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Power-to-gas: potential cost and global energy efficiency estimates of synthetic natural gas (e-gas) produced from green hydrogen and biogenic carbon

TES Canada case study

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May 2024 update: "The authors met with TES Canada on May 17th 2024, where certain figures (capacity factor, cost of electrolysis stack replacement, Sabatier reaction efficiency) were disclosed under confidentiality. Some of these factors (Sabatier reaction efficiency, stack replacement cost) were more optimistic than our estimates, while others (capacity factor) were less optimistic. However, without estimates for electricity cost from wind and solar, which TES Canada cannot provide due to commercial considerations, further updating of our report's cost estimates would not be meaningful."

Summary

To ensure that the contribution of green hydrogen technologies towards the decarbonization of the economy is optimal, their premises – including costs and energy losses from production to final end-uses - must be evaluated transparently[1], and their opportunity cost compared with other options prioritising more structural cost-effective actions to decarbonise the economy. In this analysis, we aim to understand whether synthetic natural gas (e-gas), produced using green hydrogen and biogenic carbon, offers a cost-effective and optimal use of renewable electricity for decarbonizing the economy. Our estimate is based on a case study of TES Canada's green hydrogen project, which proposes to convert 66% of its green hydrogen production to e-gas for injection into Québec's main gas network – privately owned by Énergir. We estimate both the potential global energy efficiency and the cost per gigajoule of e-gas produced.

TES Canada has stated that the Mauricie Project would be profitable for the company.[2] However, it has yet to address publicly two key challenges: will e-gas be

[1] Whitmore, J., Martin, P., 2024. TES Canada : un appel à la transparence, *La Presse*, January 2 2024, www.lapresse.ca/affaires/2024-01-02/forum-des-affaires/tes-canada-un-appel-a-la-transparence.php
[2] Beaudry, F., 2024. Le projet de TES Canada « mal ficelé », selon un expert, *La Presse*, March 15 2024, https://ici.radio-canada.ca/nouvelle/2057479/eoliennes-tes-canada-hydrogene-vert

affordable for end-users, and will it be the most efficient use of renewable electricity to decarbonise our economy?

Global efficiency of e-gas

Considering the losses across the electricity to e-gas conversion chain we estimated, under two scenarios, very optimistic and slightly more realistic, the overall energy loss associated with different end-uses of e-gas.

- **Building heating** would result in an overall energy loss in the range of 57% to 70%
- **Low temperature (200°C) industrial process** using high efficiency industrial furnaces or boilers, would result in an overall energy loss in the range of 59% to 70.5%
- **High temperature (200-1,500°C) industrial process** would result in an overall energy loss in the range of 62% to 73%.

Estimated costs of e-gas

Due to the high electricity requirements and energy losses in its production, e-gas will be expensive not only to produce, but also to consume. According to our estimates, the production cost could vary between **C$40 per gigajoule (GJ),** under a very optimistic scenario, and **C$90/GJ** under a more realistic one. In comparison, natural gas currently sells for around C$3-7/GJ in Quebec, including carbon fees, and renewable natural gas around C$20-$25/GJ. Our estimates are comparable with estimated production costs for e-gas published by Énergir (C$38 to C$80/GJ in 2030).

Given the high cost of e-gas and the declining trends in voluntary demand of Natural gas from renewable sources in the industrial sector (-49% between 2022 and 2023), it is not clear how TES Canada can claim that the e-gas would exclusively be used for industrial uses. For this, TES would have to confirm that a purchasing agreement has been signed between Energir and industrial companies willing pay a premium for purchasing the environmental benefits associated with the production of e-gas compared to conventional gas. Otherwise, the e-gas will also end-up being consumed in heating buildings, which is not a priority sector given that cheaper, more efficient options are available for their decarbonization. Under these circumstance, TES Canada may not fully meet the criteria established by the government for authorising hydrogen projects.

TES Canada states that its project is "essential to the decarbonization of Quebec". However, it hasn't disclosed any data analysis and scenarios to support this claim, including the expected overall energy efficiency of e-gas (from production to consumption). Our analysis suggests that the e-gas chain promises to be inefficient and costly for the Quebec economy. Green hydrogen will play a role in the energy transition, but for its contribution to decarbonization to be optimal, the premises of the TES Canada project must be transparent and supported by publicly available evidence.

This working paper is an invitation for decisionmakers to publish their data to compare analyses. In addition to the cost and global efficiency of e-gas, other information should be made available to better understand the project (see the Conclusion section).

Introduction

The climate science is clear: we need to decarbonize the global economy by mid-century. A well-designed energy transition is integral to this, with innovative solutions like green hydrogen providing an important piece of the solution. However, producing green hydrogen, using renewable electricity, is an energy-intensive and expensive process. When hydrogen is used as an energy vector rather than as a chemical, electricity needs can be 2 to 14 times higher compared to direct electrification solutions due to energy losses.[3] For this reason, many studies emphasize the need to maximize its exploitation by focusing on sectors that require hydrogen for its chemical properties (i.e. to produce ammonia for use as a fertilizer), where hydrogen can be used to replace fossil-derived chemicals (i.e. the reduction of iron ore to iron metal), or which do not lend themselves to direct use of electricity, such as the maritime sector.

To align with climate goals, hydrogen can be produced from renewable electricity and other net-zero sources. Currently, 99% of the world's hydrogen is produced from natural gas, coal or petroleum products, emitting over 900 Mt of global greenhouse gases (GHGs) – equivalent to around 2% of global emissions – in the process.[4] It is mainly used as a commodity chemical rather than a fuel. While decarbonizing existing uses of fossil-based hydrogen should be a priority, governments are increasingly advocating for its use as a direct or indirect fuel for replacing existing fossil fuels.

A key obstacle for the large-scale use of green hydrogen is the lack of transportation infrastructure and equipment suitable for its direct use.[5] Blending green hydrogen with natural gas can partly overcome this barrier. However, research suggests utilities can only safely blend between 5% and 20% using today's pipelines and appliances, even after extensive testing and targeted pipeline retrofits.[6, 7] For “many existing gas-fired power plants, this limit is 5% volume”.[8]

These constraints have led some to proposes combining green hydrogen (H_2) with biogenic carbon dioxide (CO_2) to produce “synthetic” natural gas (CH_4), also called synthetic methane or e-gas, equivalent molecularly to conventional natural gas, for injection into existing natural gas networks. This conversion process, also known as

[3] Ueckerdt, F., et al., 2021. Potential and risks of hydrogen-based e-fuels in climate change mitigation, *Nature Climate Change*: 11, p. 384–393, www.nature.com/articles/s41558-021-01032-7

[4] IEA, 2023. *Hydrogen*, web site, www.iea.org/energy-systedm/low-emission-fuels/hydrogen

[5] Topolski, K., et al., 2022. H*ydrogen Blending into Natural Gas Pipeline Infrastructure: Review of the State of Technology*. National Renewable Energy Laboratory. Report Number NREL/TP-5400-81704, https://www.nrel.gov/docs/fy23osti/81704.pdf

[6] CGA, 2022. *Enabling Higher-Hydrogen Blending in Natural Gas Distribution Systems*, https://www.cga.ca/wp-content/uploads/2022/10/CGA-Hydrogen-Blending-Greater-than-5.pdf

[7] Whitmore, J., Martin, P., 2022. Repurposing LNG infrastructure for hydrogen exports is not realistic, *The Globe and Mail*, August 8 2022, www.theglobeandmail.com/business/commentary/article-lng-infrastructure-clean-hydrogen-exports/

[8] Erdener, B. C., et al, 2023. A review of technical and regulatory limits for hydrogen blending in natural gas pipelines, *International Journal of Hydrogen Energy*, Vol 48: 14, 15 February 2023, p.5595-5617, https://doi.org/10.1016/j.ijhydene.2022.10.254

"power-to-gas" proposes to make green hydrogen more readily useful to the economy.[9]

Gas utilities view injecting e-gas into the existing gas networks as a path to decarbonizing their activities and to maintaining market shares. It is also seen as an opportunity to extend the useful life of existing gas transmission and distribution assets. Decarbonization strategies centered around maintaining, retrofitting, and building natural gas pipelines to increase the share of hydrogen and e-gas in gas networks could potentially serve as a financial leverage to make oil and gas infrastructures more valuable throughout the energy transition and prevent stranded assets for investors.[10]

While the business case for investing in the production of e-gas appears favorable from the interest of investors and gas utilities, it's less obvious when viewed from the perspective of end-users and the overall economy. Adding a conversion step towards the production of e-gas further wastes energy and capital by reducing exergy (i.e., the potential to do useful work) due to conversion losses across the "electricity to hydrogen to e-gas" chain. From a thermodynamic perspective, this process is contrary to the search for efficiency in the transformation of energy between different forms up to its final use.

The urgency to decarbonize our economy further increases our demand for power to meet electrification goals in the transportation, industrial and building sectors. According to the IEA, global renewable power capacity will need to triple by 2030 to meet these needs and keep within the goal of limiting global warming to 1.5°C.[11] Wasting clean electricity on less efficient energy conversion processes for end-uses that could more efficiently use electricity must therefore be avoided.[12]

In this analysis, we aim to understand whether e-gas production offers a cost-effective and optimal use of renewable electricity for decarbonizing the economy. Our estimate is based on a case study of TES Canada's green hydrogen project, which proposes to convert 66% of its hydrogen production to e-gas. We estimate both the potential global energy efficiency and the cost per gigajoule of e-gas produced. We also identify the factors having the greatest impact on both cost and efficiency, and to evaluate the cost-effectiveness of this technology as a decarbonization strategy.

In the first part, we present an overview of the TES Canada project to put in context, followed by a description of the technology to produce the e-gas (Sabatier Process using green hydrogen and biogenic CO_2). The second part presents the methodology

[9] Lauwers, M. 2023. Marco Alverà: "L'objectif de Tree Energy Solutions est de transporter le soleil", *L'Écho*, News article, January 21 2023, www.lecho.be/entreprises/energie/marco-alvera-l-objectif-de-tree-energy-solutions-est-de-transporter-le-soleil/10441777.html

[10] Esposito, D. 2022. Gas Utilities Are Promoting Hydrogen, But It Could Be A Dead End For Consumers And The Climate, *Forbes*, www.forbes.com/sites/energyinnovation/2022/03/29/gas-utility-hydrogen-proposals-ignore-a-superior-decarbonization-pathway-electrification/amp/

[11] IEA, 2023. *Tripling renewable power capacity by 2030 is vital to keep the 1.5°C goal within reach*, Commentary, July 21 2023, www.iea.org/commentaries/tripling-renewable-power-capacity-by-2030-is-vital-to-keep-the-150c-goal-within-reach

[12] Energy Ireland, 2023. *National Hydrogen Strategy published*, web site, www.energyireland.ie/national-hydrogen-strategy-published-2/

used for our estimates, including the assumptions, data sources and limits. The report concludes with a discussion.

