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GERAD HEC Montréal
3000, chemin de la Côte-Sainte-Catherine
Montréal (Québec) Canada H3T 2A7

Tél. : 514 340-6053
Téléc. : 514 340-5665
info@gerad.ca
www.gerad.ca

The prospects of hydrogen trade between Canada and Germany: Insights from energy-economic modeling approaches

Jonathan Siegle [a] **Jithin Jose** [a] **Kamyar Amirmoeini** [b, c]
Tobias Schließ [a] **Ryan Baker** [c, d] **Sara Ghaboulian Zare** [c, e]
Elizaveta Kuznetsova [f] **Olivier Bahn** [b, c] **Dogancan Besikci** [c, f, g]
Pierre-Marie Manach [h] **Miguel Morales** [i] **Jianjun Yang** [d]
Ulrich Fahl [a]

[a] *Institute of Energy Economics and Rational Energy Use, University of Stuttgart, Stuttgart, Germany*

[b] *Department of Decision Sciences, HEC Montréal, Montreal (Qc), Canada*

[c] *GERAD, Montréal (Qc), Canada*

[d] *Clean Energy Innovation Research Centre, National Research Council of Canada, Ottawa (On), Canada*

[e] *Department of Computer Science and Operations Research, Université de Montréal & CIRRELT Montréal (Qc), Canada*

[f] *ESMIA Consultants, Montreal (Qc), Canada*

[g] *Department of Construction Engineering, École de technologie supérieure, École de technologie supérieure, Montréal (Qc), Canada*

[h] *Artelys Canada, Montreal (Qc), Canada*

[i] *Grid Consulting, Siemens Energy, Erlangen, Germany*

kamyar.amirmoeini@hec.ca
sara.ghaboulian.zare@umontreal.ca
olivier.bahn@hec.ca

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Abstract : This multi-model analysis examines the prospects of hydrogen in the Canadian and German energy systems, and particularly of hydrogen exports from Canada to Germany. A common scenario framework captures different future techno-economic pathways for electrolysis as well as large-scale hydrogen production and trade subsidy schemes. The common scenario framework aligns eight energy-economy-environment (E3) models and a prospective LCA based on E3 model results.

In the E3 model results, climate targets in Canada and Germany lead to a phase-out of unabated fossil hydrogen production. Besides that, results show varying perspectives of different models on the role of different low-carbon hydrogen production technologies and their timeline both in Canada and in Germany. For Canada, the models report 247–518 PJ of low-carbon hydrogen provision by 2050 in the standard scenario. For Germany, low-carbon hydrogen provision by 2045 in the same scenario is at 592–756 PJ, with substantial import amounts in two out of three models.

Results on Canada-Germany hydrogen or derivative trade indicate that without subsidies on trade, hydrogen derivative exports from Canada to Germany are competitive with production in Germany, but when expanding the view to domestic Canadian hydrogen demand and other potential supply countries, competitiveness based on direct cost becomes less clear. At the same time, “soft factors” that are not represented in the models, such as the existence of an experienced energy industry and traditionally stable relations between both countries, could change the picture in real-world considerations.

The direction of macroeconomic effects of electrolysis technology development and hydrogen policy shows no consistent strong tendency in the analyzed model results.

Findings of the prospective LCA on liquid hydrogen and ammonia exports from Canada to Germany reveal a substantially higher GWP100 for ammonia compared to liquid hydrogen.

Acknowledgements: This work is the result of a Canada-Germany 3+2 international collaboration, and specifically the Hydrogen Call (https://nrc.canada.ca/en/stories/supporting-collaborative-research-projects-between-canada-germany-low-carbon-hydrogen-technologies)

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An AI-based language model (ChatGPT, OpenAI) was used to enhance readability and style. The authors verified all outputs to ensure accuracy and originality.

1 Introduction

Decarbonization of energy system requires increases in energy efficiency, carbon capture and substitution of energy supplies. In the realm of substitution, the use of low-carbon hydrogen promises substantial emission reduction potential besides direct electrification.

In Canada, hydrogen strategy and policies have been outlined by Environment and Climate Change Canada (ECCC) (ECCC 2020) and Natural Resources Canada (NRCan) (Government of Canada 2020). NRCan estimated a range of Canadian hydrogen production potentials from less than 35 TWh/126 PJ up to 694 TWh/2498 PJ, considering natural gas with Carbon Capture and Sequestration (CCS); electrolysis; and bio energy with CCS (BECCS). Estimated Hydrogen production for domestic consumption and export was also a range from less than 35 TWh/126 PJ domestic with no export, up to 100 TWh/360 PJ domestic plus and 353 TWh/1271 PJ export (Government of Canada 2024). The Canadian Hydrogen Strategy envisions 4 Mt/480 PJ of low-carbon hydrogen production in Canada by 2030 and 20 Mt/2400 PJ by 2050 (Government of Canada 2020).

In Germany, despite an ambitious national electrolyser capacity target of 10 GW by 2030 (German Federal Government 2023), the government expects a significant amount of imports will be needed to cover all German hydrogen demand. Specifically, 45 to 90 TWh/162 to 324 PJ of hydrogen and hydrogen derivative imports are expected to be required in Germany by 2030 (German Federal Government 2024).

Canadian and German governments have created policies and programs to incentivize real world low or zero GHG hydrogen projects. To facilitate cooperation between Canada and Germany in relation to energy matters, an official energy partnership was established in 2021 (https://canada-germany-energy-partnership.org/). Furthermore, a joint funding window in the course of the H2Global hydrogen auctioning mechanism was announced in 2024 (BMWK 2024).

In Canada, hydrogen and ammonia production facilities are under consideration, have been announced, or are in development in all ten provinces from the Atlantic to the Pacific. Provinces with access to the Atlantic are focused on exporting hydrogen and hydrogen derivatives to Europe, while those with access to the Pacific are focused similarly on Asia. Canada US cross border hubs are under consideration for Vancouver in British Columbia, on the Pacific, as well as Sarnia, Windsor and Niagara Falls areas in Ontario on the Great Lakes (Government of Canada 2024). A non-exhaustive table summarizing known hydrogen projects of regional or national significance according to Natural Resources Canada (NRCan) can be found in the appendix of this paper.

Although real world hydrogen projects have been well supported on the supply side by government policies, they have faced headwinds for a few reasons, most notably a lack of offtake agreements on the demand side. According to the IEA, roughly 26% of 7,822 kt H_2/yr in Canada and 3.5% of 6,548 kt H_2/yr in Germany has progressed past concept, demonstration and feasibility stages (IEA 2025).

In this study the potential for hydrogen end use and production in Canada and Germany, as well as potential hydrogen and hydrogen derivative trade between them, is evaluated within a structured scenario framework, using systems level energy, economic and environmental modelling. Domestic Canadian hydrogen demand, but also competition among potential hydrogen exporter countries for a given market is taken into account. In summary, this work aims to shed light on the following questions:

- What are the prospects of hydrogen in the Canadian and German energy systems?
- Under which conditions can hydrogen trade be enabled between the countries?
- What are the macroeconomic and environmental implications associated with it?

The remainder of this paper is structured as follows:

After a detailed description of the energy-economy models and the scenario framework used in the "Methodology" section, modeling results are presented. Model results cover the global and national level for Canada and Germany, as well as the Canadian province of Québec and the Greater Montreal region. Furthermore, hydrogen and derivative trade between Canada and Germany is analyzed. The energy-economic results are followed by results from a prospective life cycle assessment of liquid hydrogen and ammonia trade between Canada and Germany. Lastly, conclusions are drawn from the results.

2 Methodology

2.1 Overview

The multi-model assessment presented in this paper is based on a set of scenarios designed to explore different technological or political conditions for the feasibility of hydrogen end use, hydrogen production with low-carbon technologies and hydrogen trade between Canada and Germany. The parameterization of the scenarios draws on a literature review on the cost of hydrogen production technologies and the renewable electricity potentials in Canada and Germany.

Several models covering a variety of characteristics contribute to the analysis. On the one hand, there are the energy-economy-environment (E3) models. On the other hand, there is the prospective LCA using input data from the NATEM and TAM-Supply models.

The workflow behind this multi-model-assessment is summarized in Figure 1.

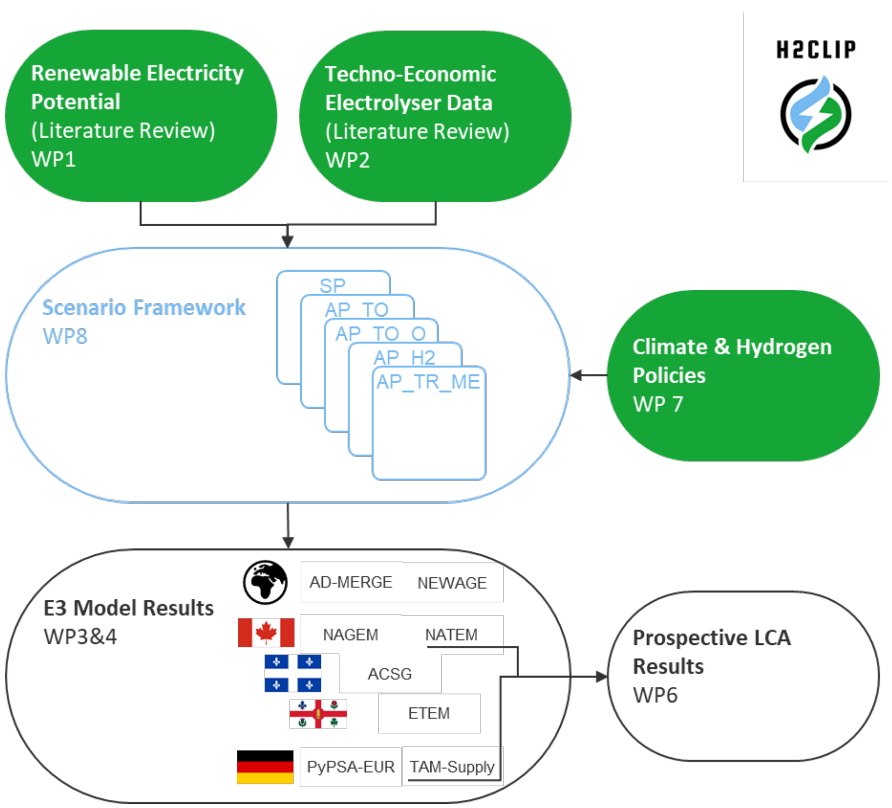

Figure 1: H2CliP workflow behind the multi-model assessment.

The set of models used represent a broad range of methodological characteristics. Despite harmonization of some essential input parameters through the scenario framework, there is still freedom in many parameters left, so models also vary considerably in input parameter assumptions (e.g. cost of electricity production technologies). Insights arise specifically from the observation of similarities and differences across the results from these models.

For this paper, green hydrogen is defined as hydrogen produced from water electrolysis, either alkaline or polymer electrolyte membrane (PEM), powered by either dedicated electricity generation, or electricity from the grid.

2.2 Energy-Economy-Environment (E3) models

The global view is represented by AD-MERGE and NEWAGE. AD-MERGE includes a general equilibrium representation of the world economy and a detailed representation of the energy system with many energy technologies. As an integrated assessment model, it includes feedback effects from progressing climate change to the economy, but also strategies for adaptation and mitigation. NEWAGE is a general equilibrium model with a highly detailed sectoral representation of the world economy. It also includes distinct technologies for electricity, hydrogen, oil and gas production. Other production or demand activities are included in aggregate production or utility functions.

Both models also contribute results for Canada, next to NATEM and NAGEM. NATEM is a detailed energy system model covering North America. NAGEM is a general equilibrium model that captures the North American economy in a highly disaggregated sectoral view. NATEM and NAGEM are run in a coupled mode and thus provide highly consistent results - not only on national, but also provincial level. Artelys Crystal Super Grid (ACSG) adds an electricity and energy system view of the Canadian province of Québec with hourly time resolution. ETEM is focused on the energy system of the Montréal region.

The analysis for Germany is carried out by NEWAGE, TAM-Supply and PyPSA-EUR. TAM-Supply provides a granular representation of the energy supply system of Germany, demands for the different energy carriers are exogenous. PyPSA-EUR models the German electricity and energy system and comes with an hourly time resolution like ACSG.

All of the aforementioned models except NAGEM contribute results on energy system parameters. Macroeconomic results are computed by AD-MERGE, NEWAGE and NAGEM.

Results from the NEWAGE model could only be computed allowing for very high uptake rates of energy production technologies (for example, wind electricity generation in Germany in the AP_TO scenario increases from 1126 to 2152 PJ from 2035 to 2040), however, the AP_H2 scenarios still remained locally infeasible with a residual below 0.01 bn €. The results are nevertheless published in this report, but should be interpreted with caution.

Key characteristics of the models in this study are summarized in Table 1. Further information about the models, the implementations that strongly influence their results and their limitations can be found in the appendix.

2.3 Scenario framework

Scenarios are designed differently along three dimensions: Climate policy, hydrogen policy and Technology (Table 2).

The **Stated Policies Scenario [SP]** describes a business-as-usual development. Therefore, only existing climate policy instruments are implemented following a “Stated Policies” emissions trajectory (IEA 2024a). Investment tax credits for hydrogen are considered in the NATEM, NAGEM and ETEM models. Electricity CAPEX follows "Stated Policies" (IEA 2024b). For electrolysis technology parameters, medium values are assumed. Some models follow energy prices from or energy price indices based on "Stated Policies" fossil fuel prices (IEA 2024b).

