GAS TURBINES FOR ENERGY NETWORK SYMPOSIUM
BANFF, ALBERTA, CANADA
OCTOBER 2023

23-GTEN-205

HOW ENERGY SYSTEMS CHANGE- THE ENERGY TRANSITION IN NORTH AMERICA

David Burns, Enbridge and Brooke Cuming, Enbridge

(David.Burns@enbridge.com), (Brooke.Cuming@Enbridge.com)

1.0 Introduction

As the global focus intensifies on achieving net-zero targets, both corporate companies and governments are increasingly considering the role of energy infrastructure in achieving carbon reduction goals. Notably, the United States and Canada have been supporting the development of emerging industries like Carbon Capture, Sequestration, and hydrogen production through tax credits and investment incentives. In a landmark move, the Inflation Reduction Act (IRA), signed by US President Joe Biden in August 2022, will direct nearly $400 Billion [1] in federal funding towards clean energy initiatives, with around 15% allocated for CCS and Hydrogen production. Additionally, the US Department of Energy has committed $7 Billion to fund hydrogen hubs. Meanwhile, Canada envisions clean hydrogen making up 30% of end-use energy by 2050.

Despite the excitement surrounding the opportunities for low-carbon energy and job creation in these new industries, it's essential to consider the current global energy landscape. Today, North America benefits from abundant domestic oil and gas reserves, which contrasts with European and Asian countries that heavily rely on importing energy. This has been brought into focus with the Russian war on Ukraine which triggered an energy crisis and laid bare the over reliance on Russian gas. So, although there is a progressive consensus on achieving net zero, it requires policy makers and energy companies to balance between energy security, energy sustainability, and energy affordability, also known as the energy trilemma. Since existing infrastructure like pipelines offer an effective and low cost pathway to connect energy producers and users, it is therefore incumbent when planning net zero pathways to pay particular attention to the role of existing infrastructure.

This paper explores the Energy Transition, with a focus on the role of hydrogen in North America. To do this the paper explores historical examples to illustrate how large systems adapt over time and how other large systems have been reconfigured and adapted over time. Historical examples from of systems transformation such as telecommunications and railroads [2,3,4] offer key insights that are relevant to the future of North American energy infrastructure.

The present day also offers examples of countries further along the curve of change such as Australia, the Netherlands, and the United Kingdom. These examples relate directly to the role hydrogen will play in the economy and the early lessons from projects and investments that are critical to accelerating learning.

Finally, the paper will examine the challenges facing the adoption of hydrogen in North America. Again, past and present examples of change in large systems teach vital lessons for the future. From this study three primary change agents emerge. Firstly, how does the scale and interconnectedness of a system affect the rate of which change can occur, and how does this pertain to the natural gas networks in the US and Canada? Secondly, as seen in past examples, regulations and policies applied to the system will be vital in determining the ability of energy users, energy producers and asset owners to interact in a way that delivers affordable energy for end users. Lastly, the role of technology, in particular renewables, could play an unexpected role in the nascent hydrogen sector as the convergence of low cost clean energy is met with congested electrical grids and long connection times for new power projects.

2.0 Past Energy Transitions

Several projects in North America have already begun blending hydrogen into local gas distribution networks. For instance, ATCO's Fort Saskatchewan Blending Project and Enbridge's Markham Blending Project to name only two and there are many more projects in planning phases. Interestingly, gas systems with relatively high percentages of hydrogen, like Hawaii Gas (15% hydrogen content) and Hong Kong's gas distribution system (50% hydrogen content) are operating today, using similar forms of synthetic gas called town gas. Hawaii and Hong Kong gas networks are unique in this regard when compared to most other gas systems which operate with much lower Hydrogen levels and predominantly use natural gas. However, as described in the following section, many natural gas systems, particularly in Europe and North America, owe a huge debt to their town gas origins which long before natural gas carried this synthetic mixture of hydrogen gas.

2.1 Town Gas

Town gas is a manufactured gas derived from coal and was first developed in Great Britain in the early 1800's. By 1816, a group of entrepreneurs started North America's first gas utility in Baltimore, which consisted of a central gas plant with a network of wooden pipes carrying gas to customers, primarily for street lights. In time the wooden pipes were replaced by cast iron and the end users grew beyond the street lamps to include industrial, commercial, and domestic lighting. This model was replicated across North America and by 1870, over 400 sperate gas manufacturing firms were in operation; however, disruption was on the horizon. In the early 1900's Thomas Eddison's General Electric was paving the way for the new era of electric light, challenging the commercial viability of the gas distribution companies. For the Town Gas producer, an even more significant change would upend the model of many small regional remote gas networks, and transform it to an interconnected gas system on a continental scale.

2.2 Long Haul Gas Transmission

Prior to the advent of long haul gas pipeline transmission, the only practical use of natural gas was close to the source of production. Towns and industries located close to gas production benefited from an abundant source of the fuel. In 1920 a pipe mill would typically manufacture seamless pipe and would seldom produce pipe larger than 6 inches in diameter. The typical pipeline was less than 200 miles. But by the 1930's improvements in construction techniques (ditch digging and hydraulic equipment) along with advances in pipe manufacturing, led to the construction of larger diameter and longer pipelines. The Californian gas fields paved the way for building new pipelines of a 1000 miles in length and by the late 1940's, 30-inch pipelines were being constructed all across North America. This now made long haul transmission possible and with it, vastly improved access to natural gas. Compared to the coal based fuels being manufactured within the city limits, natural gas was more affordable, cleaner and in abundant supply- the energy trilemma is not a new concept.