Note that the analysis presented in this working paper is based on the authors current understanding of the project based on available data and information. Results can change as further data is made public.

Overview of the TES Canada – Mauricie Project

On November 10, 2023, TES Canada, a Canadian subsidiary of Tree Energy Solutions B.V. (TES), announced plans to invest C$4 billion (US$2.9 billion) in developing a green hydrogen complex in Quebec, Canada.[13] The project consists of a 500 MW electrolyser powered by 1,000 MW of newly built, self-generated wind and solar, in addition to 150 MW of hydropower supplied by the province's public utility, Hydro-Québec, to produce annually 70,000 tonnes of hydrogen for exclusive use in Quebec. Two-thirds of this volume would be converted into synthetic natural gas (e-gas) and sold to Énergir, Québec's largest gas distributor, for injection into its gas network. The remaining third would be used directly as a fuel in long-haul transportation (see Figure 1).

TES Canada estimates that "30,000 tonnes [of its hydrogen] will be used to power around 2,000 hydrogen-powered heavy-duty trucks."[14] to provide "hydrogen volumes that have been lacking until now" to some of "Quebec's largest trucking companies." It should be noted, however, that hydrogen-powered heavy-duty truck technology is not mature - only select prototype and proof-of-concept fuel-cell electric trucks are available as pilots (e.g., Alberta and California) and there is yet to be large scale commercialization in North America.[15] In March 2024, there were no known hydrogen powered trucks in commercial operation in Quebec. It is therefore highly improbable that 2,000 hydrogen powered hydrogen trucks would be operational by 2028.

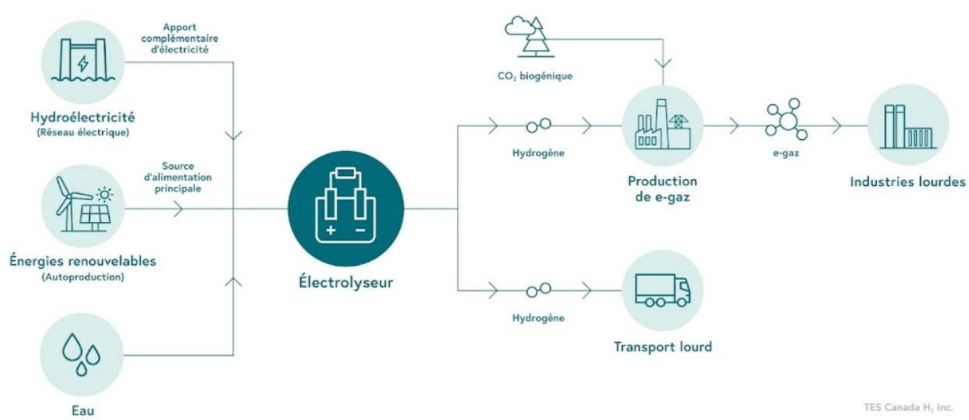
No feasibility study of the project has been made public. However, the promoters claim their initiative could reduce CO_2 emissions by 800,000 tonnes yearly starting in 2028, of which 320,000 to 325,000 tCO_2e would be associated with the e-gas.[16, 17] The balance of reductions would come from the "hydrogen used to eliminate the CO_2 emitted by diesel in heavy-duty trucks" [475,000 to 480,000 tCO_2e].

[13] TES Canada, 2023. *TES Presents Projet Mauricie*, Press release, November 10 2023, www.newswire.ca/news-releases/tes-presents-projet-mauricie-876612421.html
[14] "*Questions et réponses TES Canada - Projet Mauricie*", Questions sent to TES Canada by citizens on March 12, answers received on March 21, 2024.
[15] Roberts, N., Cyr, M., Whitmore, J., Pineau, P.-O., 2023. *Decarbonizing Long-Haul Trucking in Eastern Canada: Part 2 - A cost comparison analysis of net zero technologies on the A20-H401 Corridor Between Québec City and Windsor*, prepared by CPCS and the Chair in Energy Sector Management - HEC Montréal for the Government of Québec, https://energie.hec.ca/decabonizing-long-haul-trucking-in-eastern-canada/
[16] TES Canada, 2024. *Projet Mauricie - Une initiative de TES Canada*, PPT presentation, December 7 2023, https://mcusercontent.com/e6312cb60ed6f15721a2219e6/files/170e7498-31ba-a001-489c-2ebc7720a526/TES_Canada_Ecrans_consultations_20231207.pdf
[17] "*Questions et réponses TES Canada - Projet Mauricie*", Questions sent to TES Canada by citizens on March 12, answers received on March 21, 2024.TES answered that "E-gas eliminates the need to extract natural gas. Using a unit of e-gas (which is carbon neutral) avoids the emissions associated with extracting, transporting and using a unit of fossil gas. (which is not carbon neutral). These ~4.4 million GJ of e-gas produced therefore contribute to eliminating ~325,000 tonnes of CO_2 annually". It is not clear if the 325,000 t is associated with emissions avoided upstream, or at the consumption point.

According to the project proponents, the **e-gas would be used for industrial consumption** (see Figure 1). However, there is no publicly confirmed purchasing agreements that have been signed between Energir and industrial companies to pay a premium for purchasing the environmental benefits associated with the production of e-gas compared to conventional gas. A report by SIA Partners, produced for Énergir, suggests the e-gas would be injected in the main network with final usages including heating of buildings, heavy transportation, and industrial consumption (see Figure 2 and Annexe 1).[18]

Figure 1. TES Canada – Proposed Mauricie Project

Source: TES Canada, 2023.



The environmental benefits of the e-gas could also used to create compliance units (CU) sold under the Federal Clean Fuels Regulations (CFR).[19] TES Canada stated that "Énergir will obtain the necessary credits so that the e-gas they buy is indeed considered green, and so that they can meet their decarbonization obligations".[20] However, the *Regie de l'énergie du Québec* (Quebec Energy Board) decided that the activity related to CU under the CFR does not fall within Energir's regulated activities.[21] The decision could still be appealed.

A modified version of Energir's value chain has since been published in a TES Canada presentation (December 2023) showing only the industrial end-use.[22] But unless the project builds a dedicated pipeline directly to industrial installations or confirms a

[18] Énergir and Sia Partners, 2023. *Gaz naturel renouvelable produit par methanation - Étude du potentiel technico-économique du GNR de 3e génération au Québec*, Technical report, https://energir.com/files/energir_common/import/Fichiers/Corporatifs/Publications/Fiche-technique-GNR_FINALE.pdf

[19] Government of Canada, 2022. *Clean Fuel Regulations (SOR/2022-140)*, https://laws-lois.justice.gc.ca/eng/regulations/SOR-2022-140/

[20] "*Questions et réponses TES Canada - Projet Mauricie*", Questions sent to TES Canada by citizens on March 12, answers received on March 21, 2024.

[21] Régie de l'énergie du Québec, 2024. *Décision sur le fond relative à l'Étape E - Demande d'Énergir, s.e.c. concernant la mise en place de mesures relatives à l'achat et à la vente de gaz naturel renouvelable*, D-2024-028, 21 mars 2024, https://www.regie-energie.qc.ca/fr/participants/dossiers/R-4008-2017/doc/R-4008-2017-A-0505-Dec-Dec-2024_03_21.pdf

[22] TES Canada, 2024. *Projet Mauricie - Une initiative de TES Canada*, PPT presentation, December 7 2023, https://mcusercontent.com/e6312cb60ed6f15721a2219e6/files/170e7498-31ba-a001-489c-2ebc7720a526/TES_Canada_Ecrans_consultations_20231207.pdf

signed purchasing agreement between Energir and industrial clients, there it is no guarantee that the e-gas, or its environmental benefits, will be exclusively used for industrial processes. Furthermore, the voluntary demand for natural gas from renewable sources (NGRS) by Energir's industrial clients has declined by 49% between 2022 and 2023 (see Table 1).

The project targets a production of 115 million cubic meters (Mm^3) of e-gas in 2030, equivalent to 1.8% of fossil natural gas consumption in Quebec in 2021.

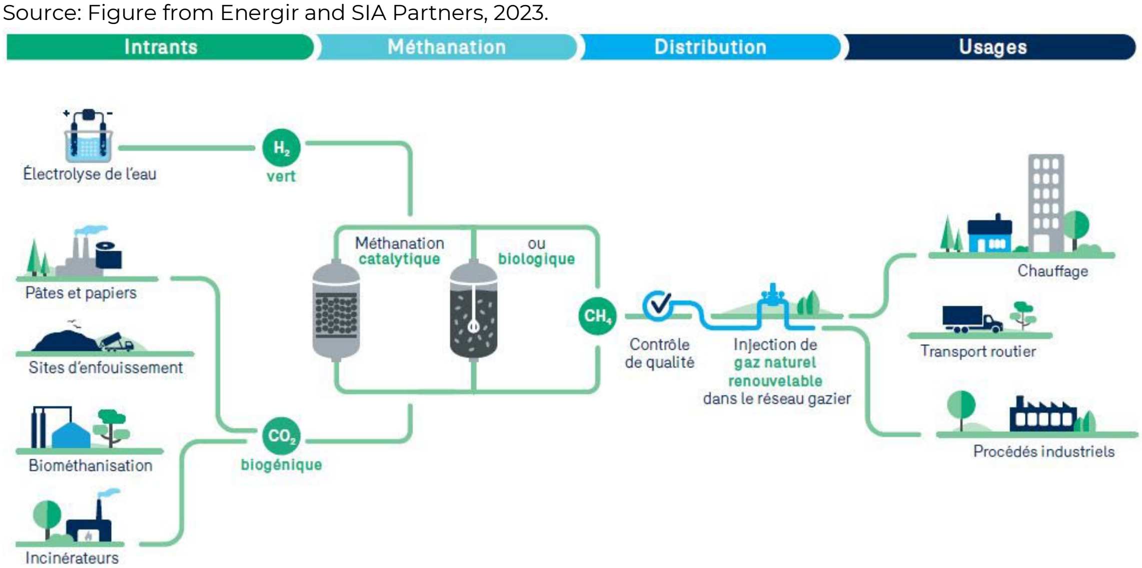
Table 1. Voluntary consumption of natural gas from renewable sources by client type of Énergir, 2022-2023

Sources: Énergir, 2023, 2024.
Note: 2022 = total as of December 31, 2022; 2023 = total as of December 31, 2023

Client	Number of clients		2022-2023 variation	Volumes (Mm^3)		2022-2023 variation
	2022	2023		2022	2023	
Residential	1,004	1,227	22%	0.97	0.92	-5%
Commercial	203	225	11%	4.34	4.88	12%
Institutional	102	115	13%	8.38	8.24	-2%
Industrial	73	79	8%	46.52	23.62	-49%
Total	1,382	1,646	19%	60.26	37.65	-38%

Figure 2. Value chain of synthetic natural gas (e-gas) proposed in Québec

Source: Figure from Energir and SIA Partners, 2023.



