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RESEARCH ARTICLE

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How Canada can supply Europe with critical energy by creating a Trans-Atlantic energy bridge

Thomas A. Adams II

Norwegian University of Science and Technology, Department of Energy and Process Engineering, Trondheim, Norway

Correspondence
Thomas A. Adams II, Norwegian University of Science and Technology, Department of Energy and Process Engineering, Trondheim, Norway.
Email: thomas.a.adams@ntnu.no

Abstract

Public policy decisions made over the past 10–15 years have significantly impacted the resiliency of Canadian and European energy systems. Rightly or wrongly, these decisions have included shifts away from coal and nuclear energy for electricity in favour of wind and solar, scuttling oil pipeline developments in all directions in Canada, how world governments responded to the pandemic, and increased reliance on Russian and US energy networks. The pandemic and subsequent Russian invasion of Ukraine have significantly tested the resiliency of these systems and caused major impacts on prices and everyday life. It has revealed weaknesses in Western energy security, and Europe is scrambling to adjust to sudden and drastic reductions in imports of Russian energy. In this perspective, I review the challenges to our energy systems. Then, I propose the creation of a Trans-Atlantic energy bridge to Europe and highlight some technologies and strategies Canada can use to create it.

KEYWORDS

energy security, energy technology, energy trade, global energy systems

1 | INTRODUCTION

The February 2022 invasion of mainland Ukraine by Russia drastically upset the energy trade in Europe. Prior to the attack, the European Union imported about 35% of its natural gas and 25% of its oil from Russia.[2] Over time, this dependence on Russian energy grew as European countries began to scuttle their nuclear and coal power plants in response to nuclear risk fears or climate change goals. Energy security was unfortunately sacrificed in the process. Warning signs were not lacking—after all, Russia already invaded Crimea (region of Ukraine) as early as February 2014.[3] As Russian troops began to amass along the Northern and Eastern borders of Ukraine in January 2022 and the reality of what was about to happen became undeniable, pundits began to discuss how Europe might have to manage without Russian energy imports.[4] But by then, it was too late! Resiliency and security must be built into national and regional energy systems by design and well in advance of problems seen or unforeseen. To address this important issue, I propose the creation of a Trans-Atlantic energy bridge—an oceanic supply chain of energy from Canada to Europe using a diverse array of resources and technologies and for the benefit of both continents.

This work was presented at the 2022 Canadian Chemical Engineering Conference in Vancouver, BC, 23–26 October 2022. Small portions of the text were reprinted or modified from the corresponding extended abstract.[1]

2 | ENERGY SECURITY WEAK POINTS IN CANADA AND EUROPE

2.1 | Canadian pipelines

Canada's major energy systems are similarly at risk. Despite being the world's fourth-largest producer of oil,[5] its energy transportation systems are heavily dependent on the United States. A map of Canada's major oil pipelines is shown in Figure 1. Crude oil works its way down from Western Canada (Alberta, Saskatchewan, parts of eastern British Columbia, and the Northern Territories) south across the US border. Although some oil is transported for export to terminals in Victoria, BC, the vast majority heads toward the US Gulf Region. Some crude heads eastbound through the US Midwest via Line 5, and then back again to Canada at Sarnia, Ontario, and eastwards through to Quebec, supplying Canadian refineries. This is an important point—the refineries in Eastern Canada are almost completely dependent on US pipelines since Canada has no oil pipelines connecting East and West on its own. Similarly, Eastern Canada heavily imports refined products through similar routes.[11]

Despite Canada's special relationship with the United States, recent events have shown that Canadians are extremely vulnerable to sudden American public policy changes taking place outside their control. The fact that the US—Canadian border was shut down for 19 months during the pandemic, preventing friends and families from visiting each other for years, is shocking enough. More shocking is that after Canada finally decided to reopen the borders to Americans, the United States did not reciprocate until several months later.[12,13] Other Trump-administration upsets to longstanding trade relationships included the imposition of newsprint, steel, and aluminium tariffs and the renegotiation of the North American Free Trade Agreement,[14] but such disruptions were not limited to that administration.

When it comes to energy security, the status quo was most recently threatened (and perhaps still is) by the potential closure of Line 5 in the state of Michigan. Line 5 carries nearly half of the oil needs of both Ontario and Quebec[15] and is a key part of the Canadian oil transportation system.[16] In 2021, the governor of Michigan ordered the closure of Line 5 because of environmental sensitivity associated with the Straits of Mackinac and other areas,[15] upsetting the international trade agreement. This caused a political firestorm concerning the distribution of powers between the State and Federal governments, the jurisdiction, and whether the Governor of Michigan had the power to shut down the pipeline.[17] Although it has not (yet) been closed, the position on Line 5 was a campaign issue for the candidates in the November 2022 Michigan Gubernatorial election, with the incumbent victorious and a promise to pursue the shutdown intact.

The Saga of Canadian pipelines serves to show the external and self-imposed difficulties of security-improving projects. Figure 1 shows four recently proposed pipelines: Enbridge Northern Gateway, Energy East, Keystone XL, and the TransMountain Expansion. Each one has its own storied history, best characterized by political uncertainty. The Enbridge Northern Gateway, first proposed in 2006,

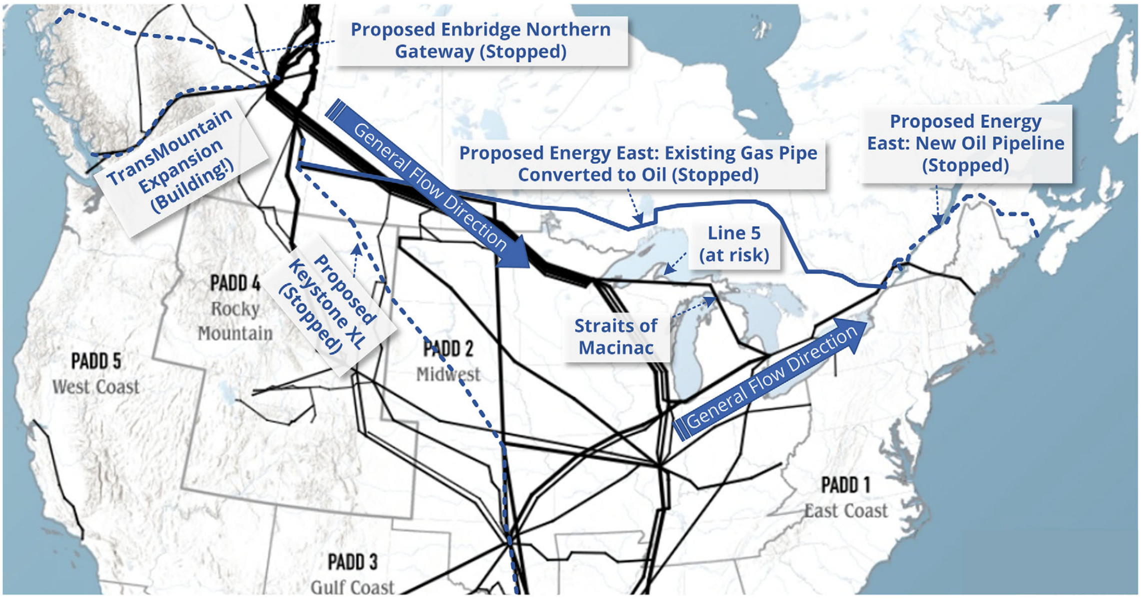

FIGURE 1 Major North American oil pipelines, modified from the original published by the Visual Capitalist.[6] Author's modifications are in blue, which include annotations and approximate sketches of proposed pipelines, using information from the literature.[7–10]