2.3 Energy Transition Town Gas to Natural Gas

From the 1950's to 1980's the rapid expansion of natural gas transmission pipelines combined with the abundance of natural gas in the producing regions of Western Canada and Texas led to broad adoption of natural gas. And with that the demise of Town Gas, shown in *Figure 1* below:

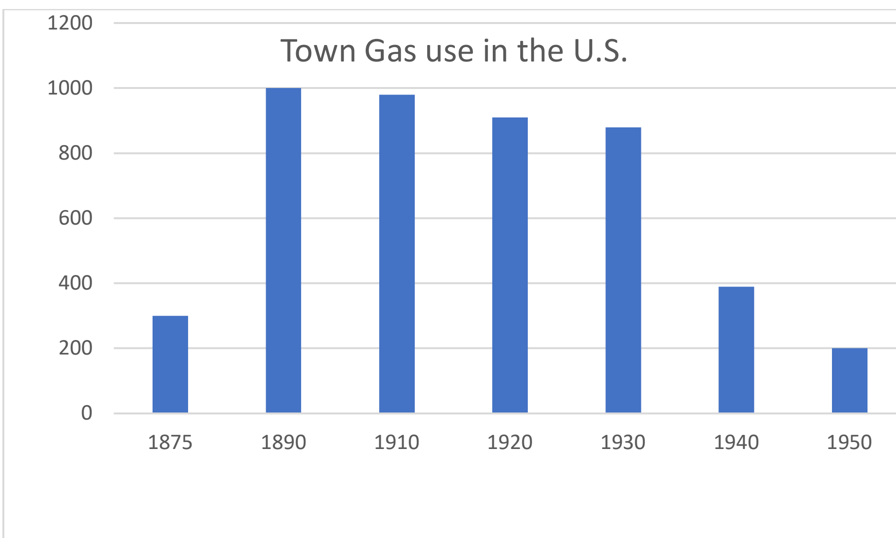

Figure 1: the decline of town gas use 1875 to 1950

Despite the relative advantages of natural gas, the transition took over 30 years in the United States. In Europe, a similar transition occurred, but in contrast the change was far more rapid. The United Kingdom's adoption was a systematic switch over of every end user and it took place over 8 years, cost roughly £1 Billion (at the time), and impacted 14 million domestic customers. It was described as, "perhaps the greatest peacetime operation in the nation's history." by the then Chairman of British Gas Sir Denis Rooke. In contrast, the US phase out of town gas took 30 to 40 years and involved individual utilities making decisions to switch to natural gas and this resulted in a variety of scenarios playing out. Some utilities chose to switch directly to natural gas, whereas others adopted a blending approach, slowly transitioning over time. The drawn-out process of the US transition to natural gas is partly due to the scale of the system and embeddedness of existing networks, but also the regulatory framework clearly played a significant role. In the UK, at the time, the Gas Council had responsibility for strategic oversight of the gas industry and could make decisions unilaterally, assuming there was political support for the decisions. In the US, the regulatory framework involved both federal, state and even city level approvals and so the decisions to change to systems involved many more stakeholder and as a result took longer. These contrasting examples demonstrate that the Regulatory Framework of any system is an important agent in determining the rate of change a system will undergo.

2.4 Piggybacking and Leapfrogging: Technological Disruption

As the natural gas systems expanded, reaching continental scale it achieved levels of interconnectedness that even by modern standards are exceptional. Over the course of 40 years, regional distinct utilities became increasingly connected to a larger system which today delivers 32.3 trillion cubic feet (tcf) of natural gas annually or 33% of the US energy demand [8]. In the case of the UK, switch over from town gas the role of regulatory framework greatly increased the rate of change within systems through a centralized strategic decision making process. The US town gas transition also teaches a lesson on how scale and how embeddedness can play a change resistance role. There is, however, another factor to consider in system change and that is the role of technological disruption. The next example highlights that technological disruption can have transformative impacts on the system and even society.

In historical examples, emerging technologies have two pathways to scale. The first is to utilize the existing system to gain market access- for the purposes of this paper this is called piggy-backing. The path is to supplant the existing system altogether effectively bypassing it - this will be called leapfrogging. The clearest example of leapfrogging is the rapid advancement of mobile telecommunications networks that proliferated globally since the early 2000s. India offers the clearest historical lesson where, unlike Europe and North America, India skipped the build out of a land line based telephone system and leapfrogged into the mobile age.