In addition to the authorised energy bloc of 150 MW, the project requires 1,000 MW of self-generation of renewable energy. A total of 800 MW would come from the installation of around 140 wind turbines in the Mékinac Regional County Municipality by 2026, while solar power would provide the remaining 200 MW (see Figure 3). According to TES Canada "the entire construction is expected to be carried out in one phase" for the wind turbines, solar and plant. The "duration of the entire project is estimated at around 3 years". The green hydrogen plant would be in Shawinigan, Québec.

According to TES Canada, "Hydro-Québec will transmit electricity to the site via their own power line. The wind turbines and the solar farm will supply the site separately via a separate power line. Between them, the wind turbines will be connected via an underground collector network, meeting at a common point. From there, the project will build a short above-ground power line to the site."[23]

The project could benefit of Hydro-Québec's peak load management programs. According to TES Canada, the "project could physically make its production available to the grid during peak periods", however, to date, "no agreement has been negotiated or concluded."[24]

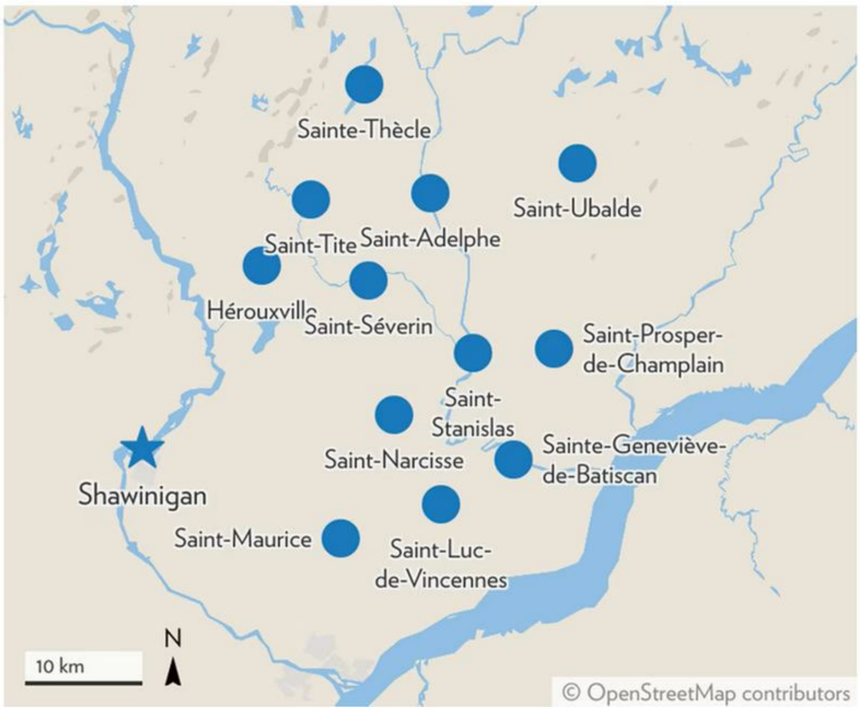
TES Canada states "to ensure e-gas is carbon-neutral, we will require that all CO_2 to come from biogenic sources"[25] (see left side of Figure 2). They've also stated that their "sources of supply are limited to specific phases of pulp and paper production", and "can also come from landfill sites" and "a few additional sources". TES Canada has not confirmed how the CO_2 would be transported beyond acknowledging that "transportation of the biogenic CO_2 is typically in liquid form by truck (ideally with fuel cells) or via a dedicated pipeline."

It would be "mandatory" for TES Canada "to measure the carbon index of its e-gas throughout their agreement with Energir." [26] As of March 27, 2024, TES Canada has not publicly confirmed any purchasing contracts with biogenic CO_2 suppliers, or whether measurements of its carbon index would be made publicly available.

[23]"*Questions et réponses TES Canada - Projet Mauricie*", Questions sent to TES Canada by citizens on March 12, answers received on March 21, 2024.,
[24] "*Questions et réponses TES Canada - Projet Mauricie*", Questions sent to TES Canada by citizens on March 12, answers received on March 21, 2024.
[25] "*Questions et réponses TES Canada - Projet Mauricie*", Questions sent to TES Canada by citizens on March 12, answers received on March 21, 2024.
[26] "*Questions et réponses TES Canada - Projet Mauricie*", Questions sent to TES Canada by citizens on March 12, answers received on March 21, 2024.

Figure 3. Proposed location of wind (800 MW) and solar (200 MW) farms for the TES Canada Mauricie Project in the Mékinac Regional County Municipality of Québec

Source: Figure from *Le Nouvelliste*, 2024.



Quebec Government criteria for hydrogen projects

Following the unveil of the *Quebec Green Hydrogen and Bioenergy Strategy*[27], Hydro-Québec received multiple requests, totaling 9,000 MW, in green hydrogen project proposals requiring a connection of 5 MW and more. Of these, TES Canada, which required an energy bloc of 150 MW, was one of the few to obtain government authorization. To be eligible, the project had to comply with several "elimination" criteria, including[28]:

- A demonstration that the production of green hydrogen, or its derivatives, is consumed in one or more **priority sectors**: heavy transport, industry, energy storage and management. The injection of hydrogen into the gas network is not considered a "priority sector" according to the government criteria.

- A demonstration that the **majority** of the green hydrogen produced, or its derivatives, be **consumed in Quebec** in priority sectors.

[27] Gouvernement du Québec, 2022. *Québec Green Hydrogen and Bioenergy Strategy*, www.quebec.ca/en/government/policies-orientations/strategy-green-hydrogen-bioenergy
[28] MEIE, 2024. *Critères applicables aux projets d'hydrogène*, web page, July 10 2024, https://www.economie.gouv.qc.ca/bibliotheques/conformite/autorisation-projet-electrique/criteres-hydrogene

Currently, there is insufficient public information (e.g., purchasing agreement with industry or trucking companies) to guarantee that the TES Canada project complies with these key criteria.

It is also not clear to which extent these "criteria" are legally binding. Beyond political intentions, there are no regulations that quantitatively define "majority" (i.e., what is the minimum percentage that must be consumed locally?). There is also no information on what the legal recourse and sanctions are available to monitor and enforce these criteria through time.

In March 2024, the Federal Government signed a Memorandum of Understanding (MoU) with the German Government to strengthen a transatlantic hydrogen corridor and to establish a "bilateral program" to "accelerate commercial-scale hydrogen trade between Canada and Germany, secure early access for clean Canadian hydrogen producers in the German market."[29] It is not clear what would happen if a hydrogen project that received authorization from the Quebec Government decided to participate in the Canada-Germany export program.

TES "Green Cycle" Business Model

Tree Energy Solutions B.V. (TES) is a private enterprise, based in Belgium, that aims to become a leader in producing e-gas from green hydrogen and captured carbon (CO_2) from biogenic sources for replacing fossil natural gas use and exports to Europe. TES was co-founded by Marcel and Paul Van Poecke. Marcel van Poecke is also Chairman of Energy at Carlyle, a global private equity fund, which manages an energy portfolio of "approximately US$22.4 billion in carbon-based energy, and US$1.4 billion committed to renewable and sustainable energy companies". [30, 31, 32] Carlyle is also among the largest holders of gas-fired power generation in the US. [33]

According to TES "e-NG can be put to use straight away as we create it using already proven technologies and can implement it in infrastructure built for fossil fuels [...] As a result, there is no risk of stranded assets when fossil fuels are phased out. Infrastructure upgrades will of course happen over time, but e-NG's flexibility means it can be supplied to gas pipelines now and easily reconverted to green hydrogen when the H_2 infrastructure becomes available.[34] In 2022, TES partnered with Australian-

[29] Government of Canada, 2024. *Government of Canada and Germany Land Arrangement Securing Early Market Access for Clean Canadian Hydrogen*, Press release, March 18, 2024, https://www.canada.ca/en/natural-resources-canada/news/2024/03/government-of-canada-and-germany-land-agreement-securing-early-market-access-for-clean-canadian-hydrogen.html

[30] Watts, R., 2018. Oil and gas business still holds value for Van Poecke, *Upstream*, www.upstreamonline.com/weekly/oil-and-gas-business-still-holds-value-for-van-poecke/2-1-401413

[31] Private Equity Climate Risk, 2023. *The Carlyle Group's Hidden Climate Impact : Exposing a decade of fossil fuel investments*, https://6000718.fs1.hubspotusercontent-na1.net/hubfs/6000718/PE%20Climate%20Risks/PECR_Report_Carlyles-Hidden-Climate-Impact_April2023.pdf

[32] Carlyle, 2024. *Marcel van Poecke,* web page, www.carlyle.com/about-carlyle/team/marcel-van-poecke

[33] Lakani, N. 2023. *A leading private equity firm claimed to be a climate leader – while increasing emissions*, The Guardian, April 27 2023, www.theguardian.com/environment/2023/apr/27/carlyle-group-carbon-emissions-doubled-climate-leadership-claims

[34] TES, 2024. *Step 5 - We deliver e-NG and green hydrogen to our customers*, web page, https://tes-h2.com/green-cycle/step-5-green-energy-solutions

based Fortescue[35], to develop the Wilhelmshaven energy import terminal in Northern Germany.[36, 37, 38] This terminal is to "import LNG to meet Europe's energy crisis", with a later view of becoming the "centrepiece of a planned integrated Green Energy Hub to import synthetic methane (as a H2 carrier) in the long term."

