose of the workshop series would be to:
   i. introduce audiences to the model and orient them to its utility in scenario development and simulations for hydrogen system planning purposes;
   ii. gather feedback from experts and stakeholders, sector-by-sector, regarding changes to the model inputs that yield more realistic scenarios and queue-up future revisions; and
   iii. promote confidence in the model as a tool of hydrogen system planning, ranging from the project level to community-wide initiatives, and to support regional coordination in market development.

   Prospective audiences and sector representatives to engage (this list is representative and is neither exhaustive nor exclusive):
   - Government of Ontario ministries, including
     - Agriculture, Food and Rural Affairs
     - Economic Development, Job Creation and Trade
     - Energy
     - Environment, Conservation and Parks
     - Mines
     - Municipal Affairs and Housing
     - Natural Resources and Forestry
     - Northern Development
   - Government of Canada departments, including
     - Environment and Climate Change Canada
     - Innovation, Science and Economic Development Canada
     - Natural Resources Canada
     - Transport Canada
   - Indigenous representatives and initiatives, including
     - Chiefs of Ontario
     - Indigenous Clean Energy

- Regional and municipal representatives
  - Association of Municipalities of Ontario
- Industry associations, including
  - Association of Canadian Port Authorities
  - Canadian Hydrogen and Fuel Cells Association
  - Canadian Federation of Agriculture
  - Canadian Fuels Association
  - Canadian Manufacturers and Exporters
  - Canadian Steel Producers Association
  - Canadian Trucking Alliance
  - Cement Association of Canada
  - Chemistry Industry Association of Canada
  - Hydrogen Business Council
  - Fertilizer Canada
  - Forest Products Association of Canada
  - Mining Association of Canada
  - Motion Picture Association – Canada
  - Ontario Energy Association
  - Ontario Federation of Agriculture
  - Ontario Waste Management
- Civil society
  - Conservation Ontario
  - Pollution Probe
  - Toronto and Region Conservation Authority

2. Identify near-term hydrogen projects that have potential to serve as foundations on which to build up Ontario's low-carbon hydrogen future. Promising initiatives would have characteristics that are consistent with the Base Case scenario findings, as identified earlier in this section. These are:
   i. intensifying low-carbon hydrogen production to keep pace with demand, thus maximizing benefits for Ontario;
   ii. levering least-cost hydrogen production pathways, which rely on low-carbon electricity for electrolysis and natural gas for methane reforming; and
   iii. promoting hydrogen end-use applications that are les reliant on capital-intensive, dedicated infrastructure.

   General examples of such projects could include:
   - Hydrogen production at cement plants
   - Hydrogen consumption at iron and steelmaking plants
   - Hydrogen distribution for local commercial vehicle fleets and materials handling equipment within the Toronto Pearson Eco-Business Zone
   - Hydrogen-powered locomotives for freight and passenger railway service

Specific examples of promising hydrogen initiatives that do *not* reside within the 13 hydrogen markets mapped in this report, yet could be instrumental in accelerating the adoption of hydrogen systems in practice, should be developed and curated. Potential sites of prospective hydrogen production and use to add to this list could include:

- Tiverton – potential site of low-carbon hydrogen produced via electrolysis for local use as transportation fuel and as feedstock for low-carbon methanol to domestic use and for export to international markets;
- Nanticoke – potential site of low-carbon hydrogen produced via electrolysis and methane reforming to support decarbonization of steel production and other local industrial applications;
- Timmins – potential site of low-carbon hydrogen production and distribution to local mining operations for use in ore haulers and surface mining vehicles; and
- Terrace Bay – potential site of low-carbon hydrogen production via electrolysis, using local hydropower resources or biomass gasification at pulp and paper mills, to supply to local transportation demands (noting that Highways 11 and 17 could become corridors of hydrogen-powered, on-road freight transport) and local industrial applications.

3. Develop a public, web-based interface with the model that encourages individual citizens of Ontario to develop simplified scenarios of hydrogen production and use – using visual tools and slider-bar inputs – and generate their own output simulations. The intent is to engage and inform the public about hydrogen as a low-carbon pathway for Ontario, through interactive, play-based learning. An example of this can be found in New Zealand. There, to cultivate public input to the development of New Zealand's Hydrogen Roadmap, the national government developed a online, visual dashboard, called the Modelling Project and Modelling Tool [30].