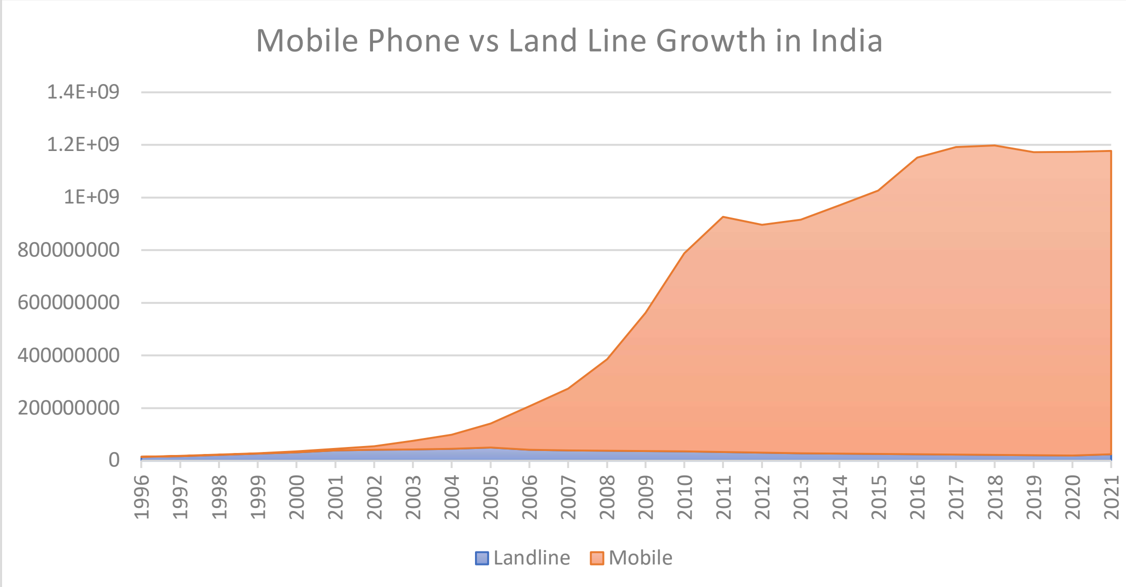

Figure 2: Mobile Phones in India leapfrog the use of land lines starting in 2000. Source: Our World in Data Org

In 1998, there were 21.5 million telephone lines in India with growth flat up to present day. Over the same period mobile phone usage grew from zero to 1.2 billion users.

Mobile phone adoption is a drastic example of how disruptive technology can drive rapid expansions of a new system. Historically speaking, these examples are rare and as with the technological transformations, the emergent forces are more likely to take advantage of the existing systems i.e., piggyback rather than leapfrogging. The town gas to natural gas transformation is an example of piggybacking but to list a few others, the electrification of railway locomotives in Europe, early adoption of the internet via landlines and LNG in the 1960's which leveraged existing gas terminals as import locations. The reasons many systems favour the piggybacking approach is that, particularly in the early stages of market penetration using existing systems lowers the costs of entry into the market allowing the emerging technologies to become established. When thinking about hydrogen it is clear that there is corollary here in particular for the hydrogen producers exploring ways to access the market.

2.5 Lessons on How Systems Change:

The historical examples of system reconfirmation serve as a model for future transformations. It also underscores the factors that can either accelerate or impede change. Beyond energy transitions, studying how other large technical system change yields valuable insights into the factors influencing change. Those change agents can be summarized as follows:

1. **Scale and Interconnectedness:** Large systems spanning vast geographical regions tend to change slower due to the need for inter-regional coordination.
2. **Regulatory Reform:** Complex and slow regulatory frameworks can hinder the pace of change in systems requiring updates.
3. **Technological Disruption:** The relative benefits of adopting a new technology can accelerate its adoption, bypassing existing systems.

These factors provide a lens at which to look at the present situation but also the future dynamics impacting energy systems.

3.0 State of the Art- Hydrogen in Pipelines

As mentioned in the introduction, governments worldwide are implementing Hydrogen strategies to support the emerging industry. Over 30 countries have already published Hydrogen strategies, with the US being the latest to join in June 2023 [8]. The US is relatively late to the game with Japan publishing its strategy in 2017. Admittedly though the US Hydrogen Roadmap is extremely comprehensive and, backed up with the funding via the IRA, is a compelling package. The industry is responding with technology advancements and capital deployment plans to propel the hydrogen sector forward. Original Equipment Manufacturers (OEMs) of gas equipment are also testing for hydrogen blends and developing new equipment to handle up to 100% hydrogen.

Despite the growing list of projects announcements, the existing Hydrogen industry is confined to industrial uses and is a critical component in fertilizer production and oil refining. In the US 10MT of Hydrogen are produced annually compared to 94 MT globally. The US, plans to grow that to 50MT annually by 2050 through expansion of clean Hydrogen.

3.1 Hydrogen Blend and Carbon Reduction Benefits

When burning pure hydrogen, it produces zero carbon emissions, making it a viable net-zero fuel. As described in Section 3.4, the relationship between CO2 reduction and the percentage of hydrogen blended with natural gas is non-linear due to the volumetric density difference between the two fluids. Hydrogen has roughly a third of the volumetric density of methane, requiring higher flow rates to achieve the same energy content. This leads to the relationship in CO2 reduction as shown in Figure 3. Net zero reductions at the burner tip can be achieved with modest volumes of Hydrogen as a result of its role as a transitional fuel. For example, a 20% blend of hydrogen will lead to a 7% reduction in CO2 emissions.