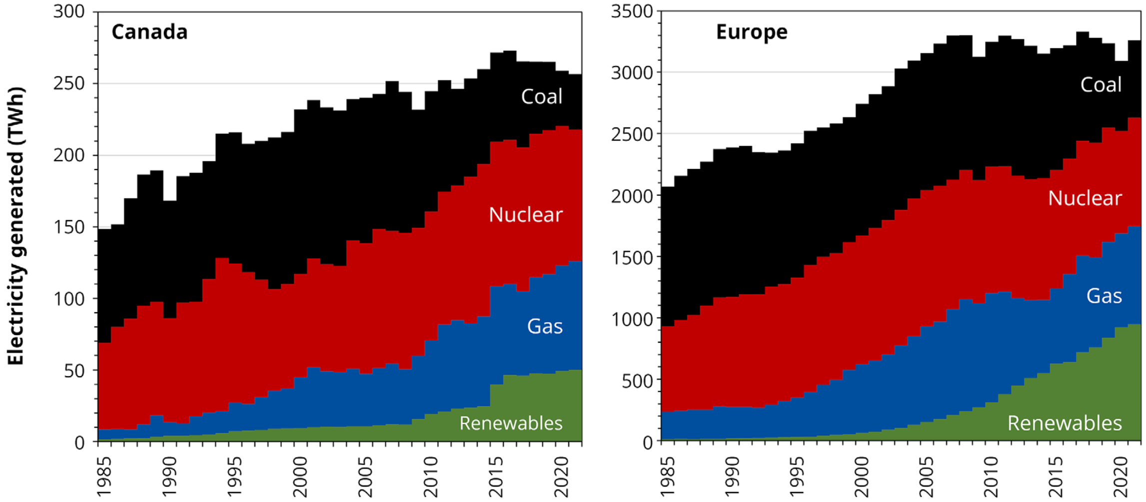

FIGURE 2 The electricity generation mix for Canada (left) and Europe (right) from 1985–2021. Data from BP Statistical Review of World Energy.[2]

would have taken oil from the main Alberta network to Kitimat, BC for Pacific exports, but was cancelled after the Federal government revoked their permits in 2016 following a court ruling quashing 2014 approvals, saying it was not in the public interest.[9,18] The Energy East pipeline would have taken crude from Alberta all the way East to the Atlantic, providing both an all-Canada route for Ontario and Quebec's refinery sources as well as a way to export East. After the initial application in 2014, TransCanada faced political battles in 2016 and 2017 over the National Energy Board panel, including a 2017 decision by the Board to essentially throw out all previous decisions and start over. TransCanada eventually pulled out in October of that year.[10,19,20] Keystone XL has its own epic tale,[8] including repeated Obama-administration holds and blocks on the approvals process from 2011 to 2016, which were then reversed by the Trump-administration with a greenlight in 2017. After years of construction, President Biden cancelled the project on his very first day in office in 2021, leaving Alberta taxpayers on the hook for $1.3 billion in loses.[21]

Despite failures to go West, East, and South with new pipelines, the TransMountain expansion proposed in 2012 is finally under construction a decade later, with a projected cost of $21.4 billion, almost doubling original estimates.[7,22,23] This will (essentially) twin the route from Edmonton to Kamloops and provide some expanded export possibilities in the Pacific. In one rather interesting bit of drama, after 6 years of court battles, the pipeline owners (Kinder Morgan) threatened to give up, and so the Federal Government made an offer to purchase it for $4.5 billion.[24] The open offer sat on the table for 3 months until yet another federal court decision quashed a permit. Within 30 min, shareholders voted to accept the government's offer with a 99.98% margin,[23] leaving Canada on the hook for the project, which had just had its permit rejected. Despite this, project construction began the following year and is ongoing.

2.2 | Changing electricity landscapes

2.2.1 | Coal

In both Canada and Europe, coal production has declined over the past decade. As shown in Figure 2, Canadian coal power generation has dropped 66% since its peak in 2000, and Europe has dropped coal power generation 46% since its peak in 2007.[2] The decline in coal is both economic and environmental. Coal is politically unpopular for environmental reasons in Canada and much of Europe, but it is not that attractive economically either. Despite the fact that coal is generally cheaper than natural gas per joule of energy (see Section 2.1), coal power plants typically have a much higher capital cost per joule of electricity produced than their natural gas analogues.[25] Considering that natural gas prices have generally dropped over the past decade due to advances in North American shale gas production, the result is a generally lower cost of electricity when using gas than when using coal. Furthermore, the greenhouse gas emissions of modern natural gas power plants are about half those of modern coal per joule of electricity produced,[26] making the case for new coal power development very weak. It is no wonder almost no new coal power has been built in Canada, the United States, or Western Europe for decades.[27]

Despite Western apathy for coal, CO_2 emissions from coal power plants reached a global peak in 2021[28] due in large part to its availability, low price, and stability. This is because Western coal declines have been more than offset by growth in China and India, which together are responsible for almost two thirds of the world's coal power generation. They have increased coal power production by 503% and 326%, respectively, since 2000.[2]

2.2.2 | Nuclear

Nuclear power has similarly stalled or declined in the West (see Figure 2), with Canada's nuclear power production down 14% from its 2014 peak. Despite having extremely low greenhouse gas emissions compared to fossil fuels, nuclear power faces practical challenges concerning safety and waste handling, leading to very high capital costs, very long construction periods, and the persistent problem of public unease. In Europe, nuclear power production has dropped 14% since the 2011 Fukushima nuclear power plant failure in Japan. This decline was largely political, the result of policies either to shutter or prevent the renewal of nuclear power facilities across the continent. Interestingly, one survey was conducted in the months just before and then again 2 weeks after the Fukushima incident (using the same participants in both surveys), measuring the immediate impacts of the accident on public opinion in Europe.[29] The researchers found that there was a surprisingly small decline in trust in nuclear power compared to just a few months before the incident, given the seriousness of the incident. In fact, they found that the participants were more educated than before and predicted that they would likely return to pre-Fukushima support levels after some time had passed and media influences had worn off. The authors noted that German and Swiss politicians were very quick to withdraw support for nuclear power, which was not in line with the general public in those countries. Nevertheless, it was the primary driver for the decline in nuclear power.