TES describes itself as "an end-to-end energy company committed to becoming the biggest e-NG producer in the world".[39] It developed a "Green Cycle" business model based on a loop that uses renewable electricity to produce green hydrogen and combine it with "recycled" CO_2 to transport it as e-gas to replace fossil natural gas (see Table 2). Currently, TES Canada's contribution to this model is constrained by the Quebec Government's requirement that the green hydrogen, and its derivatives, produced be mainly used to decarbonize local markets (see above). For that reason, TES' focus is on supplying "green hydrogen to support the mobility transition with a view to also providing e-NG for Canadian industrial partners."[40]

Currently, TES Canada has not made public whether it intends to request additional hydropower supplied by Hydro-Québec – i.e., beyond the 150 MW authorized by the Government – to scale up its production, improve financial returns, and further expand its business model as part of its Green Cycle. However, the firm stated that although it's "too early to talk about expansion" of the Mauricie Project, they do "have ambitions to replicate this project in other Canadian provinces."[41]

[35] Martin, P., 2023. 'Fortescue Future Industries' to disappear as Forrest unites hydrogen and metals businesses under same brand name, *Hydrogen Insight*, July 20 2023, www.hydrogeninsight.com/production/fortescue-future-industries-to-disappear-as-forrest-unites-hydrogen-and-metals-businesses-under-same-brand-name/2-1-1489389
[36] Allen & Overy, 2023. Allen & Overy advises Fortescue Future Industries on its joint venture with Tree Energy Solutions to develop the Wilhelmshaven terminal, Press release, March 16 2023, www.allenovery.com/en-gb/global/news-and-insights/news/allen-overy-beraet-fortescue-future-industries-bei-joint-venture-mit-tree-energy-solutions
[37] TES, 2022. *Fortescue Future Industries and TES team up to develop world's largest green hydrogen project*, Press release, October 4 2023, https://tes-h2.com/news/fortescue-future-industries-and-tes-team-up-to-develop-world-s-largest-green-hydrogen-project
[38] Parkes, R., 2024. Hydrogen-derived e-methane import terminal moves a step closer to FID after exemption, *Hydrogen Insight*, March 28 2024, www.hydrogeninsight.com/policy/hydrogen-derived-e-methane-import-terminal-moves-a-step-closer-to-fid-after-exemption/2-1-1618530
[39] TES, 2024. *TES products help you reduce emissions*, web page, https://tes-h2.com/green-cycle/step-5-green-energy-solutions
[40] TES, 2024. *Global Impact – Canada*, web page, https://tes-h2.com/global-impact/canada
[41] "*Questions et réponses TES Canada - Projet Mauricie*", Questions sent to TES Canada by citizens on March 12, answers received on March 21, 2024.

Table 2. TES "Green Cycle" business model for large scale commercialization of synthetic methane (e-gas) and green hydrogen, and TES Canada contribution to it

Source: TES, 2024.

Steps	Description	How TES CANADA could contribute to the TES Green Cycle
Step 1. Produce renewable energy	Generate renewable energy at scale in the world's sunniest and windiest places	Yes, through hydro (150 MW) and the self-generation of wind (800 MW) and solar (200 MW) energy. This step is the most valued.
Step 2. Produce green hydrogen	Use renewable energy to power a electrolyser which splits water into hydrogen and oxygen	Yes, up to 70,000 t H_2/year
Step 3. Produce synthetic methane (e-gas)	Combine the green hydrogen with « recycled » CO_2 to make e-gas	Yes, 2/3 of the H_2 is to produce 115 Mm^3 of e-gas a year (equivalent to 1.8 % of Quebec's total natural gas consumption in 2021).
Step 4. Transportation and distribution	Transport, ship, store and distribute e-gas and green hydrogen using existing infrastructure	Transportation and distribution expected to use existing infrastructure in Québec. Not for export at this time.
Step 5. Deliver e-gas and green hydrogen to customers	Provide a range of green energy products to customers who want to reduce GHG emissions cost-effectively.	Injection of e-gas for distribution in Energir's local gas network. The other 1/3 of hydrogen for use as fuel in heavy transportation. But no purchasing agreement have been confirmed.
Step 6. Capture and recycle CO_2	After the e-gas is used, CO_2 is captured and recycled to produce more e-gas	Not known

Key challenges: cost and efficiency

The appeal of the TES model is its promise to make a seamless energy transition using existing gas infrastructure which would allow for the least disturbance to the economy and our consumption patterns.[42, 43] TES Canada has stated that the Mauricie Project would be profitable for the company.[44] However, TES has yet to address publicly two key challenges: will e-gas be affordable for end-users, and will it be the most cost-efficient use of renewable electricity to decarbonise our economy?

TES Canada hasn't disclosed any information on the expected overall energy efficiency of e-gas (from production to consumption) compared to other options for decarbonizing the same end-uses, nor on the cost of its production. However, a report produced for Énergir, the gas distributor that would purchase the e-gas produced by TES Canada, estimated that the production costs could range from C$38 to C$80/GJ

[42] Marco Alverà: "L'objectif de Tree Energy Solutions est de transporter le soleil", *L'Écho*, www.lecho.be/entreprises/energie/marco-alvera-l-objectif-de-tree-energy-solutions-est-de-transporter-le-soleil/10441777.html
[43] Addison, V., 2023. TES Americas CEO: Electric Natural Gas Bigger Than Shale, *Hart Energy*, June 7 2023, www.hartenergy.com/exclusives/tes-americas-ceo-electric-natural-gas-bigger-shale-205332
[44] Beaudry, F., 2024. Le projet de TES Canada « mal ficelé », selon un expert, *La Presse*, March 15 2024, https://ici.radio-canada.ca/nouvelle/2057479/eoliennes-tes-canada-hydrogene-vert

in 2030 and from C$31 to C$73/GJ in 2050.[45] In comparison, fossil natural gas currently sells for around C$3-7/GJ in Quebec, including carbon fees, and renewable natural gas from residual biomass for C$20-25/GJ.[46]

According to Cynthia Walker, CEO of TES America, two major feedstocks account for the bulk of the production cost of e-gas. “Renewable electricity to produce the hydrogen is about 70% of the overall cost structure.” Then, depending on the source of the CO_2 and its location, “it’s about 7% to 10% of the overall cost of our molecule.” Similarly, Energir’s study finds that, in all 60 case scenarios analysed, “the cost of producing green hydrogen weighs heavily in the balance, representing up to 80% of e-gas production costs (see Figure 4).”

TES Canada says it can carry out its C$4 billion project without subsidies.[47] Its financial arrangement is confidential, but the project will likely benefit from indirect subsidies, such as various tax credits, fiscal advantages, low interest loans, and other government incentives available to industries and clean technology investments. TES Canada can also receive subsidies through the Quebec Government *Programme de soutien à la production de gaz naturel renouvelable*. [48] Other organizations supported by public funds (e.g., Business Development Bank of Canada, Investissement Québec or Caisse de dépôt et placement du Québec) could also invest in TES Canada.

According to Marco Alverà, CEO of TES, the TES business model only becomes economically viable if harvesting multiple subsidies: “There's a lot of money to be made in layering the different subsidies. So, you get a subsidy for capturing the CO_2, you get a subsidy for producing the renewables, you get a subsidy for producing the hydrogen. And guess what, you can export that molecule, so we may even be able to get additional subsidies in Europe."[49]

The need for subsidies to make green hydrogen projects, and its derivatives, viable was also echoed at the CERAWeek Annual Conference. Aramco CEO told delegates that ”in energy terms, the cost of green H_2 amounted to the equivalent of $400 per barrel of oil — roughly five times the current price”, and that green hydrogen would only be affordable with a “significant amount of [government] incentives and offtake agreements of at least 15 years”.[50]

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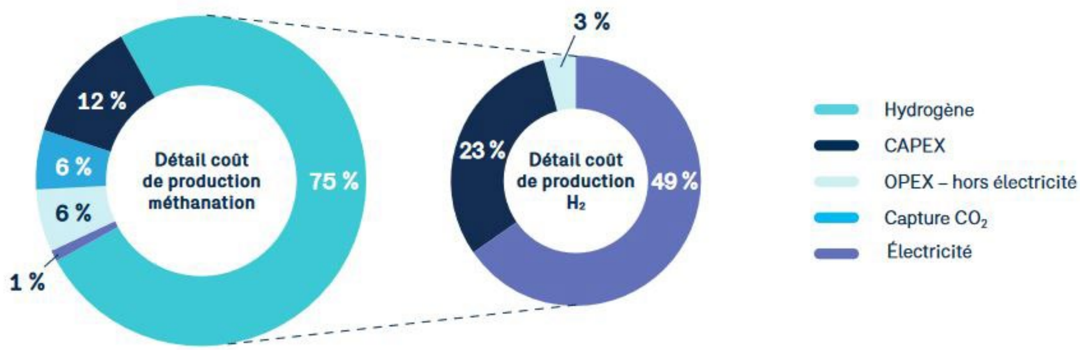
[45] Énergir and Sia Partners, 2023. *Gaz naturel renouvelable produit par methanation - Étude du potentiel technico-économique du GNR de 3e génération au Québec*, Technical report, https://energir.com/files/energir_common/import/Fichiers/Corporatifs/Publications/Fiche-technique-GNR_FINALE.pdf
[46] Whitmore, J., Pineau, P.-O., 2024. *État de l’énergie au Québec 2024*, Chair in Energy Sector Management, HEC Montréal, https://energie.hec.ca/eeq/
[47] Bergeron, P., 2023. TES Canada investit 4 milliards pour un « premier projet d’hydrogène vert » au pays, *Le Devoir*, www.ledevoir.com/economie/801737/quatre-milliards-investissement-usine-hydrogene-vert-shawinigan?
[48] Gouvernement du Québec, 2024. *Programme de soutien à la production de gaz naturel renouvelable*, www.quebec.ca/entreprises-et-travailleurs-autonomes/aide-financiere/production-commercialisation-distribution/production-gaz-naturel-renouvelable
[49] Liebreich, M., 2023. Ep126: Marco Alverà "Subsidies Everywhere All at Once", *Cleaning Up*, Podcast, May 10 2023, www.cleaningup.live/ep126-marco-alvera-subsidies-everywhere-all-at-once/?trk=article-ssr-frontend-pulse_little-text-block
[50] Collins, L., 2024. Nobody wants to pay for it' | ExxonMobil and Aramco CEOs say green hydrogen is too expensive to replace fossil fuels, *Hydrogen Insight*, March 19 2024, www.hydrogeninsight.com/production/nobody-wants-to-pay-for-it-exxonmobil-and-aramco-ceos-say-green-hydrogen-is-too-expensive-to-replace-fossil-fuels/2-1-1614462

Figure 4. Structure of production cost of e-gas in the Québec context (2022)

Source: Figure from Energir and SIA Partners, 2023.
Note: Based on a median scenario using CO_2 from the Pulp and paper and paper industry with direct injection.