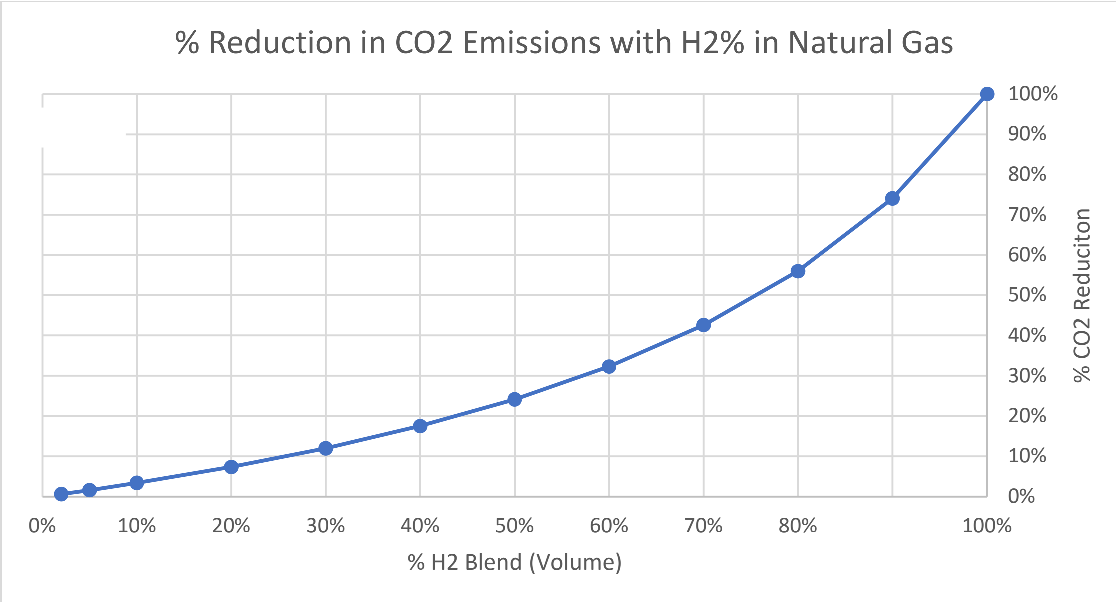

Figure 3: Effect of Hydrogen Blends on CO2 emission reduction at end use

3.2 Material Compatibility- Hydrogen Impact on Carbon Steel

Hydrogen affects steel properties, in particular toughness, as Hydrogen atoms (H^+) diffuse into steel. The introduction of hydrogen in pipelines is detrimental as it decreases the fatigue crack resistance of the material, effectively increasing the likelihood of cracks developing. The rate at which hydrogen diffuses into steel is a function of the partial pressure of Hydrogen. Relatively low partial pressure of hydrogen of 85kPa have been measured to reduce some steel samples by 25% [10]. As an example, a transmission pipeline at 900 psi would start to see toughness reductions in the presence of 1.3% H2.

This poses a significant barrier for repurposing existing transmission pipelines for hydrogen as integrity management plans will need to be updated to evaluate existing flaws and fatigue assessments in pipelines. However, there are many examples of successful conversions. Notably, in 2020 a paper [12] was presented on the successful conversion to 30% Hydrogen blend in the Gasunie systems, with a subsequent paper [13] demonstrating modelling for a 100% hydrogen conversion by the same operator. This continues to be an area of research with more data and study required on the impacts of Hydrogen on steel and even polyethylene pipes for distribution systems.

3.3 Thermodynamics of Hydrogen Transportation

On a mass basis hydrogen has three times the amount of energy as methane. But on a volumetric basis, which is more relevant when transporting energy, Hydrogen has a third of the energy content of Methane. To put this into perspective the world’s first ever liquified hydrogen ship, the Suiso Frontier carried roughly 1250 cbm of liquid hydrogen from Australia to Japan which is roughly 1100 GJs of energy. At the same time an LNG Q-Max carrier transports 266,000 cbm with 590,000 GJ or 530 times more energy than the Suiso Frontier. This was a pilot and there are plans to build larger shipping vessels capable of moving larger volumes of Hydrogen even with the largest planned vessels will only carry roughly 4 times less energy than today’s LNG Q-Max carriers.

The other issues are that Hydrogen liquifies at extremely cold temperatures- at -253°C, which is only 20°C warmer than absolute zero and presents challenges from liquefaction and boils off during handling. Clearly though these challenges have engineering solutions as the Suiso Frontier successfully completed its voyage in February 2022. On a mass basis, hydrogen contains three times more energy than methane. However, when it comes to transporting energy, the volumetric basis is more relevant. In this aspect, hydrogen possesses only one-third of the energy content of methane.

Nonetheless, engineers have been able to address these challenges successfully, as evidenced by the Suiso Frontier's successful voyage in February 2022. Despite the hurdles, advancements in technology and engineering solutions are expected to enable the future transportation of larger volumes of hydrogen safely and efficiently.