Table 1: Key characteristics of the models used in this study, based on (Ghaboulian Zare et al. 2025)

Model	AD-MERGE	NEWAGE	NAGEM	NATEM	ACSG	ETEM	TAM-Supply	PyPSA-EUR
Economic Approach[*]	GE	GE	GE	PE Energy System	PE Electricity System	PE Energy System	PE Energy Supply System	PE Electricity System
Mathematical Structure[**]	IO/NLP	RD/MCP	RD/NLP	LP	LP	LP	LP	LP/MILP
Modeling Spectrum	Perfect Foresight	Myopic	Myopic	Perfect Foresight	Perfect Foresight	Perfect Foresight	Perfect Foresight	Myopic
Model Perspective	Hybrid	Hybrid	Top-Down w/ coupling	Bottom-Up	Bottom-Up	Bottom-Up	Bottom-Up	Bottom-Up
Climate Modeling	Internal Modules	-	-	-	-	-	-	-
Time Horizon	2015-2150	2017-2050	2016-2050	2016-2050	2025-2050	2015-2050	2013-2045	2030, 2045
Time-Step	10 years	5 years	5 years	5 years	1 hour, 5 years	1 hour, 5 years	5 years	1 hour
Technological Change	Endogenous	Exogenous	Endogenous	Endogenous	Exogenous	Exogenous	Exogenous	Exogenous
Geographical Coverage	World (15 Regions)	World (16 Regions)	Canada (13 Regions)	Can., USA, Mex. (26 Regions)	Québec	Greater Montréal (5 Regions)	Germany (4 Regions)	Germany (15 nodes)
Developing Institution	GERAD – Group for Research in Decision Analysis, Canada	IER University of, Stuttgart, Germany	ESMIA Consultants Inc., Canada	ESMIA Consultants Inc., Canada	Artelys Canada Inc., Canada	GERAD – Group for Research in Decision Analysis, Canada	IER University of, Stuttgart, Germany	Siemens Energy Global GmbH & Co. KG, Germany

[*] GE and PE stand for General Equilibrium and Partial Equilibrium respectively.
[**]The mathematical structure of models is mainly Intertemporal Optimization (IO) or Recursive Dynamics (RD), with (Non)Linear Programming ((N)LP) formulation. (MCP) stands for Mixed Complementarity Problem.

Table 2: Scenario overview.

	Stated Policies (SP)	Announced Pledges Technology Open (AP_TO)	Announced Pledges Technology Open – Optimistic Electrolysis (AP_TO_O)	Announced Pledges Hydrogen Focus (AP_H2)	Announced Pledges Hydrogen Trade (AP_TR_ME)
Climate Policy	"Stated Policies"[*]	"Announced Pledges"[*]	"Announced Pledges" [*]	"Announced Pledges"[*]	"Announced Pledges"[*]
Hydrogen Policy	(-)	(-)	(-)	Subsidy on hydrogen production to reach national targets for green or low-carbon hydrogen production	Subsidy on hydrogen and hydrogen derivative trade from Canada to Germany to reach amounts based on the German Hydrogen Import strategy
Technology	"Stated Policies" Electricity CAPEX[**]; Medium values for future efficiency, CAPEX & OPEX of electrolysis	"Announced Pledges" Electricity CAPEX[**]; Medium values for future efficiency, CAPEX & OPEX of electrolysis	"Announced Pledges" Electricity CAPEX[**]; Optimistic values for future efficiency, CAPEX & OPEX of electrolysis	"Announced Pledges" Electricity CAPEX[**]; Medium values for future efficiency, CAPEX & OPEX of electrolysis	"Announced Pledges" Electricity CAPEX[**]; Medium values for future efficiency, CAPEX & OPEX of electrolysis

[*](IEA 2024a)
[**](IEA 2024b)

The **Announced Pledges Technology Open Scenario [AP_TO]** contains additional policy measures compared to the existing ones, so "Announced Pledges" (IEA 2024a) GHG mitigation targets representing the Climate Policy dimension are reached. While target ambition varies widely for different world regions, Canada reaches net zero emissions by 2050 and Germany by 2045. Investment tax credits for hydrogen are considered in the NATEM, NAGEM, ETEM and AD-MERGE models in Canada. On the technology dimension, electricity CAPEX follows "Announced Pledges" (IEA 2024b), while medium values are used for electrolysis technology parameters. This scenario serves as the baseline for the other "Announced Pledges ..." scenarios. Accordingly, some models follow energy prices from or energy price indices based on "Announced Pledges" fossil fuel prices (IEA 2024b) in all "Announced Pledges ..." scenarios.

The **Announced Pledges Technology Open Optimistic Scenario [AP_TO_O]** follows AP_TO, introducing one difference in the technology dimension: Assumptions on future development of efficiency, CAPEX and OPEX of electrolysers follow an optimistic trajectory.[1] The optimistic trajectories differ from the medium trajectories from 2025 on. By 2050, optimistic efficiency is assumed at 115% of the medium efficiency, CAPEX and OPEX are assumed at 75% of the medium values.

The **Announced Pledges Hydrogen Focus Scenario [AP_H2]** is different from AP_TO in hydrogen policy: Government subsidies on hydrogen production are introduced so achievement of national targets for green or low-carbon hydrogen production is ensured. For Germany, this means reaching 10 GW of green hydrogen production capacity by 2030 (German Federal Government 2023) or 0,8 Mt of yearly green hydrogen production. For Canada, 4 Mt of low-carbon hydrogen are to be produced by 2040 and 20 Mt of low-carbon hydrogen by 2050 (Government of Canada 2020).

The **Announced Pledges Hydrogen Trade Scenario [AP_TR_ME]** is also based on AP_TO, but with a different hydrogen policy than AP_H2: Government subsidies on hydrogen and hydrogen derivative export from Canada to Germany are introduced, so certain trade amounts are realized. The subsidy payment is shared between the Canadian and German government. The trade amounts are based on the German Hydrogen Import Strategy. The German Hydrogen Import strategy expects 45 to 90 TWh/162 to 324 PJ of hydrogen and hydrogen derivative imports to Germany by 2030 (German Federal Government 2024). The mean value of this range is 67,5 TWh/243 PJ. Assuming that 10% of this amount is imported from Canada yields the target export amount of 6,75 TWh/24,3 PJ by 2030. A similar procedure is applied for the following years, leading to a target amount of 44,1 TWh/158,76 PJ by 2045.

3 Results

In the following, results from the modeling exercise are presented and discussed. First, the global results provide some background information on the emergence of hydrogen in the worldwide energy system. Then, Canada and Germany are focused individually, both from an energy system and a macroeconomic perspective. The part on Canada contains a deep-dive into the province of Québec and the Greater Montréal region. Finally, the hydrogen trade between Canada and Germany is analysed.

In general, the results for the whole world and for Canada are analysed with respect to 2030 and 2050; for Germany the focus years are 2030 and 2045, because 2045 is the target year for climate neutrality in Germany.

[1] NEWAGE, ACSG, TAM-Supply and PyPSA-EUR models follow the same specified absolute values for medium and optimistic efficiency, CAPEX and OPEX. AD-MERGE, NAGEM and NATEM use other assumptions on the absolute starting values, but follow the same relative developments.

3.1 Global

3.1.1 Final energy demand

For global final energy demand (Figure 2), AD-MERGE projects a rise of total final energy demand between 2030 and 2050, while NEWAGE projects a decline. This pattern can be observed throughout all scenarios, and points to differences among the models in the interplay of effects that increase energy demands such as population growth and general capital accumulation and effects that decrease energy demands such as efficiency and productivity improvements. Morerover, AD-MERGE shows a noticeable increase of biomass final energy use in all scenarios between 2030 and 2050. This potentially low-carbon or even carbon-negative energy carrier is not available in NEWAGE (except partly in electricity generation), requiring stronger reduction of emissions through other means.

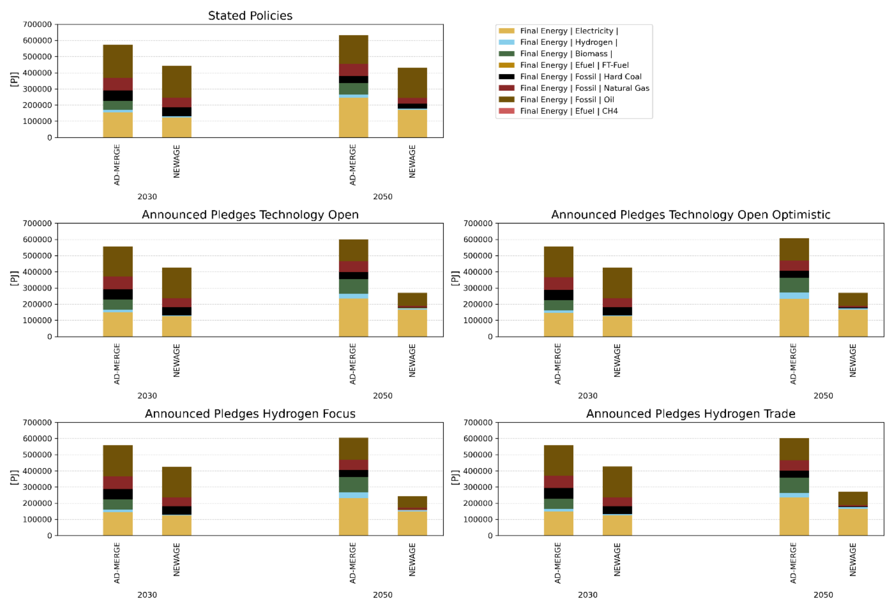

Figure 2: Final energy demand globally.

Fossil fuels maintain a substantially higher share of final energy demand by 2050 in the SP scenario compared with the AP scenarios in both models, as climate policy is less strict.

In all AP scenarios, both models show a rising share of electricity and hydrogen demand. NEWAGE and AD-MERGE results differ remarkably in the degree of end use electrification. However, despite a growth, the overall share of hydrogen in final energy demand remains on a relatively low level in both models (maximum 6,4% for AD-MERGE and 4,2% for NEWAGE in 2050).

In summary, the results point to a significantly rising share for electricity in final energy demand, but not so much for hydrogen.

3.1.2 Hydrogen provision

In the SP scenario, grey hydrogen production continues to be the dominating production route by 2050 in both models (Figure 3). Hydrogen production in total increases little from 2030.

Looking at the AP scenarios, a stronger increase of hydrogen production between 2030 and 2050 is visible. However, this increase is far more pronounced in AD-MERGE. Furthermore, the technologies active in hydrogen production are very different: In all AD-MERGE results for AP scenarios, already in 2030 there is a higher production of low-carbon hydrogen than grey hydrogen. By contrast, in NEWAGE results, blue and green production together make up for less than half of global hydrogen

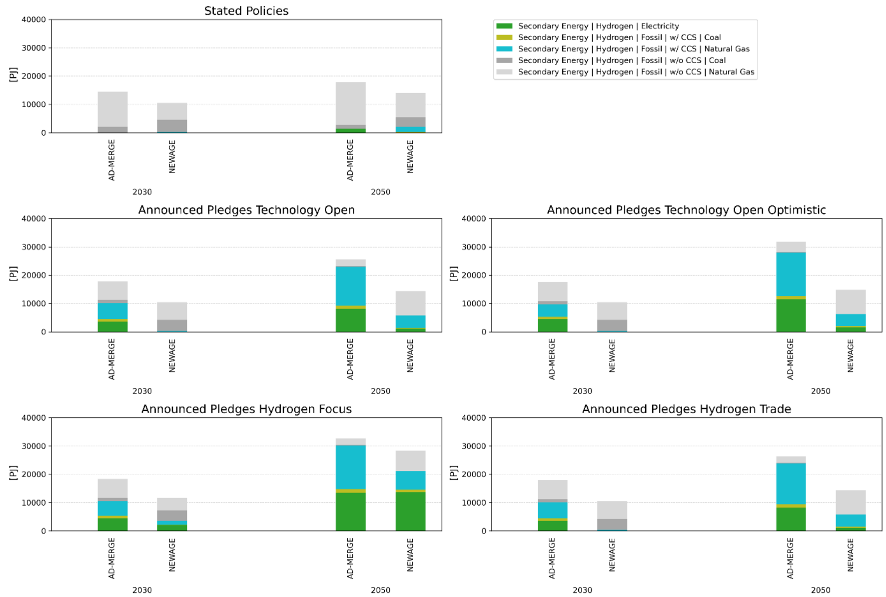

Figure 3: Hydrogen provision globally.

production even in 2050. The scenario with optimistic assumptions about future efficiency, CAPEX and OPEX of electrolysers (AP_TO_O) leads to a moderate effect on electrolytic hydrogen production (11427 PJ instead of 8095 PJ in 2050 for AD-MERGE, 1585 PJ instead of 1069 PJ in 2050 for NEWAGE).