According to Fortescue CEO Mark Hutchinson, a major partner of TES in the development of the Wilhelmshaven LNG import terminal in Northern Germany, “renewable power for green hydrogen and ammonia production will have to cost less than US$30/MWh for projects to compete on a global market.”[51] In Quebec the cost can vary between C$30-50/MWh (US$22-50/MWh) for industries, depending if an industry is eligible to participate to Hydro-Québec’s *Program for electricity cost reduction applicable to Rate L customers*[52], capacity to self-generate electricity or obtain special agreements negotiated with the Quebec government (e.g., as with the aluminum industries).

In addition to receiving favorable rates, TES Canada Mauricie project plans to “be part of Hydro-Québec’s peak management programs” to balance the network[53], such as the *Demand Response Option* (DMO) program.[54] Hydro-Québec spent C$59.5 million in 2023 for its various measures to reduce consumption during peak winter periods and expects this cost to rise to nearly C$700 million by 2032.[55] Just the 150 MW block granted to TES Canada by the Quebec government could, today, bring in revenues of

[51] Martin, P., 2024. ‘Renewable power prices must be $30/MWh or less for green hydrogen projects to compete’: Fortescue, *Hydrogen Insight*, March 11 2024, www.hydrogeninsight.com/production/renewable-power-prices-must-be-30-mwh-or-less-for-green-hydrogen-projects-to-compete-fortescue/2-1-1610699
[52] Hydro-Québec, 2024. *Program for electricity cost reduction applicable to Rate L customers*, web site, www.hydroquebec.com/business/customer-space/rates/rate-l-industrial-rate-large-power-customers.html
[53] According to Greiner (2013), H_2 storage unit in the e-gas production plant can be used for balancing the electricity network and offering ancillary services, by reducing or increasing the proportion of electricity used for electrolysis depending on grid demand. In the event of high demand, hydrogen production can be reduced, and conversely, if electricity production exceeds demand, the plant can draw electricity from the grid to increase hydrogen production.
[54] Hydro-Québec, 2024. *Demand Response Option*, web page, www.hydroquebec.com/business/customer-space/rates/demand-response-option-credit.html#gdp-options-flexibles
[55] Baril, H., 2023. Gestion de la demande de pointe - Les coûts explosent, *La Presse*, May 29 2023, www.lapresse.ca/affaires/2023-05-29/gestion-de-la-demande-de-pointe/les-couts-explosent.php

over C$8,2 million, based on the DMO calculator. If we consider the self-generated wind and solar power (1,000 MW) and the increasing value of the DMO credits by 2032, this source of income, paid by the state company, will be much higher. The Quebec government is also considering legalizing the direct sale of electricity from one company to another, which is currently prohibited. At present, only Hydro-Québec (and a few municipal utilities) has the right to sell electricity in Québec. The proposed bill would modify the *Loi sur la Régie de l'énergie* (art. 60) to allow private producers to sell electricity to private entities through power purchase agreements (PPA).[56] This legislative change could therefore provide additional revenues.

TES Canada has not disclosed what are the indirect government subsidies or favorable rates it could receive, nor its potential revenues from participating in Hydro-Québec's peak management programs or selling its wind and solar energy through power purchase agreements (PPA).

Overview of the technology: Sabatier Process

TES Canada stated it will use the Sabatier Process to produce its e-gas. Discovered by a French chemist in 1897, it is the most popular approach for producing e-gas. However, the process is energy inefficient. To make e-gas, green hydrogen must be produced via water electrolysis before being reacted with captured CO_2 to make water and methane (CH_4) Combining these two processes yields an overall efficiency between 50 and 60%, with nearly half of the input energy lost as heat, according to Hisataka Yakabe, a physical chemist at Tokyo Gas.

The Sabatier method is also highly exothermic (occurring at roughly 300—900°C), which means that much of the energy from the input hydrogen is lost as heat. The process therefore requires "highly sensitive thermal management" to capture the lost heat and reuse it. "The whole process involves capital equipment, such as electrolyzers, compressors, hydrogen storage tanks, catalytic reactors and heat exchangers, all of which add to the production costs."[57] The process also produces water. In the end, for every kilo of hydrogen that goes in, only half a kilo of hydrogen is embodied in the resulting e-gas.

[56] Gerbet, T., 2024. Québec veut légaliser la vente d'électricité entre compagnies privées, *Radio-Canada*, January 19 2024, https://ici.radio-canada.ca/nouvelle/2042313/hydro-quebec-vente-electricite-fitzgibbon-compagnies-monopole
[57] Tokyo Gas, 2023. Synthetic methane could smooth the path to net zero, *Nature*, www.nature.com/articles/d42473-022-00166-2#:~:text=For%20a%20start%2C%20the%20reaction,lost%20as%20heat%2C%20says%20Yakabe

Methodology

Modelling approach

TES Canada has not published any techno-economic or efficiency analysis of their project. The analysis by SIA Partners, prepared for Énergir, provides some results on the cost of e-gas, but doesn't detail data sources and assumptions. For this analysis, we present our data and assumptions in Table 3a-b and compare them with those presented in Greiner (2013; Figure 6), which estimated the cost of e-gas at around C$37 and C$46/GJ in the context of Québec.[58] The data sources and assumptions were limited and often relied on the author's "personal choices". Although the study is outdated, it does provide a basis for comparing our analysis, short of having publicly available data and methodology from TES Canada.

For our analysis, we estimated the cost of e-gas, and estimated the global efficiency for e-gas for several end-uses based on 1 MWh of electricity input. The data and assumptions are summarized in tables 3a-b and 4 below.

As previously mentioned, to be eligible to receive the 150 MW energy bloc from Hydro-Québec, TES Canada must demonstrate that the production of its green hydrogen, or its derivatives, is consumed in one or more priority sectors, including heavy transport, industry and energy storage and management. The injection of hydrogen into the gas network is not considered a "priority sector."

TES Canada's claim that the e-gas would exclusively be used for industrial consumption (see Figure 1). However, this is inconsistent with Energir's analysis (see Figure 2) which shows it would be injected in its principal gas network for all uses, including building heating. For this reason, our analysis will evaluate the energy efficiency chain of e-gas for use in heating building in Québec, as well as for low (200°C) and high (200-1,500°C) temperature industrial process.

Note that the analysis presented in this working paper is based on the authors current understanding of the project based on available data and information. Results can change as further data is made public.

Scenario description

Optimistic (blue sky): This scenario used best case estimates for all parameters, including in some cases where values of those parameters are not possible in practice using the sources of energy input proposed by TES. Most importantly, it assumes a 100% capacity factor for the electrolyzer, which would only be possible if the electrolyzer were operated continuously without interruption. This assumption is not realistic for a plant which will make a substantial fraction of its power from wind and solar, with only 150 MW of uninterruptible hydroelectric power.

[58] Greiner, N., 2013. *Étude des coûts de production de Gaz Naturel Renouvelable à partir d'électricité et de CO_2*, Rapport de stage, Polytechnique Montréal, https://energie.hec.ca/wp-content/uploads/2024/03/Nathan_Greiner_Cout-GNR_29aout2013.pdf

Realistic: This scenario remains optimistic, includes some constraints that are closer to reality for important parameters such as the capacity factor of the capital equipment (electrolyzer, etc.) that will be required, and the delivered cost of CO_2 and electricity.

Scope and limits of the analysis

The following items are not in the scope of modelling analysis but could be included in future analysis.

Our cost analysis assumes an interest rate of zero, requiring the cost of e-gas to be sufficient only to pay back the initial capital. No profit or borrowing cost is included in our analysis.

Because we have no reasonable basis for estimates of the capital cost of the Sabatier reactor system, we have assumed that its capital cost is zero in both the overly optimistic and the realistic cases. Under real conditions, the Sabatier reactor system will have a capital cost which will need to be paid back through sales of e-gas. For this reason, our estimates of the cost of the product are low.

Data sources and assumptions

An overview of the key parameters and assumptions used in the analysis are presented in this section (see tables 3a-b and 4). The information is presented in a similar format as Figure 6 in Greiner (2013) for comparability. However, some parameters presented by Grenier (2013) were not relevant, as the present analysis considers the global efficiency of using e-gas for heating buildings, and for industrial, based on 1 MWh of electricity input.

Sabatier Process

TES Canada claims that the "conversion of hydrogen into e-gas is about 80% "efficient, and expects to recover "at least 8%" as heat, thereby estimating their "total process at overall efficiency of 65-75%."[59] However, these claims are not based on test results and appear overly optimistic based on their expected hydrogen and e-gas productions (see Section on "Data sources and assumptions" below). TES mentions that "these figures come from our preliminary engineering, and we are now completing the more detailed engineering and choice of technologies. As a result, these figures continue to evolve and consolidate. "

Our Optimistic Scenario uses factors for the electrolysis of 83% (which is optimistic relative to the performance of commercially available electrolyzers) and a conversion of hydrogen energy to energy in e-gas of 0.78*0.85 (also conservative) which is 66%, not 80% as claimed by TES Canada.

A conversion of hydrogen energy (HHV) to energy in e-gas (HHV) of 80% is thermodynamically impossible. The absolute maximum possible conversion efficiency of the Sabatier process from stoichiometry is 78%. The estimate of their efficiency is therefore overly optimistic and unlikely. TES indicated that they would

[59] "*Questions et réponses TES Canada - Projet Mauricie*", Questions sent to TES Canada by citizens on March 12, answers received on March 21, 2024.

use about 44,880 tonnes of hydrogen per year (6.37 million GJ of HHV) for e-gas production, to produce 115 Mm^3 of e-gas per year (4.25 million GJ of methane HHV). The result is a conversion efficiency of about 66% from hydrogen HHV to methane HHV, which is about 85% of the theoretical maximum of 78% from stoichiometry. We used this figure (85% approach to 100% stoichiometric energy conversion) in our optimistic case.

For the more Realistic Scenario, we have calculated the efficiency of the Sabatier conversion of energy feeds into products (e.g., methane gross or higher heating value) by optimistic analogy to e-methanol production, which is a similar process. Whereas methanol production plants achieve 70% of the maximum efficiency possible as calculated from stoichiometry, we have assumed a value of 75% for the realistic case for the conversion of CO_2 and hydrogen to methane.

What productive use the 8% heat recovery estimated by TES Canada can be put toward in the electrolyzer and e-gas plants, both of which are exothermic, is not clear. We have assumed that a small amount of electrical energy is used at another location where CO_2 is collected, separated from other gases, dried and compressed for shipment (see Table 3a). We have not assumed any energy use to transport the CO_2 by truck or pipeline, given that data on the specific CO_2 source were not available.

Table 3-a. Data and assumptions for estimating potential cost of e-gas in Quebec

Sources: HSC, 2024.