4.0 Future Energy Transition

In light of the aforementioned government incentives, the solar and wind energy industries are poised to experience substantial benefits. Intriguingly, this favorable scenario occurs at a time when the costs of wind and solar energy have been consistently decreasing, rendering them highly competitive with conventional energy sources like natural gas. Furthermore, significant advancements in lithium-ion battery technology, driven by the expansion of the electric vehicle market, have paved the way for combining renewable energy with short-term battery storage, solving the issue of intermittency, and establishing a viable alternative to traditional energy sources. Already, renewable and battery storage projects have attained cost-competitiveness with gas cycle generation, and further technological improvements are anticipated as shown in Figure 4 below.

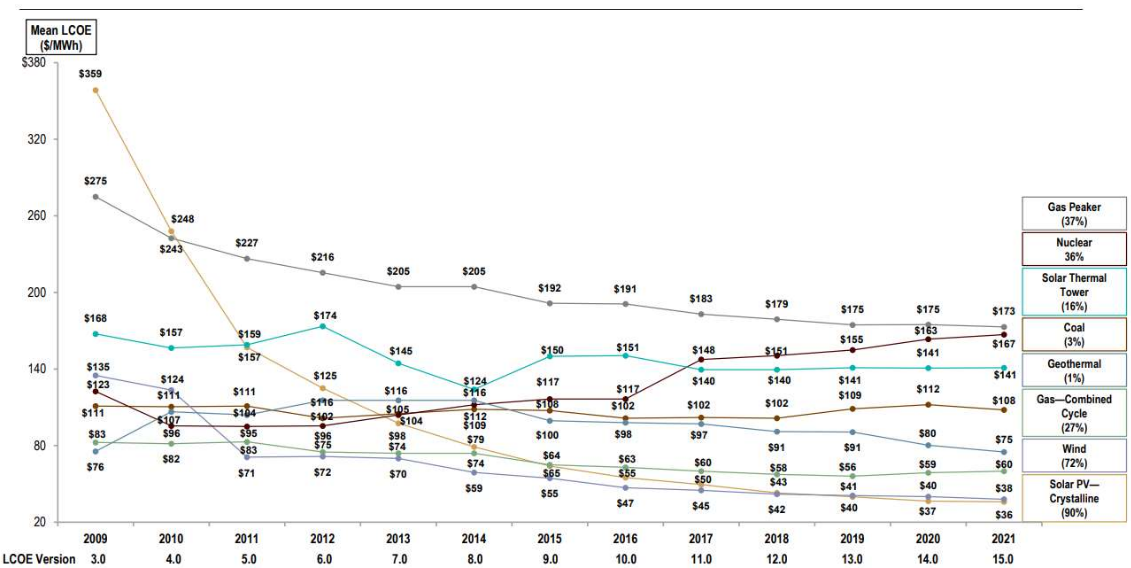

Figure 4: Levelized cost of energy. Source Lazard Levelized Cost of Energy Analysis October 2021 [13]

The growth of wind and solar energy seems to have reached a tipping point, which could cause widespread disruption and reconfiguration of energy systems globally. However, two significant challenges remain:

1. Addressing renewable power generation gaps during periods with low sun or wind.
2. Delivering renewable energy from remote production locations to distant end-users.

Hydrogen, specifically generated via electrolysis with renewable energy, can play a pivotal role in addressing these challenges. Drawing lessons from the past and present, the vast network of natural gas pipelines could be leveraged for efficient energy storage and distribution.

4.1 Hydrogen in North America- Storage Solution

Studies modelling weather patterns and renewable energy generation suggest that medium to long-term storage solutions (15 to 30 days) will be required to achieve net-zero by 2050 [6,7]. The scale and duration of storage are beyond the capabilities of current battery technology. However, Hydrogen storage offers a promising solution, utilizing the existing natural gas pipeline system as a vast storage asset. Current high-pressure pipelines can only accommodate low levels of hydrogen before embrittlement occurs (as shown in Section 3), although more work on this is required and is underway in projects such as HyBlend, a US DOE funded hydrogen blending study and H2 Pipe, a DNV Joint Industry Project.

Also, the integration and geographical scale of North America's pipeline system present challenges during the energy transition. The system's interconnectivity makes it challenging to separate sections for hydrogen usage, necessitating innovative solutions like the development of hydrogen hubs, which is discussed in the US Hydrogen Strategy and Roadmap.

4.2 Low Carbon Export - Ammonia and EFuels

The last few years have seen growing interest for low carbon ammonia both as a replacement to existing ammonia production and as an import option for countries such as Germany and Japan. When combined with low carbon hydrogen, ammonia offers a proven method of transporting Hydrogen molecules to overseas export markets.

Another opportunity are E-Fuels which leverages low carbon Hydrogen production and carbon capture to create a synthetic fuel similar to natural gas. Low carbon hydrogen is combined with captured carbon in the production process that applies the Fischer-Tropsch synthesis reaction [16]. Although not a net zero fuel, it does reduce the cycles of carbon in the atmosphere.