By mid-century, hydrogen production reaches approximately 24 EJ in AD-MERGE and 12 EJ in NEWAGE under the AP_TO scenario. These outcomes are consistent with the 25th–75th percentile range (12–25 EJ) reported for the IPCC AR6 C3–C4 categories (corresponding to pathways limiting global temperature increase below 2 °C), as analyzed by (Ghaboulian Zare et al. 2025) based on the AR6 scenario database (Byers et al., 2022). The full range of reported hydrogen production across C3–C4 pathways in 2050 extends from 5 EJ to 70 EJ, highlighting the substantial uncertainty across global mitigation scenarios. In the other AP scenarios, hydrogen production in AD-MERGE rises further, reaching 27–32 EJ, which exceeds this interquartile range and highlights the challenges of meeting such ambitious targets. Furthermore, consistent with the findings of (Ghaboulian Zare et al. 2025), both models indicate that fossil-based technologies remain the dominant hydrogen production route by mid-century. In AD-MERGE, blue hydrogen from natural gas with CCS accounts for the majority of production, whereas NEWAGE relies mainly on grey hydrogen from unabated natural gas reforming, with both pathways gradually complemented by green hydrogen from electrolysis.

In the NEWAGE model, hydrogen production from other technologies than the ones utilized in the global results (e.g. biomass) is not available. Hydrogen derivative options in NEWAGE are limited to synthetic natural gas and oil, and these can only be produced using hydrogen from domestic electrolysis. In the NEWAGE results of the AP_TO scenario, even all of the green hydrogen produced is used for production of synthetic fuels. As there are no derivatives available in AD-MERGE and the range of derivatives in NEWAGE is limited to synthetic gas and oil, more derivative options might unlock some further potential for green hydrogen production.

The differences in results for 2030 and 2050 indicate that there is no clear view on the timeline and even on the long-term scale of the uptake of green and blue hydrogen production. According to these results, both blue and green hydrogen would play a role in 2050, but the models do not agree to what extent. Optimism about the technological development of electrolysis as reflected in the AP_TO_O scenario yields rather small absolute increases in the use of this production technology.

3.2 Canada

3.2.1 Final energy demand

Across all four scenarios, the evolution of Canada's final energy demand reveals clear evidence of decarbonization, electrification, and fuel diversification (Figure 4). After 2030, the total final energy use stabilizes in AD-MERGE but declines in NEWAGE and NATEM, suggesting that rising energy efficiency and higher marginal energy costs offset the effects of economic and population growth. This convergence toward lower energy intensity is consistent with the net-zero pathway assumptions, where efficiency improvements, electrification, and behavioral changes jointly suppress overall demand growth. Electricity becomes the dominant end-use carrier across all models and scenarios, reflecting both the decarbonization of supply and the electrification of transport and industry. Its consistent expansion underscores the critical role of power system decarbonization in achieving national mitigation targets.

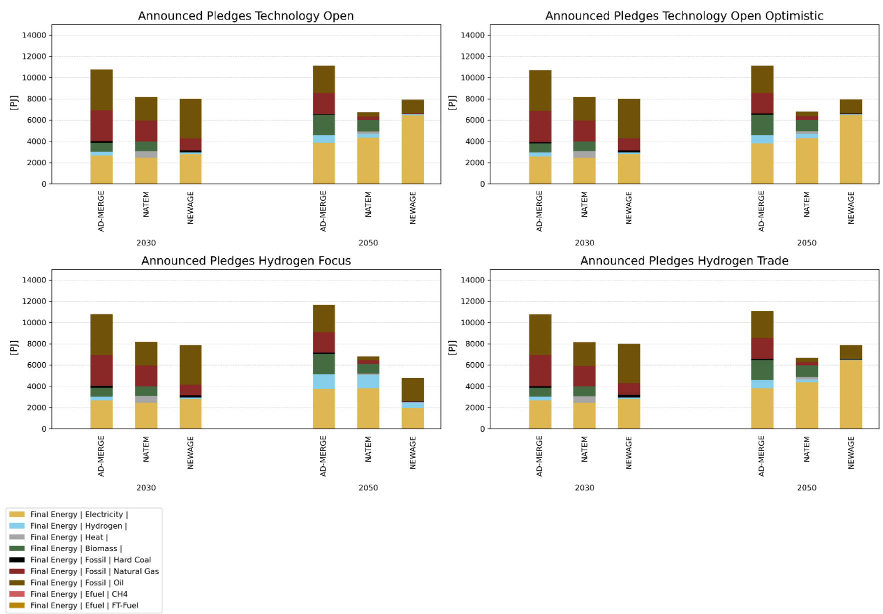

Figure 4: Final energy demand in Canada.

Fossil fuel use contracts markedly in every model, with coal virtually phased out by 2030. While oil use declines sharply across all pathways, it remains more persistent in AD-MERGE and NEWAGE and transition away from oil is slower. Natural gas, however, exhibits distinct trajectories across the three models. NEWAGE projects an almost complete phase-out of natural gas by mid-century, whereas NATEM shows a substantial but not total decline, as a portion of gas demand gradually shifts toward electricity and hydrogen-based energy systems. In contrast, AD-MERGE maintains a limited yet persistent role for natural gas through 2050, primarily in non-electric sectors and transitional DACCS applications. The availability and use of carbon dioxide removal (CDR) options such as BECCS and DACCS in AD-MERGE enable residual fossil consumption while still achieving net-zero targets. These divergences indicate differences in how models handle substitution dynamics and the trade-off between technological stringency and CDR reliance.

Hydrogen and biomass emerge as complementary low-carbon vectors, but their roles vary across models. Hydrogen domestic use expands notably in AD-MERGE and NATEM, especially in scenarios explicitly tied to hydrogen policies (AP_H_2), while NEWAGE does not represent a comparable hydrogen use transition and a significant part of the produced hydrogen is used for export. Biomass remains a consistent contributor in AD-MERGE and NATEM, functioning both as an energy carrier and a

CDR enabler through BECCS. Its persistent share across scenarios reflects its strategic importance in balancing residual emissions from other fuels. In NEWAGE, where biomass is not modeled as a distinct carrier, the absence of this flexibility contributes to sharper fossil reductions and steeper total energy use declines. Overall, the cross-model comparison underscores the importance of technological scope and system representation in shaping Canada's net-zero transition narrative.

3.2.2 Hydrogen provision

Hydrogen production by 2030 in AD-MERGE already presents a diversified hydrogen mix, combining electrolysis with SMR coupled with CCS (Figure 5). In contrast, both NATEM and NEWAGE register negligible green and blue hydrogen activity at that stage, highlighting the delayed onset of large-scale low-hydrogen deployment in their system pathways. By 2050, however, AD-MERGE and NATEM project a substantial expansion in hydrogen supply, exceeding 500 PJ in all AP scenarios, primarily for domestic energy use, whereas NEWAGE remains below 300 PJ (with the exception of the APS-H2 scenario, which is designed to meet national targets), with some production oriented toward exports. These differences reflect the uncertainty surrounding the future scale of hydrogen deployment, but also differences in input assumptions and the methodological contrast among the models. AD-MERGE (a Hybrid IAM) and NATEM (a bottom-up energy system model) both incorporate a bottom-up energy system component, which endogenously optimize technology deployment and fuel substitution based on cost and system interactions. In contrast, NEWAGE follows a top-down macroeconomic approach, where hydrogen is embedded within broader production, demand and trade structures.

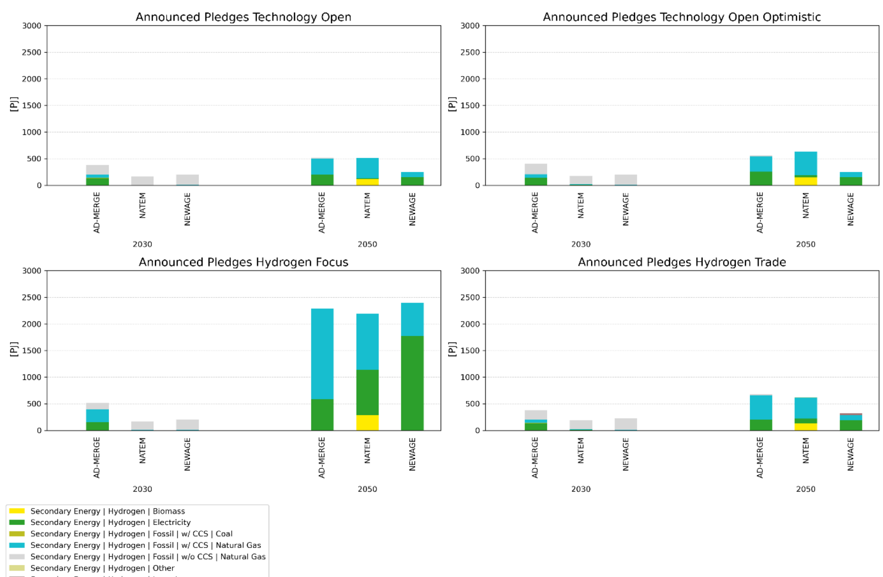

Figure 5: Hydrogen provision in Canada.

Scenario-specific results further highlight the sensitivity of hydrogen deployment to assumptions about technology learning and policy ambition. Across all models, low-carbon hydrogen production expands notably after 2030, with AD-MERGE and NEWAGE scaling up both electrolysis and blue hydrogen, while NATEM develops a more balanced mix that includes modest biomass contributions. NEWAGE relies more on electrolysis, consistent with its stronger electrification pathway. AD-MERGE does not deploy biomass for hydrogen production, while NEWAGE does not include a biomass-based hydrogen option in its technology portfolio. Although biomass-based hydrogen is generally not cost-competitive in the modeled time horizon in AD-MERGE, incorporating more explicit pathways for biomass, for e.g. advanced biofuels and biochar could improve the representation of biomass and its practical role in low-carbon energy transitions.

In the AP_TO_O scenario, optimistic electrolysis cost assumptions drive a post-2030 rise in green hydrogen across all models, underscoring the potential impact of accelerated technological learning. In the AP_H2 scenario, where explicit national production targets are imposed, hydrogen output increases further, but this higher production translates not necessarily into greater domestic use. Instead, infrastructure limitations, gradual sectoral integration, and growing export opportunities constrain domestic consumption. Finally, in the AP_TR scenario, each model raises hydrogen production using a technology mix similar to AP_TO but reallocates at least the additional share toward satisfying trade requirements. Rather than a limitation, these results suggest that Canada's hydrogen sector could leverage early export markets as a strategic pathway for scaling production, investment, and technological readiness over the long term.

3.2.3 Macroeconomic effects

GDP results for the AP_TO_O scenario show hardly any difference to AP_TO results across all models (Figure 6).

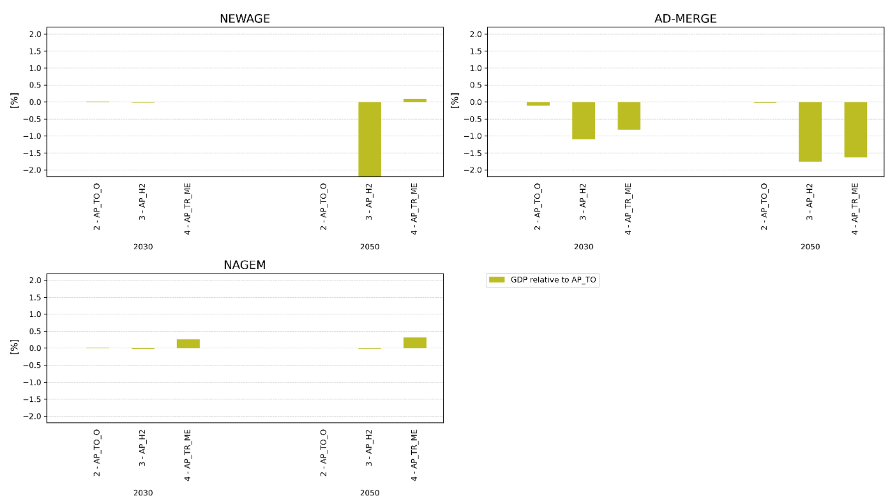

Figure 6: GDP in Canada relative to the Announced Pledges Technology Open scenario.

In the case of AP_H2, the effects are very small in NAGEM, but AD-MERGE shows a noticeable GDP loss in 2030 (-1,1%) and 2050 (-1,8%). NEWAGE reports a dramatic decline in GDP for 2050, reflecting the difficulties the model had to solve this scenario with its ambitious hydrogen production targets.

The AP_TR_ME scenario yields a consistently positive GDP effect of up to +0,58% in 2040 in NAGEM, whereas AD-MERGE reports declines of -0,8% and -1,6% in 2030 and 2050, respectively. In AD-MERGE, both production and trade subsidies are accompanied with a noticeable decline in GDP, indicating a less efficient allocation of government revenues. NEWAGE shows GDP effects below 0,1% of magnitude in AP_TR_ME.

In a Canada-only macroeconomic model like NAGEM, the benefits of domestic policies (such as clean technology investments, carbon pricing revenue recycling) are fully internalized within the national economy. All induced effects, such as higher employment, increased investment, productivity gains, and household spending, remain in Canada, since there are no competing international feedbacks or leakages. The model therefore tends to capture the gross positive impacts on domestic output and welfare without dilution from external trade adjustments.