2.2.3 | Renewables

Renewables (primarily wind and solar) have enjoyed explosive growth in both Canada and Europe as seen in Figure 2. In Europe, renewables accounted for not only 21% of the power produced[2] but also a remarkable 40%–50% of capacity.[30] This disparity between capacity and actual generation is related to the intermittent nature of renewables. Power can only be produced when the sun is shining or the wind is blowing, and you can only harvest it while the energy is available. In some cases, harvested energy must be curtailed during periods of low demand, resulting in further missed opportunity. Energy storage can help with this situation, but the current numbers illustrate the disparity between possibility and actualization.

2.2.4 | Energy security

Whether you agree with these changes or not, they are explainable consequences of technological advances, world events, and social behaviours and preferences. However, the shift away from stable and reliable baseline applications like coal and nuclear and toward intermittent renewables poses a significant challenge. The technical challenge related to intermittency, availability, harvesting, and transportation of renewable energy can be addressed with engineering solutions, for which there is no shortage of ideas. However, the challenge to energy security is more difficult to address with technology. If coal and nuclear power continue to decline, the technological solution requires even more renewable energy, vastly more energy storage capability in many forms, and more natural gas peaking systems for load following.

Although renewables provide some forms of energy security since energy is produced locally rather than imported, the intermittency challenges create many problems as well, resulting in reduced energy security with regard to grid resiliency in meeting minute-to-minute power demands, especially in the winter. As renewables grow, Europe will rely more heavily on imported natural gas, not less. Each time a stable, baseline coal or nuclear power plant is shuttered, the market stress on the system increases. Thus, when Europe finds itself suddenly unable to import massive amounts of natural gas and other forms of energy due to the Russian invasion, it has found itself in a very high-stress situation.

As renewables grow and if baseline sources continue to decline, these challenges will only get worse. This is true for Canada as well. Although Canada is not faced with energy supply issues from Russia, these general energy security challenges associated with the growth in renewables remain.

3 | HISTORIC PRICE CHANGES INDICATE FURTHER RISKS TO ENERGY SECURITY

3.1 | North American energy commodities

Energy prices are reflections of reality, incorporating the complexities of global energy systems, technology,

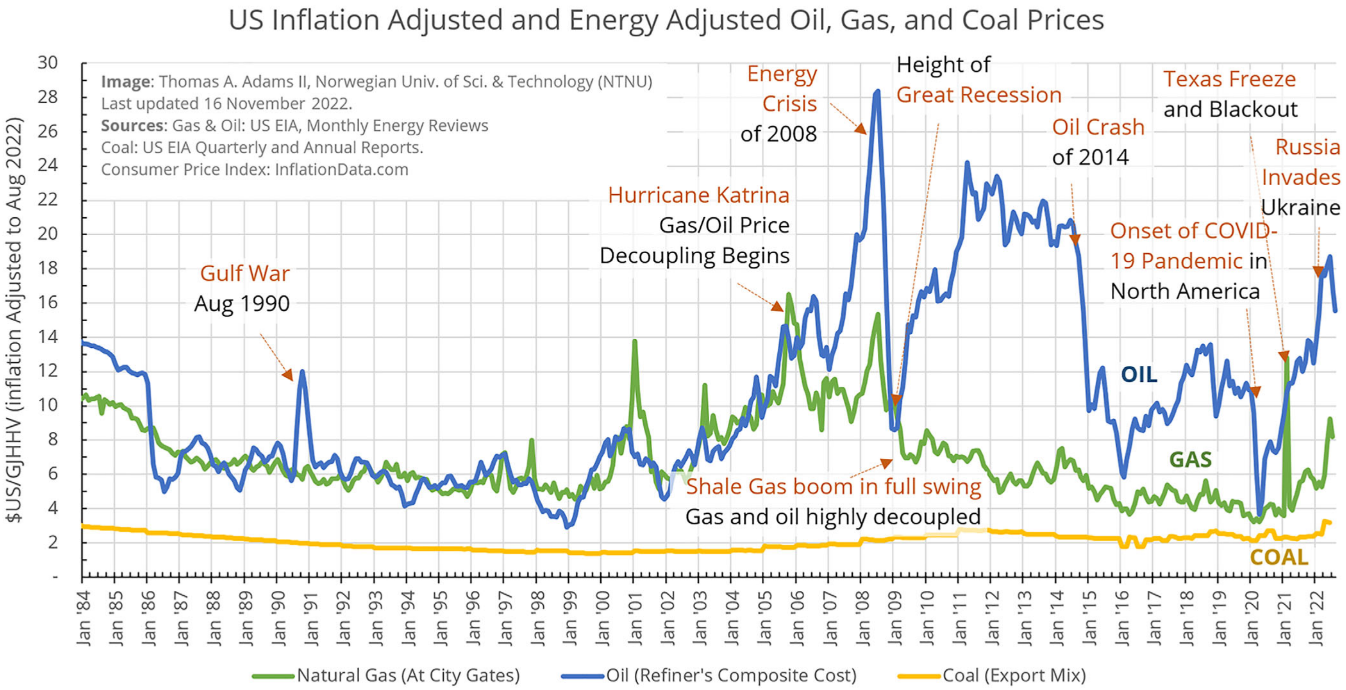

FIGURE 3 Inflation-adjusted and energy-adjusted energy prices of oil, gas, and coal, in the United States. Prices are in US August 2022 dollars per billion joules of higher heating value (GJ_{HHV}) of commodity. See the previous work[1] for methodology. EIA, US Energy Information Administration

politics, and world events. We can therefore use energy price as a rough barometer for what is going on in the world and assess the relative health, resiliency, and security of global energy systems. Figure 3 shows the US prices for crude oil (US refiner's composite cost), natural gas (US, at the city gates), and coal (US export mix), adjusted for inflation and presented in August 2022 US dollars on a per GJ of higher heating value (HHV) basis (see[1] for complete methodology, which has been updated from my previous publications on price histories). This gives us a good 'big picture' view of energy in North America.