The most impactful advantage of utilizing this technology is the ability for the product to be transported using current oil and gas infrastructure. As discussed in Section 3 hydrogen impact on steel, the North American pipeline system is designed to be interconnected; therefore, separating particular networks would require time and capital to reconfigure the system- a problem E-Fuels do not pose. Another critical positive outcome of introducing this technology is the projected effect E-fuels will have on energy affordability. Due to the cyclic nature of the process, once projects are in motion, production costs are predicted to be lower than typical fuel production costs, allowing for more affordable energy for consumers.

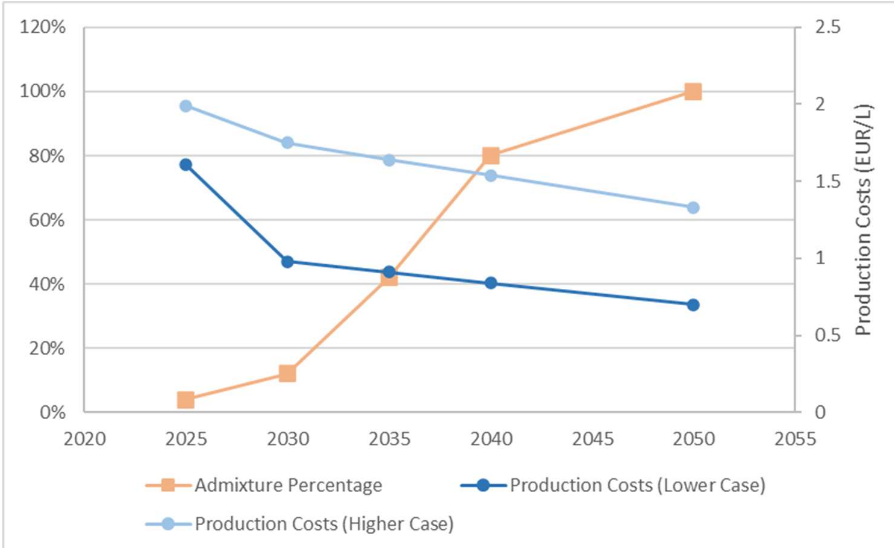

Figure 5: Production Cost Predictions (EUR/L) as a function of E-Fuel Admixture Percentages [17]

The most critical factor that will determine the success of this technology is the introduction of more renewable power to supply both private projects and the grid. Without renewable power options this cycle is no longer carbon neutral and could cause the product to not meet the carbon intensity requirements of countries seeking to import it.

Continents like North America and Australia have an advantage for implementing this technology over continents like Europe and Asia due to the quantity of land available for large scale onshore renewable energy farms. Couple this with current and planned LNG export terminals and North America has an opportunity o be a strong force as a clean energy provider. A project owned by Infinium has already been put into motion in Corpus Christi, TX, with plans to convert more 18,000 tons of carbon dioxide per year, beginning in 2023. [18].

5.0 System Challenges

5.1 Integration and Geographical scale

Pipeline and Hazardous Materials Safety Administration (PHMSA) regulates 5.3 million kilometres of pipelines in the US [19] and Canada has a network of pipelines combing to 0.76 million kilometres [20]- enough to circle planet early 151 times. The scale of pipelines in North America is vast far, and as a pioneer in oil and gas pipeline development has some of the oldest pipelines systems still in operation today. This system has become increasing interconnected and integrated, now including international markets via Liquefied Natrual Gas (LNG). Producers, midstream and end users almost take for granted the highly complex system that delivers energy seamlessly every day.

Whilst this system is a marvel of engineering and energy delivery efficiency, it also presents a challenge for the energy transition, in particular with hydrogen. Separating systems intolerant to hydrogen will be challenging given the high level of integration that exists. This was clearly a factor in the development of the US's Hydrogen Road Map where there is a clear focus on developing Hydrogen Hubs- which differs from the EU Backbone concept which is seeking to drive integration through progressive expansion of hydrogen segments.

5.2 Regulatory Frameworks

Clear regulatory frameworks and requirements are critical to the development of new energy infrastructure, both to provide confidence to investors with certainty on project economics while building trust with the public who will be impacted by the projects. The examples from past transitions show how regulatory policies and framework accelerated transitions. Conversely long permitting processes and uncertainty can stifle transitions.

As many high profile pipeline projects can attest regulatory and permitting issues have led to lengthy delays in starting construction and have resulted in some project cancellations. This can lead to the energy system becoming congested and is another challenge facing the emerging renewables industry.

5.3 System Congestion

As shown in Figure 6 below, there is a significant amount of solar, wind and battery storage waiting to be built and connected into the US electrical grid.