By contrast, in global model such as NEWAGE and AD-MERGE, Canada is part of an interdependent system where other regions' strategies and policies have an immediate impact on its economy. For instance, shifts in global demand, carbon pricing schemes abroad, or large-scale technology deployment in other countries can alter international prices, competitiveness, and trade patterns. These feedbacks may offset or amplify the domestic effects of Canadian policies. Higher domestic costs may reduce exports or attract imports, while changes in global energy markets or carbon border adjustments can directly affect Canada's balance of trade and industrial performance.

Consequently, while the same policy may yield positive domestic effects in an isolated model, its net impact becomes smaller or even negative, once international trade, capital mobility, and exchange-rate feedbacks are taken into account. This effect is observed for the hydrogen trade scenario between Canada and Germany (AP_TR_ME). In NAGEM, where Canada is modelled as a standalone national economy, exporting hydrogen to Germany generates additional domestic production, investment, and employment. These effects stimulate GDP growth compared to the reference Announced Pledges Scenario (AP_TO), as the model captures the positive internal multipliers of expanding hydrogen supply chains and export revenues without considering external leakages.

The divergence between national and global model results reflects structural uncertainty, not a modelling inconsistency. The contrasting results trend shows that evaluating policies in isolation may overestimate national benefits, as it omits adjustment mechanisms that occur in real global markets. While the national model (NAGEM) is useful to assess domestic industrial potential, the global models (NEWAGE and AD-MERGE) are essential to understand relative competitiveness and exposure. Therefore, the models provide a range of plausible macroeconomic responses under different assumptions about openness and interdependence. The results highlight that Canada's macroeconomic outcomes in trade-intensive transitions (like hydrogen exports) are highly dependent on international variables, such as global prices, competitors' strategies, exchange rates, and technology costs. A change in any of these factors can shift the sign of the impact.

3.3 Québec

3.3.1 Hydrogen provision

Results for hydrogen provision in Québec show significant differences in the absolute level and the composition between NATEM and ACSG (Figure 7).

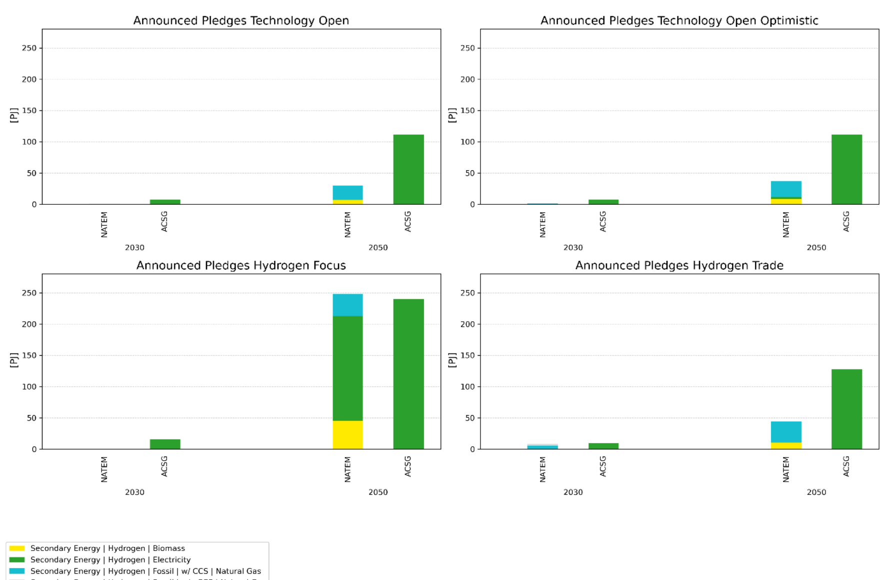

Figure 7: Hydrogen provision in Québec.

NATEM expects consistently a far lower hydrogen production throughout all scenarios and both years under consideration, except for the NZ_H2 scenario. Leaving the NZ_H2 scenario aside, Steam

Methane Reforming with CCS emerges as the main hydrogen production technology in NATEM by 2050. However, hydrogen production targets in the NZ_H2 scenario are met by more than 200 PJ of hydrogen production from electrolysis, in addition to increased production from the other low-carbon production technologies.

ACSG in contrast reports only electrolytic hydrogen production throughout all AP scenarios. Electrolysis in ACSG plays an important role in stabilizing the electricity grid through capacity services.

3.4 Greater Montréal

3.4.1 Final energy demand

To complement the global, national and provincial perspectives, we include results from a regional optimization model (ETEM) applied to the Greater Montréal region (Figure 8). The model captures hydrogen deployment pathways from supply to demand across the industrial and transportation sectors, under the AP_TO, AP_TO_O and AP_H2 scenarios tailored with regional techno-economic parameters.

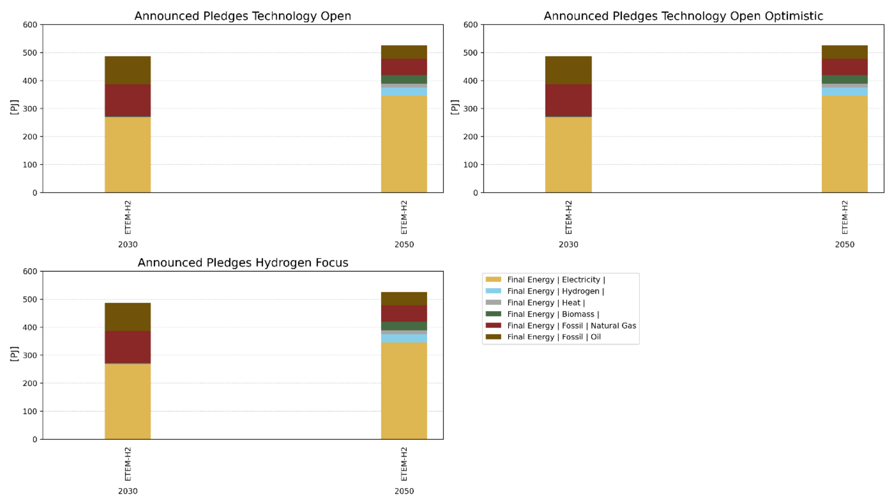

Figure 8: Final energy demand in Greater Montréal.

Results indicate a steady growth in hydrogen demand, particularly between 2040 and 2050, driven primarily by the decarbonization of heavy transport and industrial applications. In industrial facilities, grey hydrogen is progressively replaced by blue hydrogen and eventually by green hydrogen by 2050. In the most optimistic technology scenarios, total hydrogen demand reaches approximately 30 PJ by 2050, representing about 6% of the region's final energy demand.

On the supply side, the model prioritizes electrolysis for hydrogen production, except under less restrictive assumptions where electrolysers are replaced by ATR+CCS technologies. By 2050, electrolysis accounts for more than 90% of the hydrogen supply in the optimistic scenario, with the remaining demand met through hydrogen imports from outside the Montréal region. No hydrogen exports are modeled, given the regional scope of the analysis.

Hydrogen integration contributes to a cumulative 98% reduction in GHG emissions by 2050 compared to 1990 levels, with most reductions occurring after 2040. These regional insights highlight the critical influence of technological assumptions and, even more importantly, targeted sectoral policy incentives in shaping hydrogen's role in Québec and the Greater Montréal area.

3.5 Germany

3.5.1 Final energy demand

The final energy developments in Germany are not directly comparable across the models due to their inherent differences in scope and architecture (Figure 9). NEWAGE and PyPSA-EUR consider the whole German energy system while including sectors of transport, industry, supply, etc., while only the detailed supply sector is present in TAM-Supply. NEWAGE computes the general equilibrium of the whole economy for the case of Germany (and the world), while PyPSA-EUR and TAM-Supply only have the partial equilibrium considerations from the energy perspective. TAM-Supply also does not explicitly include use of fossil fuels for final energy requirements but has representations of electricity, heat, and synthetic energy carriers. Given the differences in the modelling approaches, the differences observed in terms of final energy are as expected.

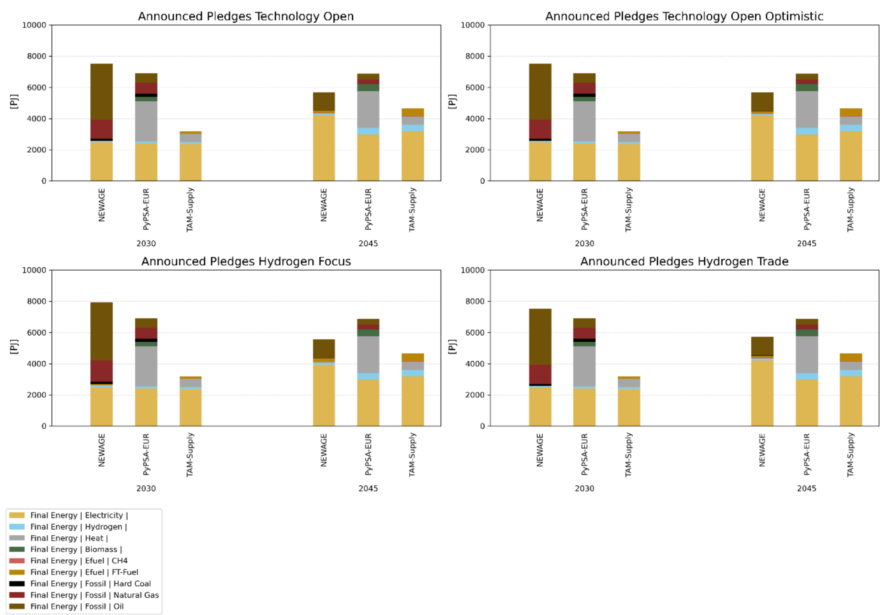

Figure 9: Final energy demand in Germany.

In the AP_TO scenario, NEWAGE observes an overall decrease in final energy consumption, while contrastingly TAM-Supply and PyPSA-EUR see an increase. The role of electricity in final energy requirement however increases across all the three models and are in consensus about needing more than 3000 PJ of electricity by 2045. This increase represents nearly doubling of the final energy requirement as electricity from the current 1660 PJ (AGEB 2025) and underlines a significantly electrified future under climate-neutral development targets. Fossil energy carriers are consecutively replaced by synthetic options and PyPSA-EUR and TAM-Supply note a significant role for these compared to NEWAGE. It should be noted here that the values reported by PyPSA-EUR for final energy of hydrocarbon fuels in 2045 actually refer to the use of synthetic carriers and are not of fossil origin.

Across the scenarios with optimistic cost and efficiency developments of electrolyser (AP_TO_O), explicit hydrogen production targets (AP_H2) and explicit trade requirements between Canada and Germany (AP_TR_ME), no significant changes across final energy developments are observed across the models.

As a major role of electricity is observed for the future, these are detailed further in the next section. The role of hydrogen and derivatives, their provision and imports are discussed in the further sections.

3.5.2 Electricity provision

In Germany, the demand for electricity and hence its provision is expected to grow significantly across all the models (Figure 10). These report a growth of more than 50% from the current electricity production of 3000 PJ (AGEB 2025) to around 4500-5300 PJ by 2045.

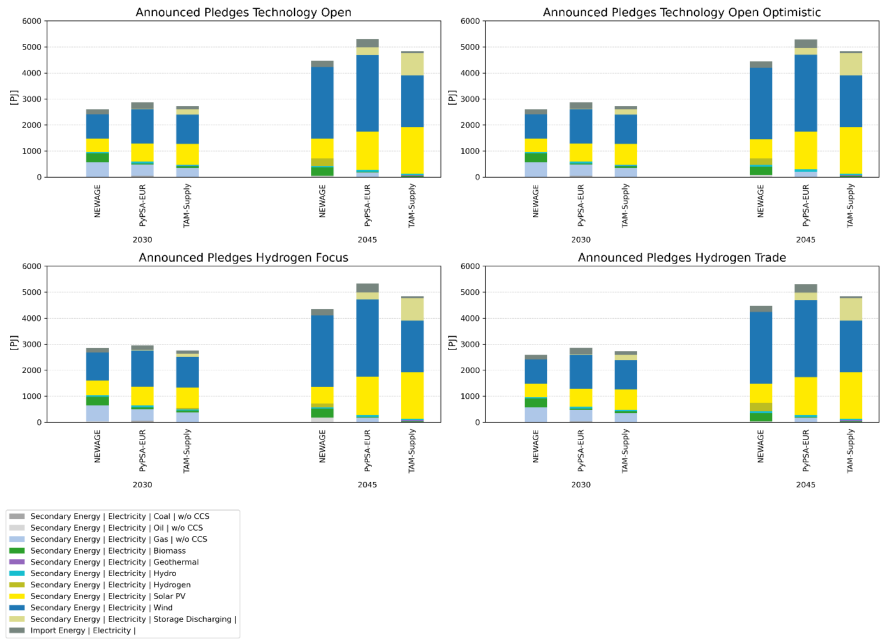

Figure 10: Electricity provision in Germany.