As discussed in more detail in prior work,[25] oil and gas prices were fully coupled from 1984 (and, in fact, much before it) until 2006, when hurricane Katrina significantly disrupted oil networks and prices. Exceptions are seen in a few places, such as from impacts on oil (and not gas) of the Persian Gulf War in August 1990, but the correlation from 1984 to 2005 (inclusive) is remarkable (see[1] for a numerical analysis of the data). This breaks down in 2008, as the paradigm shift toward shale gas production wrought by innovative technology developments in hydraulic fracturing takes hold. Gas and oil become highly uncorrelated at this point. Coal remains remarkably stable throughout the entire time range, seemingly impervious to world events until very recently.

However, three recent world events stand out strongly as warnings about the health of our global energy system.

3.1.1 | The pandemic

Billions of people across the world were either encouraged or forced to work from home or avoid travel, drastically reducing the demand for transportation fuels. The immediate plunge in oil price is evident, and it took all of 2020 to rebound to pre-pandemic levels. Headlines were made when West Texas Intermediate Futures contracts dropped below negative 40 USD per barrel on 20 April 2020.[31] The demand became so low that there was insufficient storage available for upstream oil being produced, and companies had to pay to have it taken off their hands.

Natural gas prices in the pandemic increased somewhat over their February 2020 level, partly because it is not a major transportation fuel and perhaps partly because it was needed for atypical peaking power generation uses due to drastic shifts in daily power demand cycles arising from massive changes in personal habits and behaviours.

3.1.2 | Texas freeze

The Texas Freeze impacted gas prices severely in the United States but did not affect the other two fuels significantly. In 14–15 February 2021, an extreme cold weather event (extreme for Texas at least) occurred in which parts of urban Texas were well below freezing for days at a time, with the Dallas-Fort-Worth area reaching down to −2°F (−19°C). The energy infrastructure in Texas is not built for that unusual amount of cold, and nearly 49% of Texas' electricity generation capacity was knocked out at the same time at its worst moments. Controlled outages were required, and some areas were more impacted than others because of difficulties in implementing rolling outages. By 1:20 AM on the 15th, emergency operations had reached their highest level.

The impact on the grid was massive. Electricity prices in Texas from 14–19 February 2021 averaged roughly $6600 USD per MWh (the price was typically about $21 per MWh the previous winter!) and returned to normal by 20 February.[32] Despite the relatively brief outage in just one US state, the country's average natural gas price for the whole month went up by 258%. It is the biggest single-month impact on gas price in both absolute and relative terms for the entire data range.

3.1.3 | Russia's invasion of Ukraine

The 2022 invasion of Ukraine sparked more massive price fluctuations. Oil grew quickly over its already relatively high pre-invasion price, and gas had its third highest single-month and two-month percentage increases. Coal reached an all-time high (noting the annual and quarterly inflation-adjusted prices used) in April 2022, shortly after the invasion. The coal price jump is significant because it reflects Europe's reliance on Russian oil and gas; prior to the invasion, the European Union (EU) imported about 35% of its natural gas and about 25% of its oil from Russia.[2]

3.2 | European electricity prices

Reductions in consumption of Russian imports (largely self-imposed by Europe for both punitive and other measures) caused increased demand for coal for power purposes. The subsequent impact on electricity prices is huge; electricity prices in Europe have more than doubled since the invasion and peaked about 9–10 times as high as pre-pandemic prices,[33] as shown in Figure 4. Although they have dropped from their peak, they are still presently almost four times as high as in 2015.

The big picture view of electricity prices in Europe is stark, showing that times of relative stability and low cost are at an end. It is important to note though that electricity prices were already rising very quickly as early as late summer 2021, meaning that the energy security of the electricity system was already showing cracks. In other words, the problems are more than Russia alone, and so the system as a whole needs to be addressed beyond Russia singularly.

4 | BUILDING THE TRANS-ATLANTIC ENERGY BRIDGE

4.1 | Energy security goals

Europe's main task is to live with Russian imports reduced by 90%–100%. As shown in Figure 5, this is a huge task—reducing annual gas and liquefied natural gas (LNG) from Russia by at least 193 million tonnes (Mt) of oil and refined products and 181 billion standard cubic metres (Gm^3, noting that 181 Gm^3 of gas is about 127 Mt).[9] Compare this to the just 4.5 Mt of oil and refined products exported from Canada to mainland Europe last year. Russia's 2 Mt of wood exports are now banned too,[34] and considering that 85% of Canada's wood pellets (1.3 Mt in 2021[2,35]) are already exported to the EU, there is not much Canada can do to increase wood pellet exports immediately either.

With no eastbound Trans-Canadian oil pipelines or any LNG-exporting terminals,[36] Canada does not have many options for the short term. Although Ottawa fast-tracked Equinor's application to develop an off-shore oil

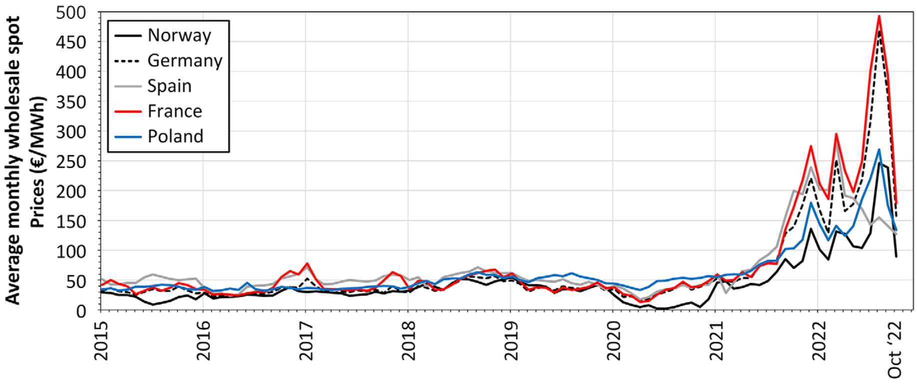

FIGURE 4 Europe's average monthly wholesale spot prices for electricity in selected European countries. Data originating from the European Association for the Cooperation of Transmission System Operators for Electricity (ENTSO-E) and sanitized by Ember Climate.[33]