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APPENDIX 1: SUPPORTING INFORMATION

A1.1 MASS WATER BALANCE

The study team was alerted to concerns about exporting hydrogen produced via water electrolysis and water splitting. The question, “Could this be perceived as exporting Ontario’s water?” was posed. Where water is feedstock for hydrogen production, it would be ideal for the hydrogen to be used locally, thus minimizing inter-basin transfers as the hydrogen returns to water at the end-use application. However, the water input to hydrogen production is comparable – and often much less – that the water used in other manufactured products, including fossil fuels, which constitute major imports to Ontario markets. The threat of water scarcity is important to address, and hydrogen should be subject to scrutiny, as should all water-intensity processes and products. Under a holistic assessment of water resource management, hydrogen is not expected to be major issue.

Both electrolysis and methane reforming are processes requiring water. For hydrogen produced by electrolysis, the water follows the cycle shown in **Error! Reference source not found.**. In e ach step of this process, there is the potential for leaks and losses. These losses are not significant (less than 5 per cent), and the hydrogen released is vented to the atmosphere. The electrolysis process itself requires 9 kg of water per kg of hydrogen produced.

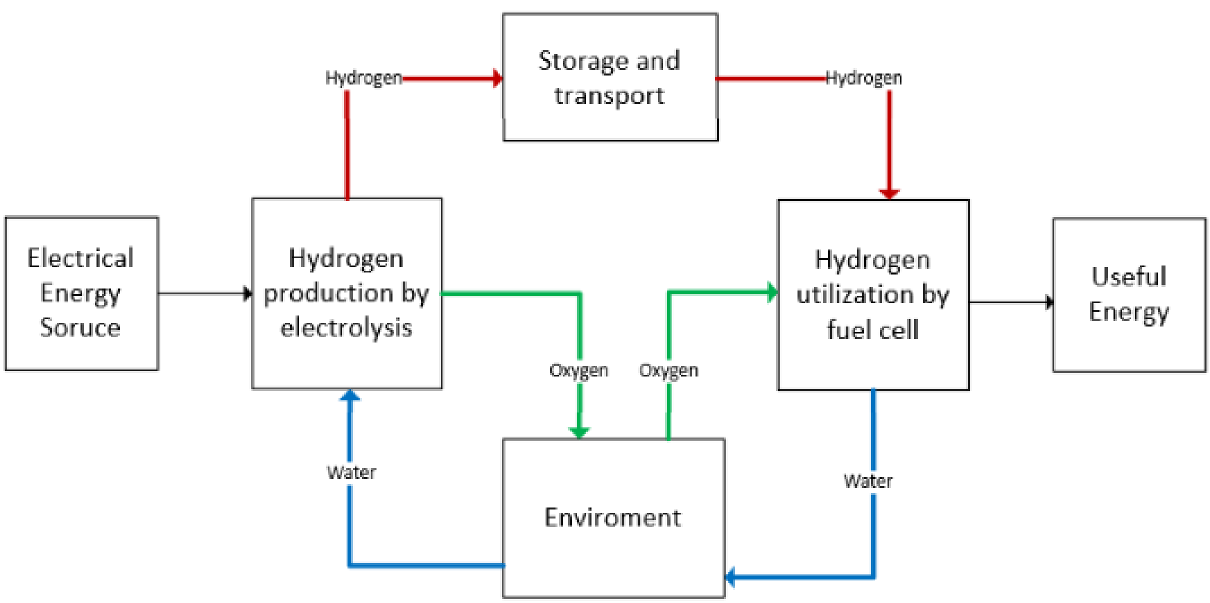

Figure 53: Hydrogen cycle via electrolysis and fuel cell

The water mass balance for steam methane reforming is more complex due to the multiple reactions that take place.

SMR Reaction:	CH_4 (methane) + H_2O + heat → $CO + 3H_2$ (hydrogen gas)
Water-Gas Shift Reaction:	$CO + H_2O \rightarrow CO_2 + H_2$ (hydrogen gas) + heat
Overall Reaction:	$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$

If a carbon dioxide capture process is included, then this will alter the water mass balance, as well. Note that if the carbon dioxide that is captured is also sequestered, then the oxygen from the water molecules that reacted to form the carbon dioxide will also be sequestered.

For the steam methane reforming process, a stoichiometric balance requires that 5.85 kg of water be consumed per kg of hydrogen produced. The process also requires 7.35 kg of excess steam per kg of hydrogen produced. Some of this steam is recycled through the plant and some is allowed to vent to the atmosphere. Significant amounts of wastewater are also generated from the process. Overall, the water required for steam methane reforming can range from 5.85 to 13.20 kg per kg of hydrogen produced.

With respect to the cases modeled, there are negligible amounts of hydrogen export from Ontario and there will be no inter-basin water transfer. This model has the capability of determining the techno-economic implications (i.e., revenue, levelized cost, energy and resources required, etc.) if Ontario were to become a hydrogen exporter. Nevertheless, the export of Ontario’s natural resources must be careful examined and considered.