To meet these requirements under climate-neutral development strategies (AP_TO), a significant development of renewable technologies in the form of Solar PV and Wind is seen across the models. By 2030, electricity from solar PV technologies is seen to contribute around 500 PJ in NEWAGE, 700 PJ in PyPSA-EUR and 800 PJ in TAM-Supply. This represents an increase of 80% or more in the next 5 years compared to the 271 PJ produced by these technologies today (AGEB 2025). By 2045, wind generation takes the lead in its contributions reaching nearly 2000 PJ through TAM-Supply, and approximately 2700 PJ and 3000 PJ through NEWAGE and PyPSA respectively. The contribution of Wind generation in PyPSA-EUR represents a sixfold increase by 2045 compared to its contribution of 500 PJ today (AGEB 2025). Grid flexibility under these very high VRE (Variable Renewable Energy) shares is provided through a combination of grid-balancing technologies including batteries, gas or oil power plants (eg. CCGTs running on synthetic gas), as well as hydrogen-based turbines. This total reaches around 300 PJ in the case of NEWAGE, followed by around 470 PJ and 860 PJ in PyPSA-EUR and TAM-Supply respectively. Additional grid balancing options of biomass, hydro, and geothermal power plants also support in this aspect. It should also be noted that electricity imports also form part of the flexibility provisions under the highly-connected European electricity grid.

With the introduction of optimistic cost and efficiency developments of electrolysers through the AP_TO_O scenario, no significant changes in terms of electricity provision are observed among the three models. A similar observation is also noted for the explicit trade scenario of AP_TR_ME. However, in the scenario with the explicit electrolyser capacity requirement of 10 GW (AP_H2), a corresponding slight increase in electricity demand is observable in 2030 to produce the required hydrogen. The effect of these scenarios on the hydrogen and derivative production as well as their imports are described in the next sections.

3.5.3 Hydrogen provision

In contrast to the case for electricity from the section above, a clear consensus among the models for hydrogen demand as well as its provision is not observed (Figure 11). The demand in 2030 lies in the range of 100-360 PJ, with NEWAGE and PyPSA-EUR representing the lower-end. By 2045 however, PyPSA-EUR observes a sixfold increase for the amount of hydrogen required reaching nearly 750 PJ, closely followed by TAM-Supply. The demand also increases substantially in the case of NEWAGE and reaches around 600 PJ in AP_TO. Most of this hydrogen is required to meet the demands from the industrial and transport applications. At the same time, the hydrogen can also be converted to form the derivatives domestically (in NEWAGE, derivatives can only be made from domestically produced green hydrogen) as well as being reconverted to produce electricity to provide grid-balancing characteristics. To put this demand growth into perspective, the current demand of hydrogen in Germany is around 200 PJ with most of it met through fossil-based production options and produced in a self-reliant manner at the industrial sites (German Federal Government 2020).

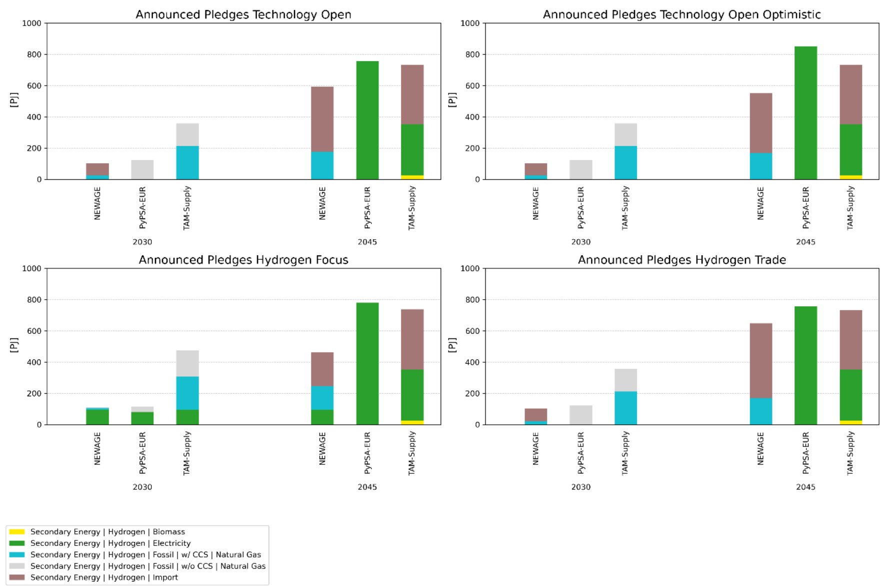

Figure 11: Hydrogen provision in Germany.

Under the climate-neutral development strategies (AP_TO), in 2030 most of the hydrogen is produced through the fossil-based gas reforming options in all the models. TAM-Supply and NEWAGE also include Blue-hydrogen production options through the usage of carbon-capture. In TAM-Supply, this captured carbon is also then used to domestically produce some of the required synthetic hydrocarbon derivatives (see next section for further explanation). Hydrogen supply in NEWAGE is mostly covered by imports. By 2045, the domestic production in TAM-Supply and PyPSA switches completely to greener options of electrolytic and biogenic hydrogen. PYPSA-EUR sees a significant expansion of electrolyser technologies for the provision of this green hydrogen, while TAM-Supply observes also the inclusion of biogenic hydrogen production options. NEWAGE however, continues to observe only blue-hydrogen production. Imports in the form of gaseous or liquid hydrogen (which is regassified to form gaseous hydrogen) are required to meet the rest of the demand and represent around 50%-70% of the provision through TAM-Supply and NEWAGE.

In the scenario with optimistic cost and efficiency development of electrolysers (AP_TO_O), an increase of around 100 PJ of electrolytic hydrogen is observed through PyPSA-EUR in 2045, while TAM-Supply and NEWAGE remain largely unaffected. This optimistic development of electrolysers also has effects on regions other than Germany through the global NEWAGE model which is reflected through additional derivative imports discussed in the following section. This scenario resultingly indicates that an optimistic development of electrolysers might directly benefit Germany through slightly higher domestic production capabilities, but also indirectly through relatively reduced hydrogen or derivative import costs.

With the requirement of a minimum electrolyser capacity of 10 GW through the AP_H2 scenario, exactly this capacity is installed in 2030 in all the models. In PyPSA-EUR, the fossil-based hydrogen is partly replaced through this electrolytic provision, while in the case of TAM-Supply, additional electrolytic hydrogen is made available along with the previously available fossil and blue-hydrogen. As the electrolytic hydrogen provisions were already above the required capacities in 2045 in PyPSA-EUR and TAM-Supply, no change is observed here. As a result, this scenario portrays that an explicit domestic hydrogen production target can help in replacing fossil-based options, and at the same time could also be beneficial to reduce the dependency on imports.

When the trade between Canada and Germany is made explicit through the AP_TR_ME scenario, virtually no difference is observed for the case of hydrogen provision through PyPSA-EUR and TAM-Supply. However, in the case of NEWAGE, some additional imports of regassified liquid hydrogen take place. This scenario result suggests that imports from Canada might not necessarily happen as pure H2, but rather in the form of derivatives. The case of the derivatives, their production and imports to Germany is explained in the following section.

3.5.4 Derivative provision

The requirement of hydrogen derivatives in the form of synthetic gas and fuel, methanol, as well as ammonia is observed to be almost the same as pure hydrogen in the early year of 2030 (<400 PJ) (Figure 12). However, by 2045 it increases significantly and is much higher than that of pure hydrogen in TAM-Supply and PyPSA, reaching almost 1600 PJ in PyPSA-EUR. This increase can be explained due to the requirement of fossil-fuel alternatives in the form of synthetic hydrocarbons in applications demanding high volumetric energy densities. In PyPSA-EUR and TAM-Supply, most of the requirement of synthetic fuel comes from the transport sector, while methanol and ammonia requirements stem from the chemical industry applications including conversion to high value chemicals (HVCs), and synthetic gas (SNG) is used mainly for heating purposes. At the same time, SNG is also reconverted to produce electricity to balance the electric grid in in PyPSA-EUR. In NEWAGE, where methanol and ammonia are not an option, synthetic gas is mostly used in transport, and synthetic oil for electricity generation.

When following strategies for a climate-neutral development (AP_TO), considerable requirements of these synthetic derivatives are observed in 2045. In 2030, some requirements of synthetic ammonia and methanol are observed from the chemical industry in both PyPSA-EUR and TAM-Supply. Additional requirements of synthetic fuels from the transport sector are observed in TAM-Supply. However, NEWAGE indicates no such demand of hydrogen derivatives would be present in Germany by 2030. While all of the derivatives are imported in 2030 in PyPSA-EUR, their domestic production is significant in TAM-Supply with only low import dependency. The domestic production in case of TAM-Supply is mainly of the carbon-derivatives of methanol and synthetic fuel, with a slight production also of synthetic ammonia. The required carbon for these derivative productions comes from the carbon captured from the production of the blue hydrogen mentioned above. This indicates a strong synergy for sourcing carbon and hydrogen through blue hydrogen production routes. However, it should be noted that the synthetic fuel produced from carbon sourced this way has still emissions associated with it and does not support reaching climate neutrality the same way if the carbon was sourced for example from biogenic sources instead. By 2045, the requirement of these synthetic fuel sources becomes significant and the majority of it is imported in all the models. Some domestic production of ammonia as well as synthetic fuel is still observed through PyPSA-EUR and TAM-Supply, but the methanol and methane are still completely imported. NEWAGE also observes a requirement of derivatives in the form of synthetic fuel and methane, and these mostly find their application in the transport and electricity sectors.

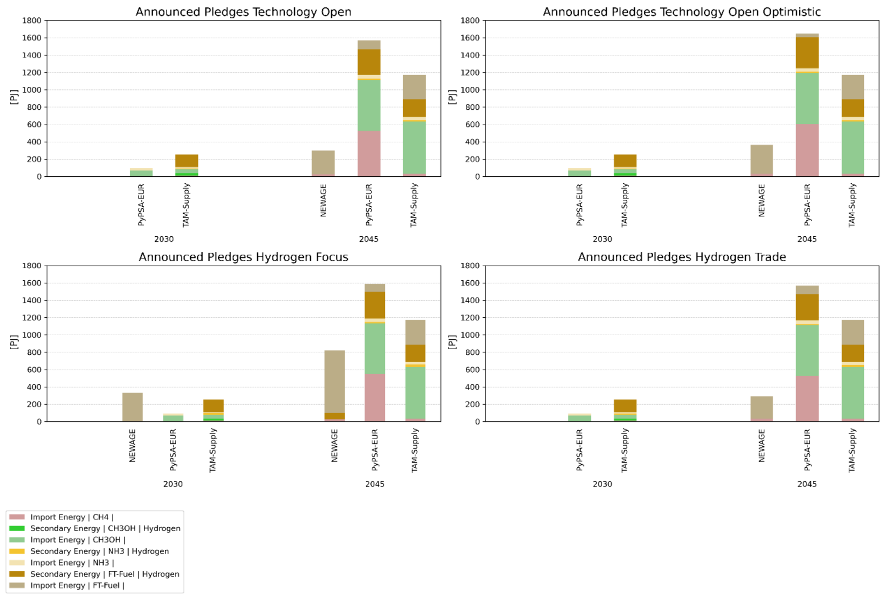

Figure 12: Derivative provision in Germany.

The optimistic cost & efficiency developments of electrolysers through the AP_TO_O scenario result in higher domestic productions of the derivatives in PyPSA-EUR. This results from the increased domestic electrolytic hydrogen production as explained above which can now be converted to form these derivatives. At the same time, an increase in the amounts being imported is also observed in NEWAGE and PyPSA-EUR. Due to the global aspect of NEWAGE, the optimistic electrolyser developments result in relatively increased and cheaper production of hydrogen and the following derivatives in some regions. These can resultingly be imported to a larger extent to Germany. As a result, this scenario indicates that the optimistic cost assumptions of electrolysers not only promotes the production of domestic hydrogen as well as derivatives, but can also increases the scope of imports if available.

With the inclusion of the explicit hydrogen production targets through the AP_H2 scenario, a slight increase in domestic production of the derivatives (ammonia) from this additional available hydrogen is observed in TAM-Supply in 2030. For PyPSA-EUR, no change is observed under this scenario since in contrast to TAM-Supply, no additional hydrogen is available as explained above. This scenario is indicative that additional available amounts of domestic hydrogen can be converted further to form derivatives. Changes in NEWAGE towards the other AP scenarios are more pronounced. In this global model, Germany can take advantage of hydrogen production targets in other world regions and import large amounts of Fischer-Tropsch fuel in 2030 and 2045 (332 and 720 PJ in 2030 and 2045 respectively).

Through the AP_TR_ME scenario defining the explicit trade between Germany and Canada, NEWAGE observes a slightly higher import of hydrogen and synthetic gas in 2045, while synthetic oil imports are slightly declining. PyPSA-EUR and TAM-Supply however do not note any changes over the years. It should be specified here that even though the total imports of the derivatives remains the same, the share of the countries providing these imports to Germany might still differ. The case of the imports from Canada are discussed in the trade specific section below.

3.5.5 Macroeconomic effects

Compared with AP_TO, the other "Announced Pledges" scenarios yield minimal differences in NEWAGE results in 2030 (Figure 13).