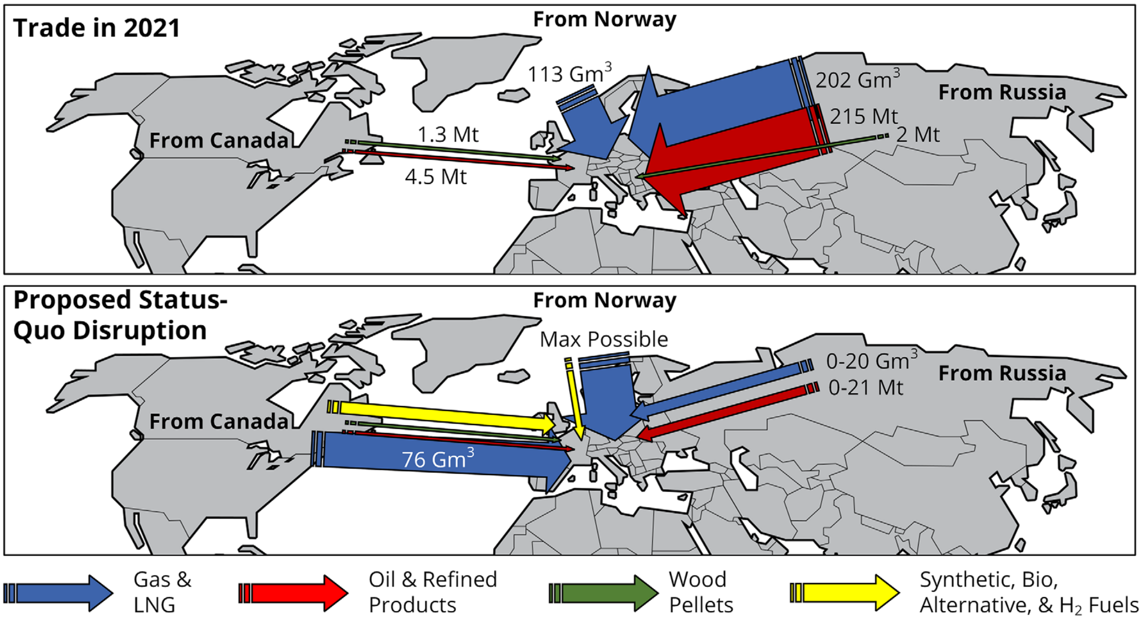

FIGURE 5 European imports from Canada, Norway, and Russia in 2021, and my suggested future goal. 2011 data from the literature.[2,34,35] Underlying map image from Pngimage.com released with creative commons licence 4.0 BY-NC. LNG, liquefied natural gas.

field in Eastern Canada shortly after the Russian invasion,[37] it will not be completed until 2028.[38] German Chancellor Olaf Scholz's August 2022 request for Canada to build an LNG terminal in the East to supply Europe was dismissed by Prime Minister Trudeau, saying that LNG has 'never been a strong business case'.[39] However, this position was immediately rejected by the CEO of Québec-based oil and gas company Utica Resources, who believes the case is 'crystal clear'.[40]

Canada could help fill the gap though with new infrastructure developments and innovative energy conversion systems, with the goal of significantly ramping up exports in the form of LNG and alternative, synthetic, bio, and H_2-related fuels. My vision is a Trans-Atlantic energy bridge, transporting a diverse supply of energy out of Canada and into Europe, providing both additional energy security and more sustainable options than fossil-based energy transportation at present.

4.2 | Technologies to build the Trans-Atlantic energy bridge

4.2.1 | LNG export terminals in Canada

Five LNG export terminals have been proposed in Nova Scotia and Quebec that could help replace much of the former supply from Russia.[36] Together, they total a potential 76 Gm^3 of LNG of export potential annually to the East, a significant amount that takes a huge dent out of the 200 Gm^3 that Europe used to export from Russia annually. These five projects have already been given federal export licences, in fact, but they still require new pipelines or pipeline expansions, plus permits at the provincial level. Given the history of Canadian pipelines since 2006, it is understandable why none of the 17 proposed LNG export facilities across the country, which have already received federal licences to export LNG, have been constructed.

This seems like the most obvious place to start. If Canada can resolve issues with getting product to the LNG terminals, it could be the foundation of the Trans-Atlantic energy bridge. Moreover, LNG only needs to be an intermediate energy carrier. It need not necessarily come from natural gas from Western Canada either. Rather, synthetic natural gas could be created from diverse sources such as biomass, nuclear energy, waste rubber and tires, and waste petroleum coke, some of which could be sourced from Eastern Canada without requiring already difficult Trans-Canadian shipping. LNG can even be manufactured using wind, solar, or nuclear energy in Eastern Canada, making it an integral part of a Trans-Atlantic, low-carbon economy. Some of the specific technologies that could be involved are discussed later.

4.2.2 | Hydrogen and hydrogen-carrying chemicals

The concept of a hydrogen economy is certainly in vogue now. The Canadian government issued a call to

TABLE 1 Potential forms of hydrogen storage

H_2 storage form	Approximate density		Storage device	Reaction notes	H_2 economy end use notes
Uncompressed H_2[a]	0.011	MJ_{HHV}/L	Gas tanks (room temperature)		Limited uses
H_2 at 300 bar[a]	2.9	MJ_{HHV}/L	Gas tanks (room temperature)		Use directly
In magnesium hydrides (MgH_2)	About 4	MJ_{HHV}/L	Solid (room temperature)	Explodes in water or air	Controlled circumstances only
Inside carbon nano-structures at 100 bar	5	MJ_{HHV}/L	Gas adsorbed in solid (room temperature)		Requires carrier return supply chain
H_2 at 700 bar[a]	5.1	MJ_{HHV}/L	Gas tanks (room temperature)		Use directly
As formic acid (HCOOH)	6.4	MJ_{HHV}/L	Liquid tank (room temperature)	$HCOOH \leftrightharpoons H_2 + CO_2$ $HCOOH \leftrightharpoons H_2O + CO$	Release H_2/CO_2 at point of use
As liquid organic chemicals	7	MJ_{HHV}/L	Liquid tank (room temperature)	$LOC + nH_2 \leftrightharpoons LOHC$	Requires carrier return supply chain
Inside metal organic frameworks, −195°C, 100 bar	7.2	MJ_{HHV}/L	Gas adsorbed in solid (cryogenic)		Requires carrier return supply chain
Liquid H_2 at −231°C, 300 bar[a]	9.2	MJ_{HHV}/L	Liquid tanks (cryogenic)		Regasify before use
Liquid H_2 at −253°C, 1 bar[a]	9.2	MJ_{HHV}/L	Liquid tanks (cryogenic)		Regasify before use
As methane (CNG at 250 bar)[a]	10.4	MJ_{HHV}/L	Gas tanks (room temperature)	$CO_2 + 4H_2 \leftrightharpoons CH_4 + 2H_2O$ $CO + 3H_2 \leftrightharpoons CH_4 + H_2O$ $CO + H_2O \leftrightharpoons CO_2 + H_2$	Convert to H_2 before use or use directly
As ammonia (LNH_3) at 11 bar[a]	12.3	MJ_{HHV}/L	Liquid tanks (room temperature)	$N_2 + 3H_2 \leftrightharpoons 2NH_3$	Release H_2/N_2 at point of use
As methanol (CH_3OH) at 1 bar[a]	16.4	MJ_{HHV}/L	Liquid tanks (room temperature)	$CO + 2H_2 \leftrightharpoons CH_3OH$	Convert to H_2 before use
As methane (LNG at −160°C)[a]	21.3	MJ_{HHV}/L	Liquid tanks (cryogenic)	$CO_2 + 4H_2 \leftrightharpoons CH_4 + 2H_2$ $CO + 3H_2 \leftrightharpoons CH_4 + H_2O$ $CO + H_2O \leftrightharpoons CO_2 + H_2$	Convert to H_2 before use or use as-is
As butanol (C_4H_9OH) at 1 bar	29.2	MJ_{HHV}/L	Liquid tanks (room temperature)	$CO + 2H_2 \rightarrow$ mixed alcohols	Convert to H_2 before use or use as-is in gasoline blends
Gasoline/diesel	35–38	MJ_{HHV}/L	Liquid tank (room temperature)	$(2n + 1)\ H_2 + nCO \rightarrow C_nH_{2n+2} + nH_2O$	Just use as-is, not for H_2 economy