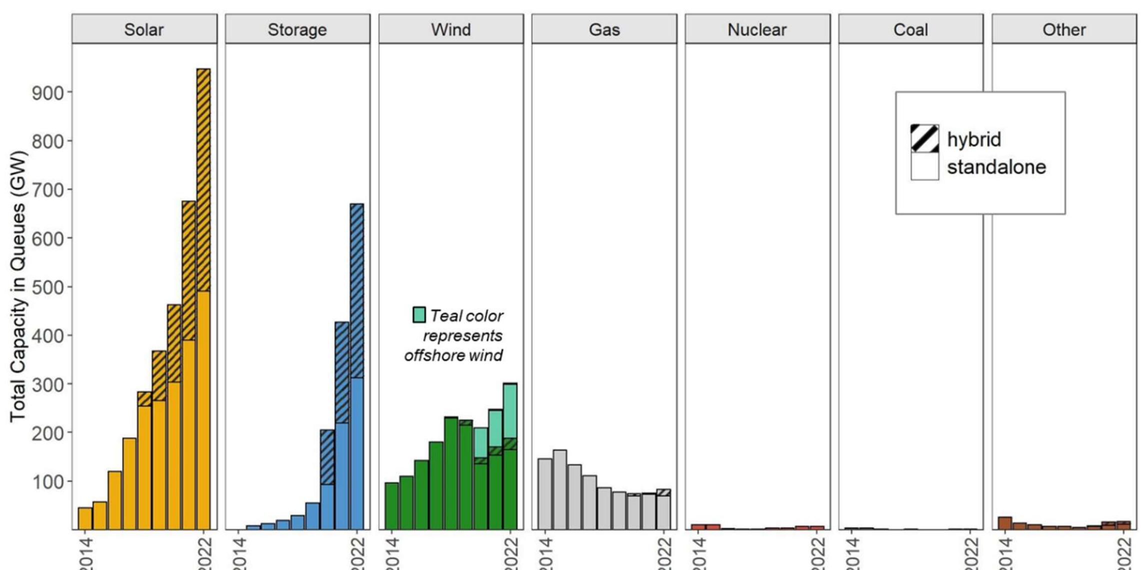

Figure 6: Electric Production Queues in the US, Source: Berkeley Lab- Electricity Markets and Policy

At the end of 2022, 1350 GW of projects were waitlisted for grid interconnection in the US, with 1100 GW coming from renewables. Solar (947 GW) accounts for >70% total active generation projects [21]. With average interconnection wait times exceeding 3 years and the high likelihood of permitting issues, many of the proposed projects will not be built. Historically only 21% of projects reached commercial operation from 2000 to 2017.

However, hydrogen is a new paradigm, and the conditions seem to be ripe for a leap-frogging scenario. Turning renewable power into hydrogen via electrolysis could become a viable alternative for power producers facing long interconnection times and uncertainty in the grid's ability to handle new loads. Another compounding issue with the 947 GW of Solar in the queue is that most of that energy production is generated when it is not required.

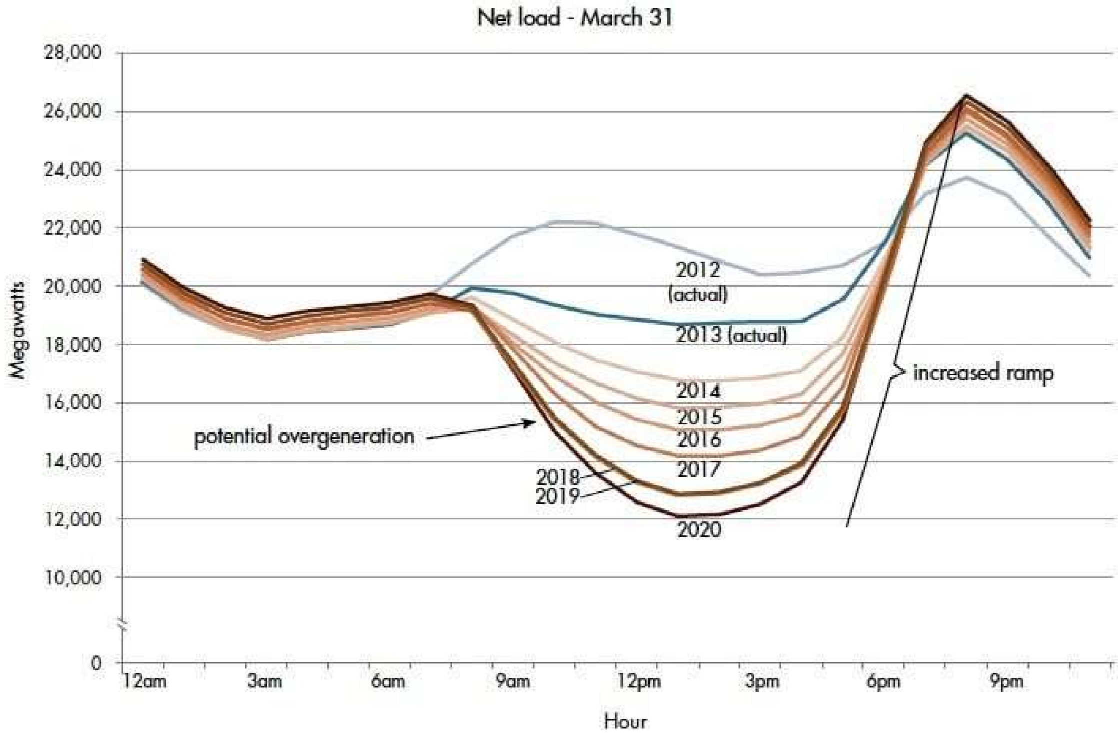

Figure 7: Solar Duck Curve Peak Solar Production Coincides with Lowest Demand, Source US Department of Energy Efficiency and Renewable Energy

Currently projects are factoring in battery storage to confront these issues, but Hydrogen has the capability to store much larger volumes of energy for much longer periods of time. In this scenario, Hydrogen projects could be a pathway to accelerate advancement of solar and wind projects whilst delivering a low carbon molecule into existing gas markets.