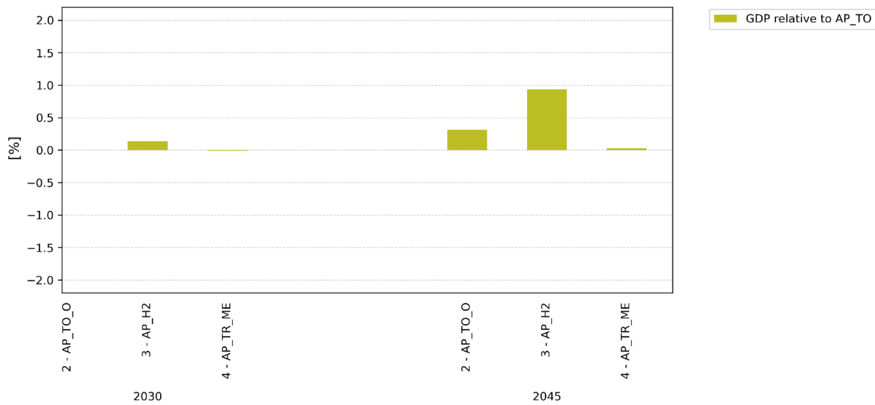

Figure 13: GDP in Germany relative to the Announced Pledges Technology Open scenario.

While Germany benefits not directly from electrolysis improvements in AP_TP_O, there are indirect effects through trade, leading to a small positive GDP effect in 2050.

With regard to the AP_H2 scenario, where a small positive effect is visible in 2045, the global coverage of the NEWAGE model and the scenario definition has to be remembered: Not just Germany (which keeps its hydrogen production target constant after 2030) and Canada, but many other countries in Europe and around the world implement ambitious hydrogen targets. This increases the worldwide supply of low-carbon hydrogen, which is beneficial for Germany.

3.6 Hydrogen trade between Canada and Germany

In the Announced Pledges scenarios besides AP_TR_ME, hydrogen or hydrogen derivative exports from Canada to Germany appear only in PyPSA, TAM-Supply and – to a small extent – NEWAGE (Figure 14). These models represent Canada as the only source of imports to Germany (PyPSA) or include a a limited set of potential supply regions (TAM-Supply, NEWAGE). PyPSA and TAM-Supply hydrogen imports from Canada occur almost entirely in the form of derivatives. PyPSA reports roughly equally large amounts of Synthetic gas and Methanol imports. Both models see a large share of several hundred PJ of Methanol imports and a small share of Ammonia imports throughout the compared scenarios.

In NATEM (and ACSG, which is not represented in the graphics due to its regional focus on Québec), hydrogen or derivatives are only exported from Canada to Germany in the case of explicit trade subsidies.

his result is partly influenced by the different export and import price assumptions in the models. In general, the level of hydrogen or derivative trade prices is highest in NEWAGE, followed by NATEM and then TAM-Supply and PyPSA-EUR. TAM-Supply and PyPSA-EUR have harmonized import price assumptions. ACSG's export prices are roughly in a similar range to TAM-Supply and PyPSA-EUR. At the same time, variations in other parameters and underlying model mechanisms prevent entirely straightforward comparisons.

Additional insights may result from two model specifics: First, NEWAGE and NATEM are more limited in the represented range of derivatives that can be traded internationally. NEWAGE has synthetic gas and oil options, but not methanol or ammonia. NATEM can only export liquid hydrogen to Germany. A wider range of potential forms of hydrogen exports could increase the probability of exports. Second, these two models take domestic Canadian hydrogen demand into account, which competes with potential exports.

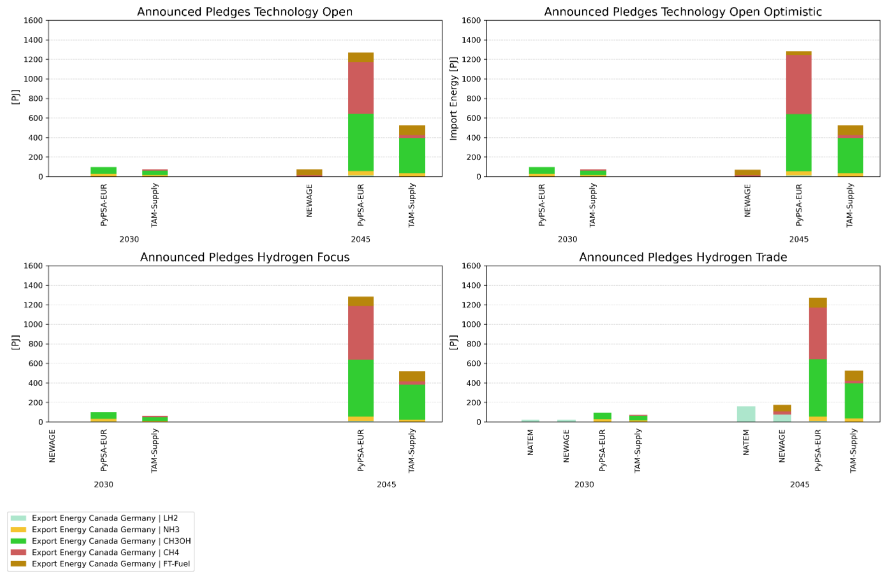

Figure 14: Hydrogen and hydrogen derivative exports from Canada to Germany.

This indicates that without subsidies on trade, hydrogen derivative exports from Canada to Germany are competitive with production in Germany, but when expanding the view to domestic Canadian hydrogen demand and other potential supply countries, competitiveness based on direct cost becomes less clear. At the same time, "soft factors" that are not represented in the models, such as the existence of an experienced energy industry and traditionally stable relations between both countries, could change the picture in real-world considerations.

3.7 Carbon intensity of hydrogen delivery from Canada to Germany

Based on the modeling results, the greenhouse gas emissions associated with the hydrogen supply from Canada to Germany are assessed in a prospective Life-Cycle Assessment under the NZ_TR_ME scenario. It is conducted based on ISO 14040/44 and ISO TS 19870 for hydrogen production systems. The system boundaries are set as cradle-to-delivery-gate, encompassing all stages of electrolytic hydrogen production in Canada, conversion to liquid hydrogen or ammonia, transport via ship from the Port of Saint John and reconversion at the port of Hamburg. The Life-Cycle Inventory is gathered using foreground grid mix data from NATEM model for the Canadian side and TAM-Supply model for the German side. NATEM shows, that export of electrolytic hydrogen happens in the province of New Foundland and Labrador, specifically produced from alkaline electrolysis. Based on the NATEM modeling results, the technological composition of the grid and the associated carbon intensity are modeled, where background electricity generators provided by ecoinvent 3.9.1 database were used.

Spatial distribution of the electrolyzer fleet is not considered, all electricity dedicated for hydrogen production is assumed to be fed into one electrolyzer system node. This follows the assumption, that future large-scale grid-connected hydrogen production dedicated for export, will take place in proximity to a port to save on additional transport and subsequently, costs. The hydrogen is stored, either liquified or converted into liquid ammonia. Heavy fuel oil powered ships transport the hydrogen carrier from the port of St John to the port of Hamburg. At the receiving port, gaseous hydrogen is obtained via regasification or cracking from liquid hydrogen or liquid ammonia, respectively. It is then ready to be injected, blending into the German natural gas grid. In the future, this will be retrofit for transporting hydrogen exclusively. The functional unit of the LCA study is "1 kg of gaseous hydrogen at 30 bar and 99.9 vol% purity delivered in 2025, 2030, 2040 and 2050", for which the Global Warming Potential over 100 years (GWP100) is calculated following the IPCC AR6 report from 2021

(IPCC 2021). As a comparison, the reference case is electrolytic hydrogen being produced directly in proximity to the port of Hamburg in Germany. Electricity mix is taken from the Northern German region as modeled in TAM-Supply, and the same electrolyzer system configuration as for Canadian hydrogen production is deployed.

Figure 15 shows the results for the Cradle-to-Delivery-Gate prospective LCA. Overall, the ammonia pathway shows a higher GWP100 compared to the liquid hydrogen pathway. This is due to the higher hydrogen input necessary to produce the final hydrogen, in turn requiring more electricity to produce hydrogen as well as to source the nitrogen required. More electricity is also needed for the Haber-Bosch and cracking processes than for liquefaction and regasification.

Within the GWP100, hydrogen production contributes the most to the overall score. Conversion to liquid hydrogen and ammonia respectively, accounts for the second highest contributions. Notably, the majority of GHG-emissions stem from building the renewable electricity infrastructures after 2030 when the remaining fossil-based electricity generators are all phased out. GHG-emissions from shipping due to fuel consumption contribute the second most. Fuel use for shipping is also the only contributor of direct, fossil-based GHG-emissions other than GHG-emissions emitted in the upstream supply chain.

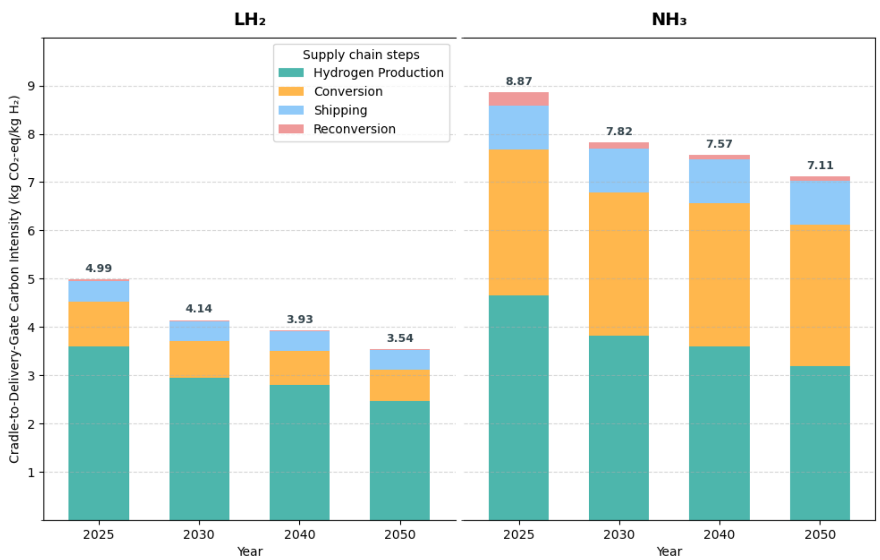

Figure 15: Carbon intensity of hydrogen delivery from Canada to Germany.

In TAM-Supply, additionally to electrolytic hydrogen imports from Canada, hydrogen is also produced domestically in Germanys' Northern region at the delivery gate, i.e. for injection into the natural gas/hydrogen grid. Comparing these shows that electrolytic hydrogen production from using the Northern German electricity mix (as seen in Table 3) is associated with a lower GWP100 overall. As fossil power plants are phased out from 2025 to 2040, GHG-emissions are more than halved.

Table 3: GWP100 of hydrogen production from alkaline electrolysers from the Northern German grid from 2025 to 2050.

Year	2025	2030	2040	2050[1]
GWP100 [$kgCO_2eq/kgH_2$]	4.47	1.91	1.41	1.41

[1] TAM-Supply delivers results up to the year 2045. Here, it is assumed the grid carbon intensity doesn't change between 2045 and 2050.

The grid in New Foundland is mainly supplied from hydro electricity and some onshore wind turbines, while the Northern German grid, after fossil power plants are phased out mostly consists of electricity from onshore and offshore wind turbines. These results are sensitive to whether the renewable energy capacity used is considered to be installed for hydrogen production exclusively or not: On the German side, onshore and offshore wind capacities are installed every year, dedicated for hydrogen production. For the case of hydro electricity, the capacity already exists before used for hydrogen production.

Key findings highlight that using ammonia as a carrier is associated with a higher GWP100 compared to liquid hydrogen. Even in grids without fossil electricity generation, GHG-emissions arise embodied in the infrastructure.

4 Conclusions

In summary, several conclusions can be drawn from the results.

Globally, a rise of electricity and hydrogen shares in final energy use is to be expected, but for hydrogen, the growth is less strong.

The main drivers for increases in global low-carbon hydrogen production are implementation of climate regulation and active hydrogen policy.

If Canada and Germany deliver on their climate targets, a phase-out of unabated fossil hydrogen production is to be expected. Besides that, model results show varying perspectives of different models on the role of different low-carbon hydrogen production technologies and their timeline both in Canada and in Germany. For Canada, the models report 247-518 PJ of low-carbon hydrogen provision by 2050 in the standard announced pledges scenario (AP_TO). For Germany, low-carbon hydrogen provision by 2045 in the same scenario is at 592-756 PJ, with substantial import amounts in two out of three models.

In the Announced Pledges scenarios besides "Announced Pledges Hydrogen Trade", Canada-Germany hydrogen or derivative trade only occurs in substantial amounts in models that do not consider domestic Canadian hydrogen demand and represent a large set of hydrogen derivatives but a limited set of potential hydrogen export countries (TAM-Supply, PyPSA). Models that include no option for international hydrogen derivative trade and consider domestic Canadian hydrogen demand (NATEM, ACSG) report the Canada-Germany trade only in case of trade subsidies.

This indicates that without subsidies on trade, hydrogen derivative exports from Canada to Germany are competitive with production in Germany, but when expanding the view to domestic Canadian hydrogen demand and other potential supply countries, competitiveness based on direct cost becomes less clear. At the same time, "soft factors" that are not represented in the models, such as the existence of an experienced energy industry and traditionally stable relations between both countries, could change the picture in real-world considerations.

The direction of macroeconomic effects of electrolysis technology development and hydrogen policy shows no consistent strong tendency in the analyzed model results.

Findings of the prospective LCA on liquid hydrogen and ammonia exports from Canada to Germany reveal a substantially higher GWP100 for ammonia compared to liquid hydrogen.

A Appendix

A.1 Hydrogen projects in Canada

Table A1: Non-exhaustive table summarizing known hydrogen projects of regional or national significance according to Natural Resources Canada (Government of Canada 2024).