Note: Data sourced from the literature.[43–49] Numbers should be considered approximate.

Abbreviations: CNG, compressed natural gas; LNG, liquefied natural gas.

[a] Author's calculation using data from Bell et al.,[50] assuming higher heating values of 14.2 MJ_{HHV}/kg for H_2, 55.2 MJ_{HHV}/kg for liquefied or compressed natural gas, 22.5 MJ_{HHV}/kg for ammonia, 23.0 MJ_{HHV}/kg for methanol, and assuming liquid tanks require an average 10% vapour head space when computing the volumetric density.

action in December 2020, arguing national need, articulating political goals of developing a hydrogen economy, and calling Canadians to act urgently to achieve it.[41] Other countries have as well, such as Germany, which recently issued its national hydrogen strategy with similar high-priority goals.[42] It is possible to ride the enthusiasm for a hydrogen economy and incorporate it into a Trans-Atlantic energy bridge. However, both policy documents pointed to two significant and related challenges: the low volumetric energy density of H_2 and the significant safety issues associated with its storage and transport.

Table 1 highlights some of the key challenges concerning storage and transport. Transportation across the

Atlantic with ocean-bearing vessels is primarily limited by vessel volume, not weight. This means that volumetric energy density is critical for efficiency and practicality. At normal pressures, the volumetric energy density of H_2 is very low (0.011 MJ_{HHV}/L). To be stored and transported, it must be compressed to a commercial standard pressure of 700 bar (note that car tires are at about 3 bar) in order to achieve an energy density of still only 5.1 MJ_{HHV}/L. Liquid H_2 can theoretically achieve about 9.2 MJ_{HHV}/L but this requires a cold supply chain. Moreover, the liquid continually degasifies during transport, and so the gaseous H_2 must either be utilized by the ship or truck as a fuel as it comes, creating some extra challenges.[51] Compare these to gasoline, which is about 32 MJ_{HHV}/L, so this creates some significant transportation issues.

Because of these low energy densities, hydrogen storage alternatives may be better options for the Trans-Atlantic energy bridge. In this case, higher density energy options may simply be to convert hydrogen to methane (synthetic natural gas), synthetic gasoline (through Fischer–Tropsch synthesis), methanol, or ammonia via the reactions listed in the table and ship those instead. That would reduce the energy consumption of the shipping step and drastically improve the transport capacity of the Trans-Atlantic energy bridge.

However, the transportation piece is only one part of the puzzle, and much research is needed to determine the best supply chain routes with regard to the hydrogen economy. The big picture question of what chemicals are best to ship and how to best make them is complex. For example, the vast majority of H_2 produced in Canada is (currently) produced by steam reforming natural gas from Western Canada. When it comes to the Trans-Atlantic energy bridge, it could be better to ship Western Canadian natural gas to the East via existing pipelines, then liquify and ship the LNG to Europe using one of the five proposed terminals. If H_2 fuel is desired as a final product in Europe, it might make more sense to convert the LNG to H_2 there (hopefully with carbon capture and sequestration) rather than making it in Canada.

On the other hand, if the H_2 is produced through non-fossil energy resources in Canada, then there is a larger question of whether it makes sense to go through the conversion step into another chemical or not. Non-fossil H_2 can be produced from renewables (e.g., wind/solar electrolysis, biomass, or waste gasification), nuclear energy (electrolysis or the copper–chlorine cycle), or captured from off-gases (metals refining), with drastically lower carbon footprints. Is the distance to Europe large enough such that the energy, cost, and environmental savings of shipping energy-dense chemicals like LNG or gasoline outweigh the energy, cost, and environmental penalties of converting H_2 to these chemicals in the first place (and potentially back to H_2 again on the other side of the ocean)? Does this answer change if LNG transport capacity is limited, or if liquid hydrogen shipping capabilities exist or not? For example, suppose it is less efficient to ship hydrogen from renewables as liquid hydrogen rather than LNG, but either LNG export capacity is maxed out or the proposed LNG terminals never get built (pipelines!). If somehow liquid H_2 export terminals could be constructed because of the political support in Canada for the hydrogen economy, then liquid H_2 may be the way to go even if it is technically inferior to LNG. Thus, liquid hydrogen could be another 'lane' on the Trans-Atlantic energy bridge.

4.2.3 | Nuclear to liquids

The goal of nuclear-to-liquids (NTL) technology is to convert the energy stored in uranium into energy stored in chemical bonds of common fuels or high-energy chemicals. Canada is the second-largest producer of uranium, particular high-grade uranium, holds about 8% of the world's reserves and exports about 85% of what it mines.[52] However, the market for uranium is quite limited, with obvious energy security issues involved. With NTL, Canada can manufacture export-friendly fuels that can be shipped and sold like any other on the open market. Moreover, nuclear energy has a very low carbon footprint, adding environmental value as well.

The system would work as follows: Uranium mined in Saskatchewan is shipped to Ontario where it is refined and upgraded (as it is now, just more of it), as shown in Figure 6. The increased amount is used in new nuclear reactors in Eastern Canada (Ontario and New Brunswick both produce nuclear power today), but their goal is not to produce electric power. Instead, most of the heat from the reactors is used to fuse endothermic chemical bonds, converting low-energy resources such as CO_2 and water into high-energy products like synthetic natural gas, methanol, hydrogen, or Fischer–Tropsch liquids. The reactors could be modern designs, like the ACR-700 (Advanced Canadian-deuterium Reactor), or more futuristic very-high temperature reactors like molten salt cooled or modular helium reactors. One key point is that since electric power is not being exported, these reactors do not need to be located near urban population centres and can instead be located far away from most of the voting public.