Parameters	*Greiner 2013 scenario*	Overly optimistic scenario	Realistic scenario	Sources and assumption notes
Electrolyser				
Installed capacity	*3 MW*	N/A	N/A	TES Canada is expected to have a 500 MW electrolyser. However, the information is not relevant, as the analysis considers the global efficiency of using e-gas for heating buildings based on 1 MWh of input.
Electrical grid distribution loss	*N/A*	1%	1%	A very small (1%) electrical distribution loss is included (1/7th of the grid average for Quebec), assuming that the electrolyzers are located close to both the hydroelectric and solar/wind resources.
Lifetime	*20 years*	10 years	7 years	IRENA, 2021. *Making the Breakthrough - Green hydrogen policies and technology costs*, (Table 1- lifetime is 50-80,000 hours).[60]
Investment cost	*2 000* $/kW	2 000 $/kW	3 000 $/kW	Schmidt, et al. 2017. *Future cost and performance of water electrolysis: An expert elicitation study.*[61] Note that the investment cost is used only for a "simple payback" calculation. No "discount rate" is applied in the cost calculations, which is similar to the assumption that the capital costs of the electrolyzer are financed 100% with an interest-free loan.
Operation & maintenance cost (% investment)	*5%*	0%	10%	0 % maintenance cost is assumed under the Optimistic scenario given that there are no available data. Under the Realistic scenario, a total of 10 % of original capital spent over 7 years of operation is assumed based on basic engineering economics.
Ultimate energy efficiency (HHV basis)	*78%*	83%	75%	Assumption based on extensive review of real quotations (from confidential sources), which never found a full electrolyser + BoP figure for existing commercial electrolyzers offered for sale of less than 55 kWh/kg. 75% HHV efficiency is 52.5 kWh/kg and is by this measure an optimistic estimate.
Capacity Unit factor	*87%*	100%	81%	Realistic scenario assumes 30% capacity factor for wind + solar (1,000 MW) + 100% capacity factor for hydro (150 MW), feeding a 500 MW electrolyzer, yielding an electrolysis capacity factor of 81%. This assumes there is a useful purpose for 100% of the electricity from wind or solar whenever it goes beyond the needs of the electrolyser.
H_2 Storage				
Capacity	*1 000 kg*	N/A	N/A	Not relevant in this analysis.
Lifetime	*20 years*	N/A	N/A	Not relevant in this analysis.
Investment cost	*700* $/kg	0 $/kg	0 $/kg	Not relevant in this analysis. We have assumed that the cost is 0 $.
Operation & maintenance cost (% of investment, or % of energy content)	*5%*	0%	5%	Not required in « optimistic scenario » as the capacity factor assumed is 100%. No adequate data were found for how much hydrogen would be stored, nor for a hydrogen storage cost. NREL (2009) used in Grenier (2013) is outdated, but it is known that approximately 5% of the *energy content* of the stored hydrogen would be needed to feed compressors if any storage at all is used.

[60] www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Nov/IRENA_Green_Hydrogen_breakthrough_2021.pdf?la=en&hash=40FA5B8AD7AB1666EECBDE30EF458C45EE5A0AA6
[61] www.sciencedirect.com/science/article/pii/S0360319917339435?via%3Dihub

Table 3-b. Data and assumptions for estimating potential cost of e-gas in Quebec

Sources: HSC, 2024.

Parameters	***Greiner 2013 scenario***	**Overly optimistic scenario**	**Realistic scenario**	**Sources and assumption notes**
Mathanation (Sabatier reaction)				
H_2 processing capacity	*1 500* kg/day	N/A	N/A	Not relevant as the analysis considers the global efficiency of using e-gas for heating buildings based on 1 GW of input.
Conversion rate	*95* mol-%	100 mol-%	100 mol-%	Method used by Grenier (2013) assumes incorrectly that 95% purity of the e-gas outlet means 95% efficiency of converting energy in H_2 to energy in methane. 100% conversion of H_2 energy to methane energy per the Sabatier reaction is only 78% efficient. (Moioli et al, 2019. *Renewable energy storage via CO_2 and H_2 conversion to methane and methanol: Assessment for small scale applications.*[62])
Ultimate energy efficiency (HHV basis)	N/A	78 %	78 %	HHV CH_4/HHV H_2 estimate from stoichiometry, cross validated with Moioli et al. (2019).
Approach to ultimate efficiency	N/A	85 %	75 %	Data for Optimistic scenario was estimated using publicly available TES data (115 Mm^3 produced vs 134 Mm^3 at 100% theoretical yields = 85%). Data for the Realistic scenario is based on optimistic comparison with other processes (i.e. methanol production).
Investment cost (% electrolyse)	*20 %*	0 %	0 %	There is no publicly available data to calculate the Sabatier reaction system cost. It was therefore assumed it is as perfect as possible, i.e. zero cost.
Operation & maintenance cost (% electrolyse)	*20 %*	0 %	0 %	Since we have assumed zero cost for the Sabatier capital equipment, we have similarly assumed zero cost to operate and maintain it.
Primary feedstock				
Electricity cost	*0,05* $/kWh	0,054 $/kWh	0,07 $/kWh	Electricity Cost for « Optimistic scenario » based on an average price (Energy and Power) of Hydro-Quebec's Rate L for large industries.[63] The Costs for « realistic scenario » based on estimated median LCOE for wind + solar in Ontario for 2023, from Dunsky, 2022. Cost of Renewable Generation in Canada, Final report, prepared for Clean Energy Canada.[64], for the portion of the electricity which would come from the wind and solar portion of the project
CO_2 cost (does not include cost of transportation and storage)	*35* $/t CO_2	30 $/t CO_2	50$ /t CO_2	Estimate based on 2.1 MJ heat/kg H_2, from NRCan data for Shell Quest, which amounts to 8% of the energy in the hydrogen used, or $30/t CO_2 at 0,05$/kWh. TES also states in a Hydrogen Insight (2023) interview that the biogenic CO_2 of their US project could come from ethanol production. IISD estimated carbon capture cost by industry at ethanol plants would between 35$- 75$ t/CO_2.[65] A cost of 50$/t is therefore a reasonable, but only if there is no transport of CO_2 required, which would further increase cost.

[62] https://doi.org/10.1016/j.rser.2019.03.022
[63] www.hydroquebec.com/business/customer-space/rates/rate-l-industrial-rate-large-power-customers-billing.html
[64] https://cleanenergycanada.org/wp-content/uploads/2023/01/RenewableCostForecasts_CleanEnergyCanada_Dunsky_2023_SlideDeck.pdf
[65] See Figure 2, IISD, 2023. Why the Cost of Carbon Capture and Storage Remains Persistently High, www.iisd.org/articles/deep-dive/why-carbon-capture-storage-cost-remains-high

Table 4. Key assumptions for estimating overall efficiency of e-gas when used in heating building and industry in Quebec
Sources: HSC, 2024.

Parameters	Value and units	Sources and assumption notes
Heating building		
Boiler/furnace efficiency	90%	Typical for low temperature, high efficiency gas heating appliances on an AFUE basis.
Gas transmission efficiency	95%	GREET model for natural gas from well to gas meter, Source Argonne National Laboratories
Heat pump alternative coefficient of performance (	2.5	Seasonal COP for air source heat pump, given that commercially available heat pumps have a COP of 2.2 even at -20°C. Source: Hitachi (2024)[66]
Industry (200°C)		
High Temperature Heat Pump COP	1.5	Assumes that industrial heating can be provided electrically by pumping heat from heat rejection streams, cooling water etc. or via mechanical vapour recompression at an average coefficient of performance of 1.5, up to a maximum of 200°C
Boiler or Furnace Efficiency (AFUE)	85%	Optimistic performance, HHV basis, for mid temperature fired boilers which cannot use the heat of condensation of the water of combustion produced when burning methane.
Industry (200-1,500 °C)		
Resistance heating efficiency	97%	Resistance electric heaters can produce heat to 1,500°C with an efficiency of nearly 100%. The only losses are grid losses and a minor loss in switchgear totaling 3%.
High temperature furnace efficiency	80%	Optimistic performance of high temperature combustion equipment, HHV basis, if economizers (e.g., heat recovery steam generators, etc.) are installed to recover nearly all of the useful heat energy from hot flue gas, other than the heat of condensation.

Results

Global efficiency of e-gas

What is the overall energy efficiency of e-gas compared to direct use of electricity? Adding a transformation step towards the production of e-gas for injection into the gas network will only exacerbate energy losses. From a scientific point of view, this process is an energy aberration, because it is contrary to the search for efficiency in the transformation of energy between different forms until its final use. Making e-gas should be understood as an attempt to trade reduced energy efficiency for greater fuel effectiveness (i.e. to produce a fuel which can more easily be transported and stored in the existing gas infrastructure than hydrogen).

[66] Hitachi, 2024. www.hitachiaircon.com/ranges/heating

Building heating

According to our estimates, the use of e-gas for building heating would result in an overall energy loss in the range of 57% (optimistic) to 70% (realistic; see Figure 5), due to losses across the electricity-to-hydrogen conversion chain from hydrogen to e-gas and from e-gas to heat production. When compared to an efficient heat pump, heating a building with e-gas would require about 5.4 times more electricity than if it were used directly for heating, in the overly optimistic case, and 7.5 times as much energy in the realistic case. The cost to deliver the same amount of heat in the home varies between 7 and 12 times the cost, assuming electricity were supplied to the home at the same price used to produce e-methane.

Low temperature (200°C) industrial process

The use of e-gas for low temperature industrial process would result in an overall energy loss in the range of 59% (optimistic) to 70.5% (realistic; see Figure 6), due to losses across the electricity-to-hydrogen conversion chain from hydrogen to e-gas and from e-gas to low industrial heat production, using high efficiency industrial furnaces or boilers. The use of e-gas for low temperature industrial processes, which is the majority of gas needs in the industrial sector[67], would result in a requirement for 3.4 (optimistic) to 4.8 (realistic) times as much electricity and 4.4 to 7.6 times as much cost, to deliver via e-gas, in comparison with using electricity directly to run mechanical vapour recompression or high temperature heat pumping with a coefficient of performance of 1.5.

High temperature (200-1,500°C) industrial process

The use of e-gas for high temperature industrial process would result in an overall energy loss in the range of 62% (optimistic) to 73% (realistic; see Figure 7), due to losses across conversion chain to high temperature industrial heat production. In calculating these losses, we have assumed a heat recovery efficiency of 80% on a higher heating value (HHV) basis, requiring that heat recovery steam generators, economizer coils or other technologies are used to recover nearly all of the heat exiting the furnace as high temperature flue gas for other purposes in the facility, which is not always either possible or economic. The use of e-gas for high temperature industrial processes would, despite our very optimistic assumptions around the efficiency of high temperature gas fired equipment, still require 2.4 (optimistic) to 3.3 (realistic) times as much electricity and would cost 3 to 5.2 times as much, relative to using resistance heaters with an efficiency of 97% to supply this heat instead.