Region	Province	Name	Funding (MCAD)	Power	Technology	Products (Mt/yr)
Atlantic	NS	Point Tupper	$125M USD	Onshore wind, solar PV	Electrolysis	H_2, 1.0 NH_3
	NL	Stephenville, Port au Port, Codroy	$95M USD	3 GW Onshore wind	Electrolysis	0.25 H_2, NH_3
	NL	Come by Chance	$49M, $37M CAD	5 GW Onshore wind	Electrolysis	H_2
	NB	Fredericton		Grid, NG	Microwave, electrified NG reforming	0.88 H_2
	NB	Port of Belledune		0.2 GW Nuclear SMR	Electrolysis	H_2
Central	QC	Bécancour		Grid	0.02 GW PEM Electrolyser	0.003 H2
	QC	Port de Baie Comeau		RE	0.3 GW Electrolyser	NH_4NO_3
	QC	Project Mauricie	$4B CAD	Onshore wind, solar PV	1 GW Electrolyser	0.07 H_2, RNG
	ON	Douglas Point		Nuclear	Electrolyser	H_2
	MB	Selkirk		RE	Electrolyser	H_2
Western	AB	Edmonton	$300M, $160M, $15M CAD	NG	ATR with CC	0.14 H_2, renewable diesel
	BC, AB	Burnaby		NG	ATR with CC	H_2
	BC	McLeod		RE, NG	Electrolysis, reforming with CC	H_2
	BC	Fort Nelson		Biomass	BECCS	0.02 H_2
	BC	Vancouver		Grid power	Electrolyser	0.006 H_2
	AB	Fort Saskatchewan	$5M, $3M, $16.5M CAD		Reforming with CC	0.085 H_2, NH_3

A.2 Additional results

Electricity provision in Canada:

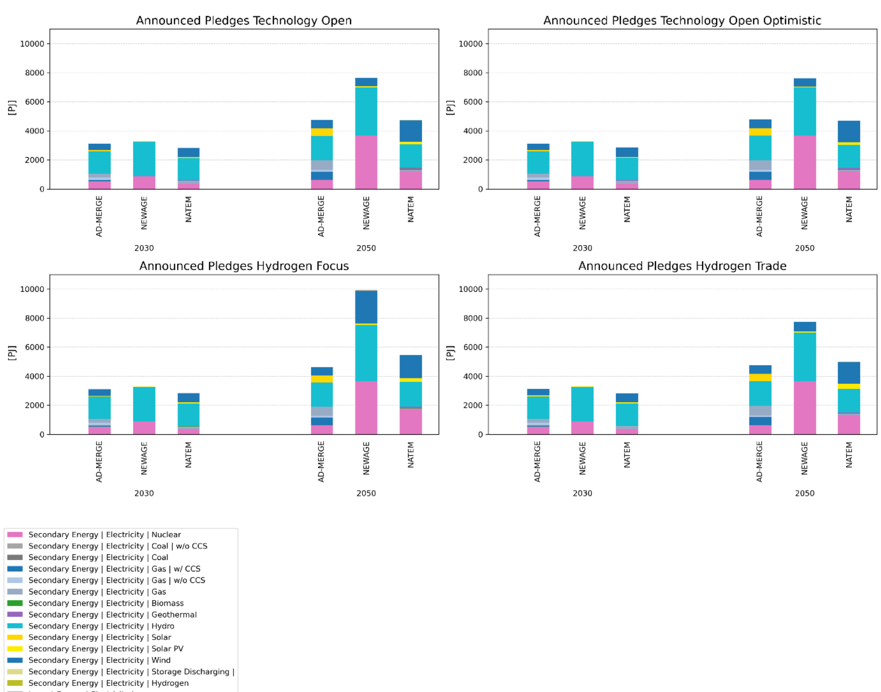

Figure A1: Electricity provision in Canada.

Electricity capacities in Germany:

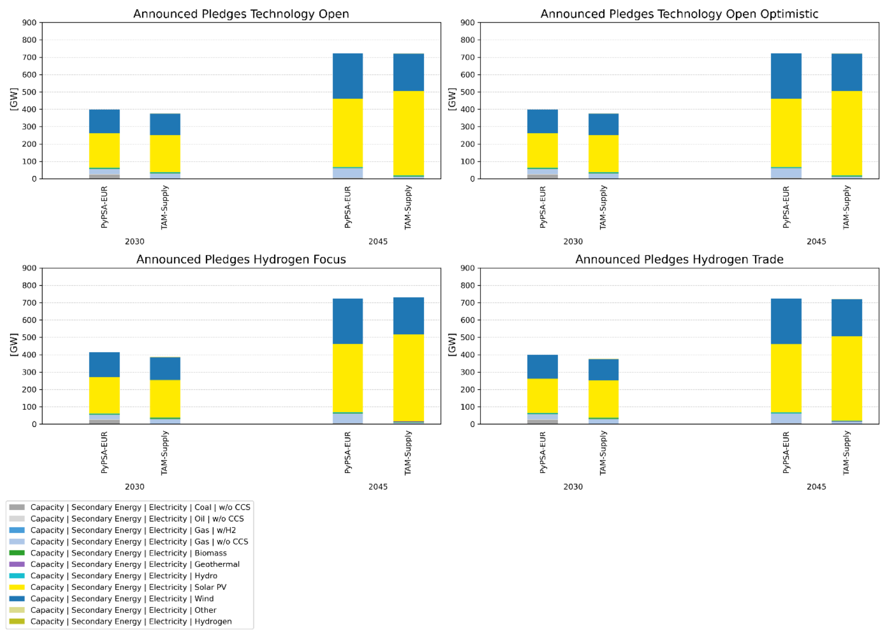

Figure A2: Electricity Capacities in Germany.

A.3 Detailed model Information

A.3.1 AD-MERGE

Model description: The AD-MERGE model is a hybrid framework that integrates detailed bottom-up energy systems with a top-down macroeconomic representation of other sectors to capture their interactions (Bahn et al. 2019). It distinguishes between reactive and proactive adaptation, dynamically modeling regional energy, economic activity, and GHG emissions. These outputs are then used to calculate climate change impacts and assess economic damages, including adaptation. AD-MERGE serves as a dynamic tool for cost-benefit or cost-effectiveness analysis of climate policies (Figure A3).

During the period overlapping with the H2Clip project, the AD-MERGE framework was advanced to version 2.0, adding the granularity required for rigorous hydrogen pathway assessment and policy analysis. The AD-MERGE 2.0 features key enhancements, including a 2015 base-year, increased regional disaggregation, improved energy system modeling (explicit technologies such as renewables, hydrogen and DACCS), recalibration of climate damage and adaptation, and scenario alignment with SSP2–v3.0 (Byers et al. 2022). The AD-MERGE model considers hydrogen production via both fossil fuels (with and without CCS) and electrolysis. The model also considers two methods for hydrogen production via electrolysis: dedicated plants using PEM electrolyzers to split water and a flexible system that utilizes surplus or curtailed electricity from solar and wind sources.

Specific model or scenario implementations strongly influencing results: Results in AD-MERGE 2.0 are driven foremost by the SSP2-v3.0 population and GDP trajectories which set the overall scale of energy demand and investment capacity, and by the model's top-level split between electric and non-electric demand, which directs growth into power generation versus direct fuel use. Within that structure, outcomes are especially sensitive to assumptions about technology costs, regional potential and availability, and learning rates, notably for electrolysis, SMR+CCS, renewables, BECCS, and DACCS. They are further shaped by scenario controls that bind feasible development: carbon budgets/net-zero timing, explicit hydrogen production or trade requirements, carbon sequestration limits, and capacity-expansion/ramp constraints. The specific 15-region partition also affects comparative advantage and interregional trade, while its coarse granularity cannot fully represent intra-regional heterogeneity.

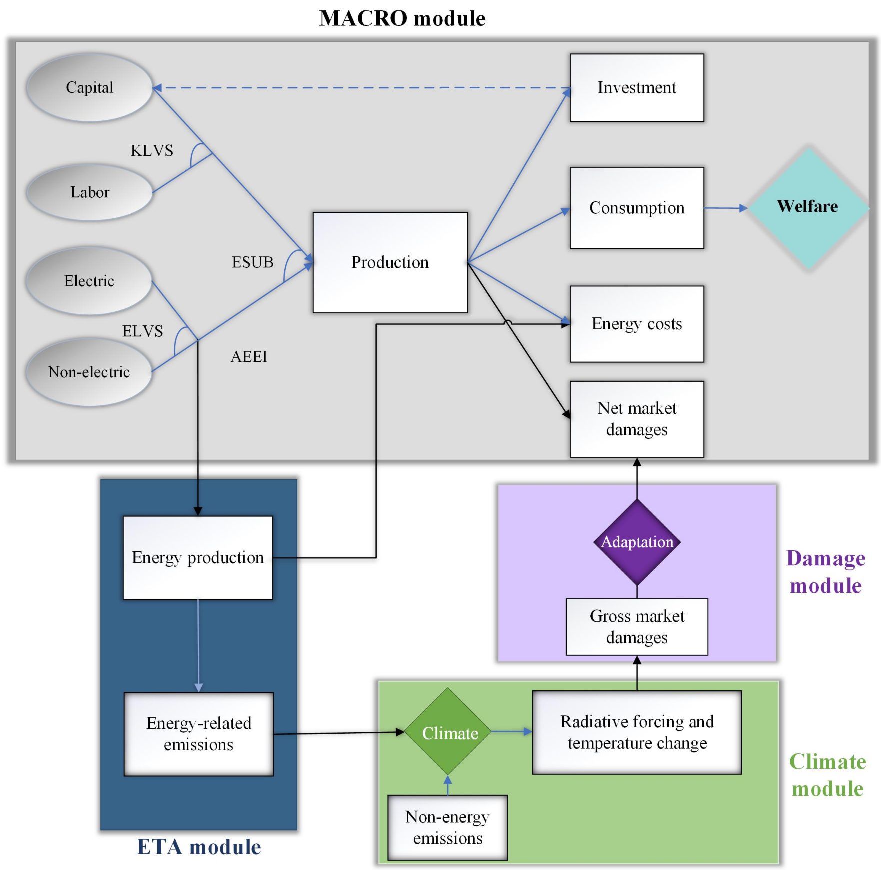

Figure A3: Structure of AD-MERGE comprises four modules. In the Macro module, AEEI stands for autonomous energy efficiencies, whereas ELVS and KLVS are elasticities of substitution among production and factors.

A.3.2 NEWAGE

Model description: NEWAGE (Figure A4) is a global, recursive-dynamic general equilibrium model with special focus on the energy sector. It is written in GAMS-MPSGE in a Mixed Complementarity formulation. CES functions are used to describe production, trade and consumption in the world economy. In the course of the H2CliP project, dedicated production technologies for electricity, hydrogen and synthetic fuels were introduced or fundamentally revised. The world economy is separated into 16 regions and 19 different production sectors. Production factors include capital, skilled and unskilled labour, resources and energy-related CO2.

The main data source is GTAP11-POWER (Chepeliev 2023), which is aggregated in a customized GTAP9inGAMS routine (Rutherford 2015). Total factor productivity and labor force development are taken from the EconMap database (Fontagné et al. 2022).

Specific model or scenario implementations strongly influencing results: NEWAGE results are strongly influenced by the choices of several parameters. Among these are elasticities of substitution, total factor productivity and labor force development, technology costs assumptions and the endowments with technology-specific factors that determine the cost associated with the ramp-up of technology and bilateral energy trade activities.

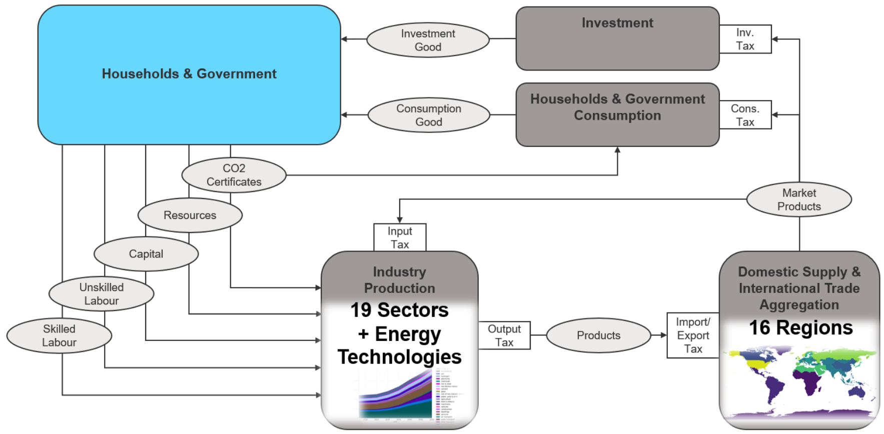

Figure A4: NEWAGE structure.

Results from the NEWAGE model could only be computed allowing for very high uptake rates of energy production technologies (for example, wind electricity generation in Germany in the AP_TO scenario increases from 1126 to 2152 PJ from 2035 to 2040), however, the AP_H2 scenarios still remained locally infeasible with a residual below 0.01 bn €. The results are nevertheless published in this report, but should be interpreted with caution.