The ideal case would use just water and CO_2 as the feedstocks. Hydrogen gas could be produced from water

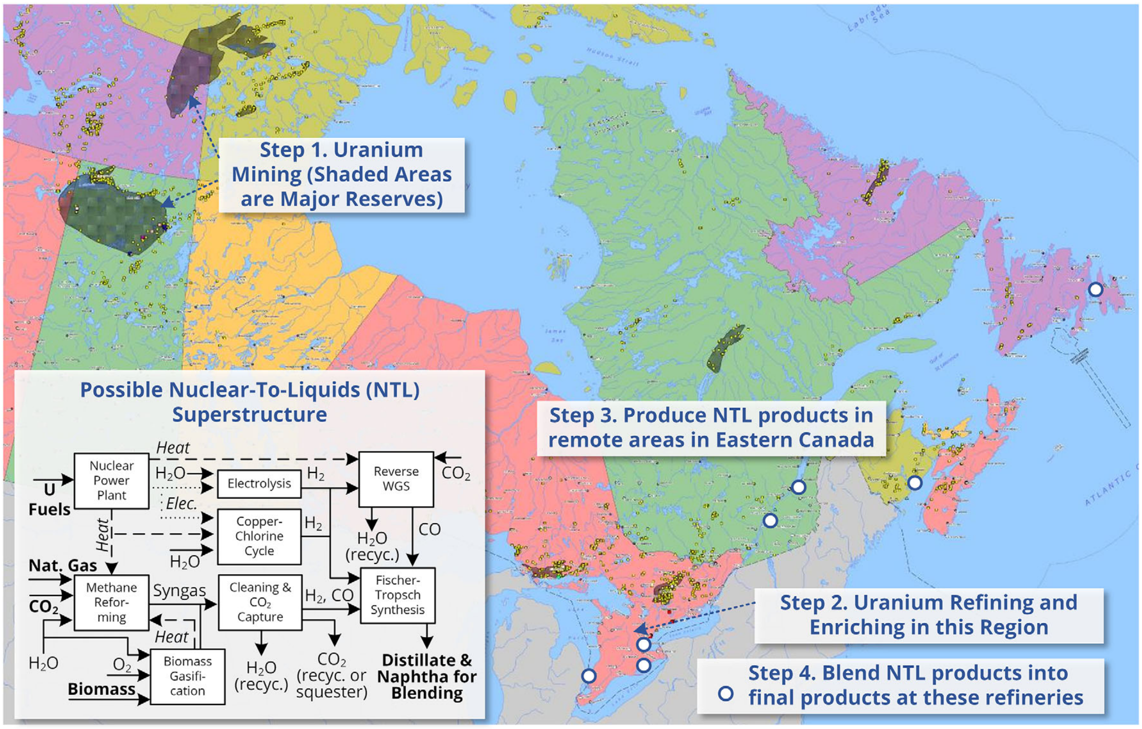

FIGURE 6 Summary of a proposed Eastern Canadian nuclear-to-liquids energy supply chain. The superstructure (inset) reflects possible combinations of process steps; actual processes would only use a portion of the steps (mix and match). Author's annotations in blue are superimposed on the underlying map from Natural Resources Canada.[53]

through the copper–chlorine cycle,[54] which requires a combination of nuclear heat and electricity, or by common electrolysis approaches. Both overall reactions are the same:

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

Thus, some of the nuclear heat would be converted to electricity using traditional power plants, but only enough electricity would be generated as needed for the process. Carbon monoxide could be produced through the reverse water gas shift reaction as follows:

$$CO_2 + H_2 \rightleftharpoons CO + H_2O$$

Noting that the water produced could be recycled to hydrogen production, any of the high-energy chemicals listed in Table 1, or others, could be produced through syngas routes (using CO and H_2 as feedstocks). In that way, virtually all the energy in the chemical bonds originated from the uranium. The resulting chemicals would be shipped (by train or pipeline) away from the remote NTL facility and onwards to world markets. Again, such products could be integrated with the hydrogen economy or the pending LNG terminals on the East coast. Or Fischer–Tropsch liquids can be used to displace oil and refined product imports to Eastern Canada via Line 5, strengthening energy security.

Although it is possible to produce the fuels using just nuclear energy, water, and CO_2, other approaches, such as using natural gas or biomass as the primary carbon source, may offer more practical benefits in terms of scaling and economics. For example, using high-temperature (800°C and above) nuclear heat to reform natural gas with water[55] and/or CO_2[56] allows for energy-rich syngas generation with high efficiency. Our research has shown that it can be profitable to make dimethyl ether (DME) from a combination of natural gas and nuclear energy using this approach. Furthermore, we found that by cleverly integrating biomass as a third resource, producing Fischer–Tropsch liquids is also profitable. We call this the biomass-gas-and-nuclear-to-liquids (BGNTL) process.[57] Furthermore, with optional carbon capture and sequestration, net lifecycle emissions can actually be negative,[58] although this needs economic incentives such as carbon credits, carbon taxes avoided, or higher sales prices that reflect the green nature of the fuels compared to classic fossil gasoline and diesel. Other configurations for BGNTL are possible using the copper–chlorine cycle, where manufacturing Fischer–Tropsch fuels in Ontario can result in 'greener' transportation fuels that if used to displace fossil fuels can avoid up to 2.1

MtCO$_2$e/year of greenhouse gas emissions at a cost of CO$_2$ avoided of only \$90/tonne.[59]

4.2.4 | Wood and agri-products

Canada has the potential to use woody biomass and agricultural products (preferably wastes or non-food-competitive resources) as a part of a bio-based economy. Several projects are already underway in Canada for this purpose across Eastern Canada, especially in Québec and the Sarnia region of Ontario.[60] Canada already exports 85% of its wood pellets to the EU (1.3 million tonnes per year[35]), so there is a big question of supply availability, and more than double the supply would be needed to fully make up the 2 Mt/year shortfall from lost Russian imports, which is highly unlikely. Furthermore, is it better to ship the wood pellets or convert the wood to a biofuel here and ship that or else ship other fuels that biofuels would displace? Should wood production for biofuel purposes be increased? There are a vast amount of possible uses for it as a feedstock, with a large body of research looking at the possibilities.

Two biofuels are the most interesting to me for the Trans-Atlantic energy bridge. The first is butanol (especially iso-butanol), which is the second most dense fuel mentioned in Table 1. This makes it an excellent candidate for the bridge, and upon arrival, it can be used as a transportation fuel or reformed to make H$_2$ for a hydrogen economy. It can be produced biochemically in Canada (through fermentation) using non-food agri-products such as barley straw, corn stover, switchgrass, wheat straw, and others. It can also theoretically be produced thermochemically from any biomass you can gasify through a mixed alcohol synthesis route, especially wood. The thermodynamic route is the most promising, with a best-known (that I can find) minimum butanol selling price of \$0.92/L and a cost of CO$_2$ avoided of about \$135/tCO$_2$e,[61] compared to the biochemical route, with a best-known (that I can find) minimum selling price of \$1.58/L and a cost of CO$_2$ avoided of \$472/tCO$_2$e.[62] The thermochemical method from wood is thus much more economical—if making butanol from it makes more sense than just shipping wood pellets. If not, agri-products could be an option to produce this high-density fuel for oceanic transport in simple tanks.