[67] McMillan, C., Ruth, M., 2019. Using facility-level emissions data to estimate the technical potential of alternative thermal sources to meet industrial heat demand, *Applied Energy*, Vol. 239: 1077-1090, www.sciencedirect.com/science/article/pii/S0306261919300807?via%3Dihub

Figure 5. Energy efficiency chain for e-gas for heating building in Québec – Realistic Scenario

Sources: See tables 3a-b and 4.
Note: Proportion of boxes in the graphic are not at scale.

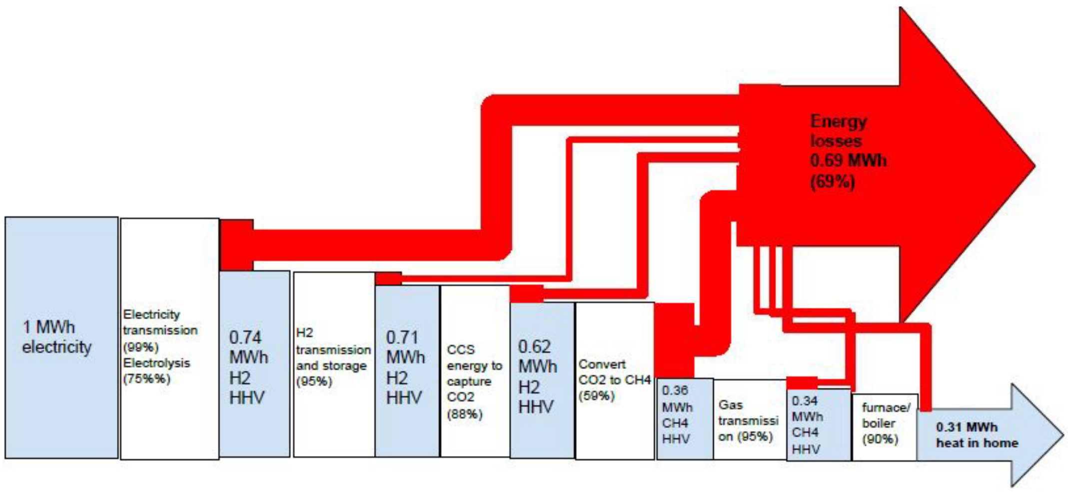


Figure 6. Energy efficiency chain for e-gas for low temperature (200°C) industrial process in Québec – Realistic Scenario

Sources: See tables 3a-b and 4.
Note: Proportion of boxes in the graphic are not at scale.

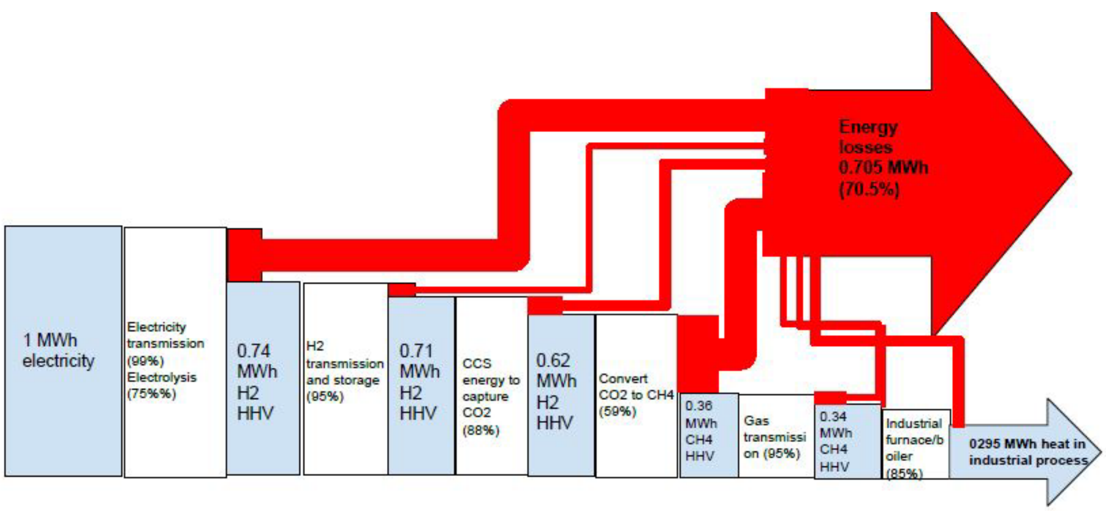
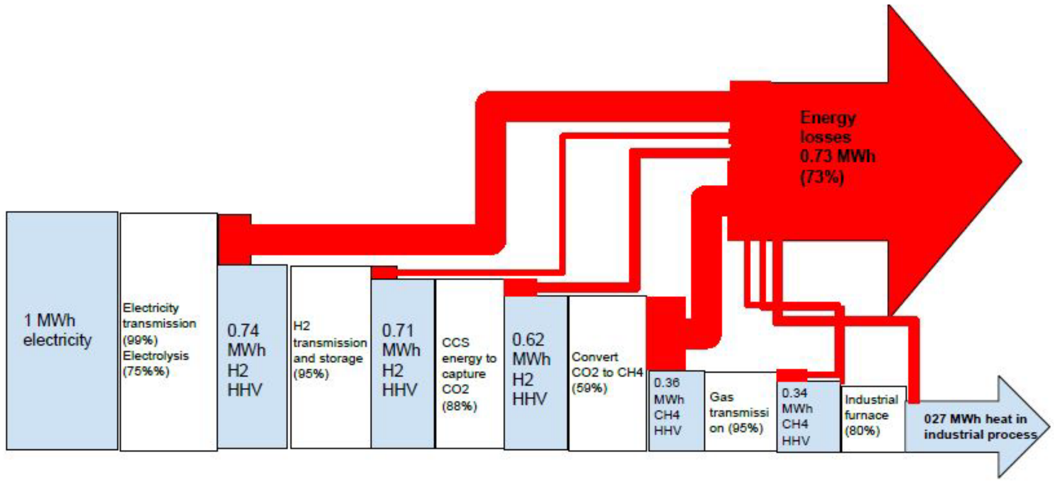


Figure 7. Energy efficiency chain for e-gas for high temperature (200-1,500°C) industrial process in Québec – Realistic Scenario

Sources: See tables 3a-b and 4.
Note: Proportion of boxes in the graphic are not at scale.



How much will e-gas cost?

Due to the high electricity requirements and energy losses in its production, e-gas will be expensive not only to produce, but also to consume. According to our estimates, the cost could vary between C$40, under a very optimistic scenario, and C$90/GJ under a more realistic one. In comparison, natural gas currently sells for around C$3-7/GJ in Quebec, including carbon fees, and renewable natural gas around C$20-$25/GJ.

In Quebec, industry accounts for over 60% of natural gas consumption, but only 40% of Énergir's revenue. Between 2022 and 2023, voluntary consumption of natural gas from renewable sources (NGRS) by industrial clients declined by 49%, from 46.5 Mm3 to 23.6 Mm^3 (see Table 1).[68] Compared to other client types, industrial clients show the least progress towards voluntarily increasing its consumption of renewable natural gas. Furthermore, according to Énergir, it is "not realistic" to impose purchase obligations of natural gas from renewable sources on industrial customers because of "global competitiveness."[69] In its "Decarbonization vision for the industrial sector" in 2050, Energir does not propose any targets, binding measures or requirements for the purchase of GSR in this sector.[70]

Given the high cost of e-gas and the declining trends in voluntary demand of GSRS in the industrial sector, it is not clear how TES Canada can claim that the e-gas would exclusively be used for industrial uses (see Figure 1). For this, TES would have to

[68] Énergir, 2024. Suivi trimestriel de la décision D-2023-022 sur la stratégie de commercialisation du GSR, *Mesures relatives à l'achat et la vente de gaz naturel renouvelable*, R-4008-2017, Régie de l'énergie, www.regie-energie.qc.ca/fr/participants/dossiers/R-4008-2017/doc/R-4008-2017-B-0993-Dem-Piece-2024_02_29.pdf
[69] Baril. H., 2024. Énergir pourra imposer le GNR à ses nouveaux clients, *La Presse*, www.lapresse.ca/affaires/entreprises/2024-01-30/energir-pourra-imposer-le-gnr-a-ses-nouveaux-clients.php
[70] Énergir, 2024. *Rapport sur la résilience climatique 2023*, p.27-30, https://energir.com/files/energir_common/Rapport-climat-2023-VF.pdf

confirm that a purchasing agreement has been signed between Energir and industrial companies willing pay a premium for purchasing the environmental benefits associated with the production of e-gas compared to conventional gas. Otherwise, the e-gas will also end-up being consumed in heating buildings, which is not a priority sector given that cheaper, more efficient options are available for their decarbonization. Under these circumstance, TES Canada may not fully meet the criteria established by the government for authorising hydrogen projects, as described previously.

Sensitivity Analysis

The estimated cost of e-gas is based on conservative assumptions as noted in Table 3. The cost is particularly sensitive to the assumed capacity factor of the electrolyzer and the cost of electricity fed to the process. Figures 8 and 9 examine the sensitivity of the cost of e-gas as each factor is varied across a range that might be expected in future e-gas projects, with all other factors held constant at the values stated in Table 3 for either the overly optimistic or the realistic scenario.

Figure 8. Sensitivity of e-gas to electricity cost

Source: HSC estimates, 2024.