6.0 Summary

This paper explores the implications of the ongoing energy transition in North America on existing oil and gas pipelines. Drawing from historical energy transitions and technical system reconfigurations, the study uses the Town Gas transformation in the US and Europe as a pertinent example, given the growing interest in blending hydrogen into natural gas systems. Additionally, it examines the impact of technological change on existing system as demonstrated by the disruptive impact of the mobile telecommunications industry in India.

The paper delves into the current landscape of proposed hydrogen projects in North America, highlighting the contrast with the coordinated transborder transformation of the EU Hydrogen backbone to a regional hub model which is not too dissimilar to the era of town gas between 1816 and 1950. As the trend of renewables power emerges, the integration into the energy mix will lead to the reconfiguration of the energy system and present challenges and opportunities. The extent of this reconfiguration and the role of pipelines in the transformation remain uncertain, but hydrogen's potential as an energy storage solution offers the opportunity to leverage the existing infrastructure network effectively whilst seizing the opportunity of renewable generation. This is particularly relevant considering the challenges faced by the electrical grid, such as long connection wait times and congestion, and the need to achieve net-zero emissions by 2050.

While acknowledging the hurdles ahead, encompassing technical, economic, regulatory, and implementation complexities, the paper adopts an optimistic outlook. It contends that embracing a diverse range of solutions will be essential for a successful energy transition and that leveraging existing systems, specifically pipelines, will play a crucial role in minimizing energy costs for consumers. Although the focus can be on energy production costs it cannot be forgotten the costs required to transport that energy to market. As such, and in conclusion the importance it is essential to have thoughtful and strategic utilization of the existing pipeline network to facilitate the transition to a more sustainable and cost-effective energy future in North America.

Acknowledgments

The concept of this paper started from reading Jane Emerton's collection of essays on changing technical systems and was complemented with discussions and articles provided by colleagues and friends. So, thank you to everyone I have interacted with on energy transition in the last 6 months. Also thank you to Ahmed Nossair of Enbridge for his technical guidance in Section 3 along with many other colleagues at Enbridge who have helped along the way.

This paper is the first of a trilogy of papers on Energy Transition in North America. With the first exploring the technical system changes, the second a deep dive on the human and organizational changes to come and the final installment a practical guidebook for navigating energy change for the next 20 to 30 years.

References

[1] The Inflation Reduction Act: Here's What's in it, Justin Baldman, Adi Kumar, Nehal Mehta, Sara O'Rourke and Julia Silvis, Mckinsey & Company, October 24, 2022

[2] Emerton, Jane, "The Systems Approach to Technological Change:, "Changing Large Technical Systems"

[3] Joerges, Bernhard, "How to Recombine Large Technical Systems: The Cae of European Organ Transplantation"

[4] Schneider, Volker, "Armies, Railroads, and Information: The Birth of Industrial Mass Warfare"

[5] Tarr, Joel, "Transforming an Energy System: The Evolution of the Manufactured Gas Industry and the Transition to Natural Gas"

[6] Share the Great Switch – Lessons from When 14 million Homes and Business Changed Fuel in Less than a Decade, Rapid transition Alliance

[7] Gas Chronology- The development of British Gas Industry, British Gas, www.oldflames.org.uk

[8] https://www.eia.gov/energyexplained/natural-gas/use-of-natural-gas.php

[9] US National Clean Hydrogen Strategy and Roadmap US Department of Energy

[10] X. Li, X. Ma, J. Zhang, E. Akiyama, Y. Wang and X. Song, "Review of Hydrogen Embrittlement in Metals: Hydrogen Diffusion, Hydrogen Characterization, Hydrogen Embrittlement Mechanism and Prevention," *Acta Metallurgica Sinica,* vol. 33, pp. 759-773, 2020.

[11] Telecom Subscription Date as on 31st October, 2020, Telcom Regulatory Authority of India, 31 October 2020.

[12] O.J.C Huising, A.H.M Krom, "H2 in an Existing Natural Gas Pipeline", ASME 2020 International Pipeline Conference.

[13] Lazard Levelized Cost of Electricity

[14] Battey cost curves, National Renewable Energy Laboratory, https://www.nrel.gov/docs/fy21osti/79236.pdf

[15] Storage Hydrogen https://m-e-wolke.medium.com/a-sun-soaked-wind-swept-world-69ea3624abdb

[16] What are eFuels? - eFuel Alliance (efuel-alliance.eu)

[17] Costs & Outlook - eFuel Alliance (efuel-alliance.eu)

[18] eFuels Production Map - eFuel Alliance (efuel-alliance.eu)

[19] Pipeline and Hazardous Materials Safety Administration is a United States Department of Transportation agency

[20] Canadian Energy Regulator

[21] Queued Up: Characteristics of Power Plants Seeking Transmission Interconnection, https://emp.lbl.gov/queues.