The second biofuel of interest is biogenic formic acid (bioFA), which is essentially CO$_2$ and H$_2$ bonded together (CHOOH). If made from biomass, the CO$_2$ is biogenic, and so it could function as a green H$_2$ carrier.[43,63] In fact, it can be broken down through either of two routes, selectively, through different catalysts at relatively mild temperatures[64]:

$$\mathrm{HCOOH} \rightleftharpoons \mathrm{H_2} + \mathrm{CO_2}$$

$$\mathrm{HCOOH} \rightleftharpoons \mathrm{H_2O} + \mathrm{CO}$$

This makes bioFA a 'green syngas carrier' that can be used to make custom syngas blends for Fischer–Tropsch liquids or other fuels. A quick check of Table 1 shows that its energy density is somewhat higher than that of the status quo for H$_2$ (compressed H$_2$ at 700 bar), but far lower than other potential bio-derived liquid fuels like butanol. Thus, I would not anticipate that formic acid itself makes a great energy carrier for ordinary H$_2$ since the penalties from the conversion steps to and from formic acid would likely offset the increased energy density benefits compared to pure hydrogen. The real value is instead that formic acid can be made directly from a wide variety of biomasses (Eastern Canadian wood and Alberta-grown beets are of particular interest) at low temperature and pressure,[65] skipping hydrogen production in the first place. Therefore, bioFA could be a 'green H$_2$' lane on the Trans-Atlantic energy bridge, especially when the end use of the hydrogen does not require H$_2$/CO$_2$ separation such as in a solid oxide fuel cell. More research is needed to quantify the benefits.

4.2.5 | Waste-to-energy

Waste-to-energy options cannot replace Russian oil and gas, as there is simply not enough concentrated and useful waste to do it. However, it can be another lane on the Trans-Atlantic energy bridge. Woody wastes such as discarded railway ties, certain pulp and paper mill wastes (sawdust, etc.), or construction waste wood are high-quality substitutes that, in theory, can be used instead of purpose-harvested wood for any of the thermochemical biomass processes discussed earlier. There is no shortage of research on the topic, but I would suggest that the number of studies is greater than the actual available supply of this high-quality waste. Due to the distributed or 'dilute' nature of most energetic waste resources, I suggest that Canada is uniquely positioned to take advantage of one key waste it produces in huge volumes and high concentration: petroleum coke or 'petcoke'.

Petcoke is a waste from the refining of heavy crudes, especially the kind produced in Canada. Some grades of petcoke are specifically useful for anode production and special metallurgical uses, but much of it is a highly energetic carbonaceous waste that is illegal to combust due to its high impurity content and associated CO$_2$ emissions. Petcoke availability worldwide ranges between 56 and 150 Mt/year, and many studies have explored methods for its valorization, mostly through gasification and syngas conversion approaches.[66] However, producing liquid fuels from petcoke consumes huge amounts of electricity, and so this only makes sense environmentally if the electricity used is very low carbon. But this is perfect for the Trans-Atlantic energy bridge since Ontario and Quebec boast grids with extremely low CO_2 emissions per kWh. One life cycle assessment showed that shipping Alberta-made petcoke to Ontario and converting it to Fischer–Tropsch liquids could produce fuels with costs of CO_2 avoided of about \$144/tCO_2e (assuming it displaces Canadian fossil diesel).[67] Even if all it displaces is Russian oil, it is a great option for the bridge.

Rubber is another potential waste that can be valorized for the bridge. Again, gasification methods (in this case, a rotary kiln) can be used to produce syngas to create the usual candidates for the bridge. With over 1 billion spent automobile tiles discarded each year, 4 billion of which remain in stockpiles around the world, there is sufficient supply potential.[68] Producing synthetic natural gas (possibly as LNG) from waste rubber is an option that would work with the proposed LNG infrastructure terminal, and, in fact, it would work anywhere in Europe that is connected to a gas pipeline and help to displace Russian gas. However, breakeven costs are high, and it requires government incentives or large rubber tipping fees to make sense economically on its own.[68] It is more economical to make methanol or DME for shipment, but that is highly dependent on market conditions.[69]

5 | RECOMMENDATIONS AND CONCLUSIONS

Stepping back and looking at the big picture with hindsight, it seems to me that the Western world is very much in a predictable situation of its own making, one that plenty of people have warned about. Many of the changes we are making are good for us on the whole, especially with a push to a global energy system that reduces environmental impacts. However, energy security has been pushed aside for far too long, and now it cannot be ignored any more. This is reflected in the historical prices of energy, which now indicate that the global energy system is very much less secure and less robust than it was a decade ago. Further disruptions and challenges to the system will not likely be tolerated well.

Canada is not in a position to directly export much more oil or gas to Europe today. The governmental appetite for future infrastructure investment to expand fossil fuel exports remains limited. The mix of alternatives presented in this paper might have a better shot because the association with reduced greenhouse gases makes them more politically palpable. They will not meet all of Europe's needs, and some of them (nuclear especially) have only a long-term outlook. The most promising option for the near term is to greenlight the five proposed LNG terminals in Eastern Canada (and that means greenlighting the entire supply chain), then boost domestic gas production supplemented with synthetic natural gas produced through biogenic, waste, and nuclear sources. Fischer–Tropsch diesel and gasoline can also be produced from biogenic, waste, and nuclear sources, as can biofuels like biobutanol. If they cannot be used to increase exports to the East, at the very least they can be produced in Eastern Canada and reduce its energy imports from the United States, thus allowing increased exports to Europe from there. All of these can contribute meaningfully to an ever-growing Trans-Atlantic energy bridge.

Regardless, Canada currently stands unable to do much to help its European allies with its existing infrastructure. Canada could be in a much better position to supply energy to the rest of the world and improve its own energy security at the same time—it just needs more infrastructure, faster regulatory processes, and a different set of political perspectives and priorities (none of which are simple matters). Given how long it takes to build infrastructure in Canada, it needs to get building right away in order to reap the rewards a decade from now. Otherwise, it risks catastrophe in the future.

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Thomas A. Adams II: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; software; visualization; writing – original draft; writing – review & editing.

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ORCID

Thomas A. Adams II https://orcid.org/0000-0002-9871-9851

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