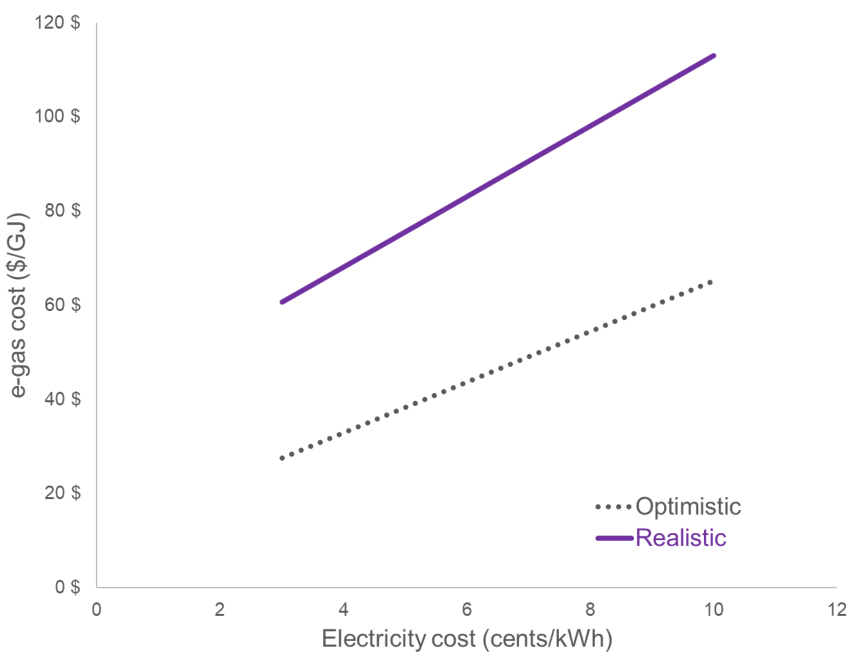
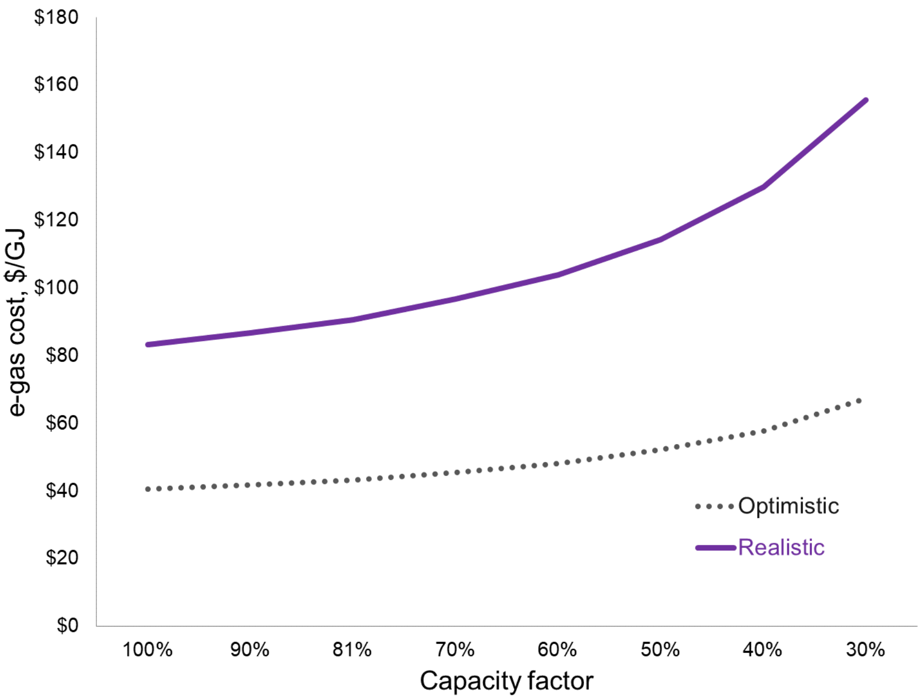


Figure 9. Sensitivity of e-gas cost to electrolyser capacity factor
Source: HSC estimates, 2024.



The sensitivity of cost to capacity factor is underestimated in both the optimistic and realistic cases, because unless a significant amount of hydrogen storage is included in the project, the Sabatier reactor will need to also operate at a lower than 100% capacity factor. Since we have assumed a zero cost for the Sabatier reactor due to an absence of reliable data, the real impact of capacity factor on e-gas cost will be greater than shown in Figure 8.

Note that the capacity factor and the cost of electricity will, to some degree, be inversely related to one another in all projects involving sources of renewable electricity. Higher capacity factor involves over-building the size of the renewable generation asset relative to the maximum possible demand of the electrolyzer for electricity. The TES Canada project, for instance, would uses 1,000 MW of low-capacity factor land-based wind and solar power plus 150 MW of premium, high-capacity factor hydroelectricity, to feed a 500 MW electrolyzer. If the project were constrained to operate only on the 1,000 MW of wind and solar, without the 150 MW hydro component, the electrolysis capacity factor would drop to 60%.

If the grid were not available to absorb the surplus of 350 MW (or 500 MW) of power when wind and sun assets are generating at their full nameplate capacity, i.e. if the project were “islanded” rather than connected to the grid, the capacity factor of that 1,000 MW of wind and solar would drop further still as a result of curtailment, by an amount which would need to be calculated based on hourly estimates of the output of real wind and solar assets installed in the project’s particular location over the year.

The pivotal role of both the 150 MW of hydropower and its associated grid connection to the economic feasibility of the project should therefore be clear.

This raises the question: if the local grid can absorb excess wind and solar power without the need to curtail the electrolyzer, and hence to pay the project operator for lost opportunity to make and sell e-gas, would it not be simpler and better for the grid to add wind and solar assets directly? Finally, any curtailment of the electrolyzer during peak periods of grid demand could further reduce its capacity factor, driving up the cost of each gigajoule of e-gas delivered to customers.

Conclusion

As part of its consultations, TES Canada indicates that its project is “essential to the decarbonization of Quebec”.[71] Our analysis, however, suggests that the e-gas chain promises to be inefficient and costly for the Quebec economy.

TES Canada claims that “4.4 million GJ of e-gas produced would contribute to eliminating ~325,000 tCO_2 annually.”[72] By our estimate, making 4.4 million GJ of e-gas would require about 8.8 million GJ of electricity, ignoring gas transmission energy loss. If 4.4 million GJ of e-gas displaced 325,000 tCO_2/year from fossil natural gas, just using 8.8 million GJ of electricity in resistance heaters instead would save 650,000 tCO_2/yr if those heaters were used to replace gas fired furnaces or boilers. Emissions reductions would be even greater if the electricity were fed to heat pumps or mechanical vapour recompression units, for instance.

TES Canada claims that “at present, the project does not involve the sale of electricity from its renewable assets to Hydro-Québec.” However, given the 150 MW of hydropower with 100% capacity factor, and 1,000 MW of planned wind and solar with a capacity factor of perhaps 30% in composite (higher for the wind portion, lower for the solar), the project could generate 500 MW more electricity than the project demands, which would be curtailed. For example, there will be times in July, when the sun is giving full output from the solar panels at noon, and if it's also windy, the wind turbines might be also delivering full output. Other times, there could be no wind and sun, when it's dark for instance, and the only power available would be the 150 MW bloc of hydropower.

Under these circumstances, if TES Canada is not selling its excess electricity to Hydro-Québec’s, the cost per kilowatt hour (kWh) for the remainder of their electricity would likely become much higher than assumed under our realistic scenario. To ensure the project’s financial viability, it therefore seems more likely that TES Canada would sell power to Hydro-Québec - not just when their generation is in surplus, but also via turning down their electrolyser input power at higher prices per kilowatt hour (kWh) during peak periods (providing demand response service to the grid). From a

[71] TES Canada, 2023. *TES présente le Projet Mauricie : Un projet essentiel pour la décarbonation du Québec grâce à l’hydrogène vert*, Press release, November 10 2023, https://projetmauricie.ca/tes-canada-presente-projet-mauricie/
“*Questions et réponses TES Canada - Projet Mauricie*“, Questions sent to TES Canada by citizens on March 12, answers received on March 21, 2024.

business perspective, this strategy could provide a significant portion of their planned revenue and a way to compensate cost from interruptions.

Green hydrogen will play a role in the energy transition, but for its contribution to decarbonization to be optimal, the premises of the TES Canada project must be transparent and supported by evidence made public. **This working paper is an invitation for decisionmakers to publish their data to compare analyses.**

In addition to the cost and global efficiency of e-gas, other information should be made available to better understand the project:

- **What are the key assumptions and data (e.g., costs, hydrogen truck technology adoption curve, industry purchase of e-gas curve) used by TES Canada to support its claim that the project would reduce CO_2 emissions by 800,000 tonnes yearly starting in 2028**, of which 325,000 tCO_2e reduction associated with the use of e-gas in industry and the remaining from hydrogen used as fuel in heavy trucks[73]?
    - **Provide scenarios and analysis (with key data and assumptions) of the impact on GHG emission reductions** if the expected hydrogen and e-gas production and end-uses aren't met by 2028. The GHG reduction potential should be based on the maximum commercial potential, which account for market barriers, and not just the technoeconomic potentials.
- **Confirm what volumes of e-gas are backed by signed purchasing agreements between Energir and industrial clients** to support the claim that e-gas will only be used for industrial end-users (Figure 1).
    - Has the **Industrial Gas Users Association[74]** (*Association des consommateurs industriels de gas*) confirm to TES Canada their interest in purchasing e-gas?
- **Explain what would happen with the e-gas volumes if they are not purchased by industrial clients in Quebec**. Could the e-gas be used by other final end-users? Between 2022 and 2023, the volume of voluntary demand of renewable natural gas (RNG) in Energir's industrial customers has declined by 49% (see Table 1).
- **Has TES Canada considered, as part of its business model, the possibility of exporting** its e-gas production, or other hydrogen derivatives, in the future as part of its Green Cycle business model?

[73] TES Canada, 2024. *Projet Mauricie - Une initiative de TES Canada*, PPT presentation, December 7 2023, https://mcusercontent.com/e6312cb60ed6f15721a2219e6/files/170e7498-31ba-a001-489c-2ebc7720a526/TES_Canada_Ecrans_consultations_20231207.pd
[74] IGUA, 2024. Industrial Gas Users Association, web site, https://igua.ca/

- **TES Canada claims the project is economically viable for the company, without public subsidies.** However, it doesn't mention whether the project intents to benefit from other incentives offered by federal, municipal or Quebec governments (e.g., fiscal advantages, tax credits, creation of conformity units (CU) under Canada's Clean Fuel Regulation, Clean Hydrogen Investment Tax Credit, *Programme de soutien à la production de gaz naturel renouvelable*, preferential L tariff), investments from public organizations (ex., CDPQ, IQ, CBD). TES has stated it plans to participate in Hydro-Quebec's Demand Response programs.
  - **What other government or public incentives or advantages does TES Canada plan on requesting or using to support the economic viability of its value chain?**
  - **What percentage of total revenue is expected to be generated from the projects participation in Hydro-Québec's demand response program or the possibility of selling electricity to other businesses through PPAs** ?
  - Given the pivotal role of both the 150 MW bloc and its associated grid connection to the economic feasibility of the project, **does TES Canada expect to request additional power supply from Hydro-Québec, beyond the 150 MW bloc, to support its project?**

ANNEXE 1 | Natural Gas Network in Québec

Source: Énergir, 2024. https://colpron.com/energir/