A.3.3 NAGEM

Model description: NAGEM (North American General Equilibrium Model) Canada is a new generation dynamic macroeconomic model able to simulate deep transformation of the economy to achieve ambitious objectives of GHG reduction. NAGEM Canada mirrors the regional structure of the NATEM model with detailed representation of 13 provincial and territorial economies including different industries and sectors, end-uses, services, and commodities (e.g., fuels and technologies), as well as inter-jurisdictional flows of trade and labour.

NAGEM combines economic theory with real economic data to simulate the impact of economic shocks on a jurisdiction. The model starts from a baseline year reflecting the structure of the Canadian, provincial, and territorial economy in equilibrium, based on regional Social Accounting Matrices (SAM) that capture all economic transactions in a single year. It accounts for the interdependencies between sectors, economic agents (industries, households, and governments), and markets.

The model features a detailed representation of the Canadian labour force using the national occupational classification, which distinguishes skill and education levels across job categories. Labour markets are modelled for each jurisdiction, including domestic and foreign workers, as well as different contracting schemes.

NAGEM has been applied in a variety of projects to assess the macroeconomic and social implications of clean energy transitions. For instance, it has been used to evaluate the economic and labour market impacts of provincial and national energy transition strategies, to estimate GDP and employment effects of electrification and decarbonization policies, and to quantify affordability and competitiveness impacts of industrial transformations. The model also supported large-scale studies examining the long-term evolution of the Canadian economy under net-zero scenarios, as well as analyses of international trade, shipping, and hydrogen supply chain development.

Specific model or scenario implementations strongly influencing results: Energy transition strategy in different economic sectors and households (energy consumption per fuel per year), capital efficiency gain due to electrification.

A.3.4 NATEM

Model description: NATEM describes the entire integrated energy system, as well as non-energy emitting sectors of the 13 Canadian jurisdictions and provide a rigorous analytical basis for identifying least-cost solutions to achieve energy and climate objectives without compromising economic growth. NATEM-Canada is part of a larger framework covering the whole North American continent. It includes a large number of technologies allowing to reach energy savings and deep GHG reduction levels, including net-zero targets by 2050.

NATEM is used for studying the transition toward a sustainable energy future in a detailed multi-regional, multi-sector and multi-fuel framework over a long-term horizon to capture the structural changes within the energy sector. It provides a very detailed representation of the technological changes required in the long term, as well as their costs, to meet growing demands and/or to reach specific goals. In addition, it provides important additional features compared with other energy system models as it provides an optimal configuration of the energy sector which makes it possible to satisfy the total demand for energy services at lower cost, while respecting system constraints (resource limitations, renewable targets, GHG taxes or mitigation targets, energy policies, etc.).

NATEM is an application to Canada and North America of the TIMES model generator, which is the most advanced and widespread; it is used by numerous teams in 70 countries. It is a rigorous methodology, well documented and which is constantly improved through an international collaboration network (ETSAP-International Energy Agency).

The NATEM model and its results have been used by numerous decision-makers in Canada and North America to: prepare energy transition and net zero pathways, draft climate action plans, assess the economic and environmental impact of energy projects and policies, quantify the reduction potential of climate change mitigation measures, prepare technology roadmaps, assess the costs and benefits of GHG reduction measures and policies, optimal reduction levels across various sectors and economic agents, define strategic research priorities to reduce mitigation costs and contribute to economic development.

Specific model or scenario implementations strongly influencing results: Net-zero emission targets/emission costs, capex and opex assumptions for hydrogen technologies, clean hydrogen production constraints, and hydrogen trade targets constraints.

A.3.5 ACSG

Model description: Artelys Crystal Super Grid is a multi-energy modeling tool designed to simultaneously optimize investments and operations for multi-energy systems integrating electricity, gas, and hydrogen. The platform provides a detailed representation of energy production, conversion, transport, storage, and consumption, considering interactions between energy vectors, technical and economic constraints, and emissions. Thanks to its joint long-term (infrastructure, technology mix) and short-term (operations, hourly dispatch over the year) optimization, the tool provides an integrated and robust view of energy transition trajectories.

As part of the H2Clip project, a model covering the province of Québec has been developed. Artelys Crystal Super Grid was used to analyze the impact of growth in demand for hydrogen, both for domestic use (industry, transport, heating) and for export. The model assesses, in particular, electricity production and electrolysis capacity requirements, the effects on consumption peaks, the necessary infrastructure investments (conversion, storage, export), and the economic and environmental impacts. It thus provides a rigorous framework for comparing scenarios, testing sensitivity to electricity or electrolysis prices, and supporting Québec's strategic planning in the development of a competitive and sustainable hydrogen sector.

Specific model or scenario implementations strongly influencing results: The results are particularly sensitive to the assumptions embedded in demand projections, especially the evolution of electricity consumption and the penetration of hydrogen for domestic uses and exports. Among others, industrial activity translated into demand projection also plays a key role, as it determines the scale and timing of new energy needs. In addition, policy targets and regulatory constraints (for example emissions caps, renewable portfolio standard) has a strong influence on the modeled investment pathways. Finally, transmission investment (e.g. new pipeline costs, electricity transmission needs related to renewable growth) was not included within the model, which limits the financial impact of new infrastructure investments.

A.3.6 ETEM

Model description: Energy-Technology-Environmental-Model (ETEM) is a regional, bottom-up linear optimization model designed to minimize the total discounted system cost of the energy system while meeting energy demand and environmental targets (Babonneau et al. 2017). ETEM-MTL (Aliakbari Sani et al. 2022) represents the entire energy system of Greater Montréal, comprising 82 municipalities across five regions. The model spans the 2020–2050 period and captures the full energy chain, including production, transformation, storage, and final consumption in the industrial, commercial, residential, transportation, and agricultural sectors. It is organized into eight decision-making periods of five years each, with every period subdivided into 96 time slices to capture seasonal and daily variations. Calibrated using 2015 data, the model incorporates 51 energy commodities and 130 conversion technologies, enabling detailed analysis of energy consumption and emissions for the Greater Montréal region.

In the current project, with the specific integration of hydrogen technologies, the model includes around 40 hydrogen-related technologies, covering grey, green, and blue hydrogen production; short- and long-term storage; transmission and distribution of gaseous and liquefied hydrogen; and end-use applications across industry, transportation, and heating, as illustrated in Figure A5. The model incorporates policy measures and scenario constraints such as CO_2 emission limits, investment tax credit (ITC) policies, electrification targets, hydrogen blending restrictions, investment incentives, and sectoral caps aligned with regional and national net-zero objectives. ETEM-MTL produces a wide range of outputs, including optimal activity and capacity expansion, import levels, hydrogen penetration, and GHG emissions, enabling the assessment of cost-effective decarbonization pathways.

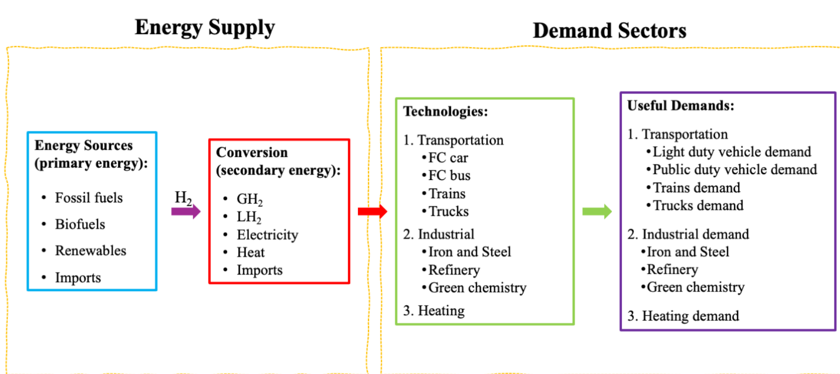

Figure A5: Representation of the Hydrogen Supply and Demand Structure in ETEM

Specific model or scenario implementations strongly influencing results: In the ETEM model, among the main influential factors are energy demand projections and policies affecting CO_2 emission levels. In addition, the technical characteristics of hydrogen, DAC, and CCS technologies also have a substantial impact on hydrogen penetration in the ETEM model.

A.3.7 TAM-Supply

Model description: TAM-Supply (Figure A6) is a technology oriented, actor integrated, linear optimisation model based on the TIMES modelling framework representing the German energy supply system. The supply or the energy provision sector is modelled in great technical detail covering four geographical regions of Germany and includes different actors' investment portfolios and capabilities to realise the least-cost developmental pathways. The model has its base year as 2013, with its horizon spanning over till 2060, however is most commonly used to represent the developments until 2045 under the specific German climate neutrality targets. The balancing of the energy carriers for their supply and demand is carried out on an annual basis, however greater temporal resolution representation is also possible through the introduction of typical periods. The supply module forms part of the family of other such TIMES Actor Models including Household (TAM-Household), Industry (TAM-Industry), Transport (TAM-Transport), and other sectors which can be connected through data-links to provide an overall energy system balance (as can be seen through the figure below). More information regarding the model can be obtained through TIMES | IER Institute of Energy Economics and Rational Energy Use | University of Stuttgart.

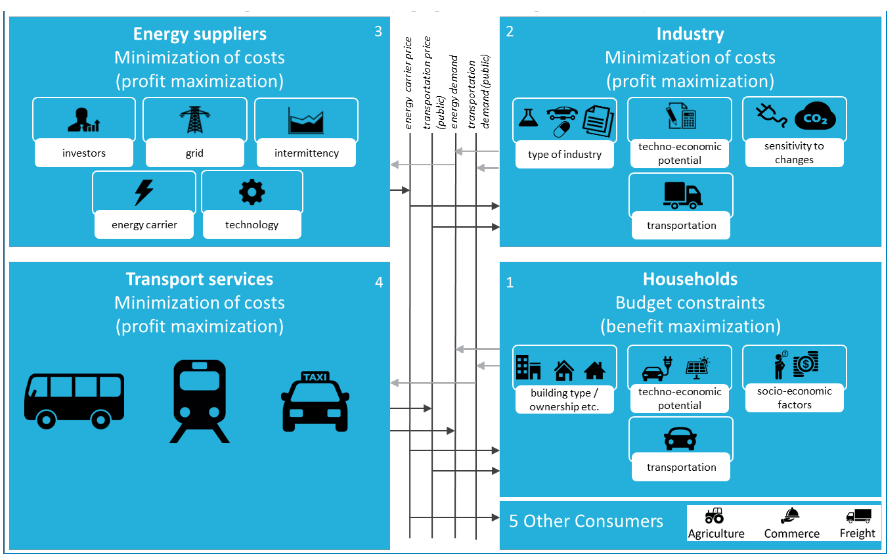

Figure A6: TIMES Actor Model family.

Specific model or scenario implementations strongly influencing results: The Supply model takes as input multiple parameters which influence the development pathways, some of the most critical of these are demand projections for energy commodities, import prices of energy commodities and policy constraints defined in the modeled scenarios.

A.3.8 PyPSA-EUR

Model description: PyPSA-Eur (Victoria et al. 2022) is an open-source, high-resolution model of the European energy system, developed using the Python for Power System Analysis (PyPSA) framework. It provides a comprehensive representation of both energy demand and supply across all major sectors.

The electricity system is modeled with alternating current (AC) and direct current (DC) transmission lines, conventional power plants, time series for electrical demand and variable renewable generation availability, as well as geographic potentials for the expansion of wind and solar power.

A sector-coupled extension enhances the model by incorporating demand and supply for transport, heating, biomass, energy consumption in agriculture and industry, industrial feedstocks, and carbon management. This includes carbon capture, usage, and sequestration. This multi-sectoral approach enables the analysis of cross-sector interactions and supports the identification of cost-effective decarbonization pathways.

PyPSA-Eur has been adapted to represent the German energy system using a 15-node configuration, each representing a different region. Additional modifications were implemented to align the model with the scenario framework of H2CliP.

Specific model or scenario implementations strongly influencing results: Emissions targets, available renewable energy potentials, the specific climate year underlying the model calculations, demand projections and import prices strongly influence model results.

A.3.9 Relevant limitations of model scopes for energy system and trade results

Table A2: Relevant limitations of model scopes for energy system and trade results.

Model	Relevant Limitations of Scope
AD-MERGE	• AD-MERGE has no representation of hydrogen derivatives. • AD-MERGE does not include bilateral resolution of international trade. Consequently, AD-MERGE results are not included in the trade graphics.
NEWAGE	• Electricity results of NEWAGE include steam, hot water and air conditioning supply according to ISIC Rev. 4 class 3530 (United Nations 2008). • Biomass use is not considered an energy carrier in NEWAGE. • Hydrogen production from other technologies than the ones utilized in the global results (e.g. biomass) is not available in NEWAGE. • Hydrogen derivative options in NEWAGE are limited to synthetic natural gas and oil, and these can only be produced using hydrogen from domestic electrolysis. • NEWAGE has a limited country set of import options for LH2 and hydrogen derivatives, among them Canada.
NATEM	• Hydrogen export to Germany in NATEM can only occur in the form of liquid hydrogen.
TAM-Supply	• TAM-Supply has a limited country set of import options for LH2 and hydrogen derivatives, among them Canada.
PyPSA-EUR	• In PyPSA-EUR, the only import option for LH2 and hydrogen derivatives is imports from Canada. CGH2 imports in PyPSA-EUR are from neighboring Europe.

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