Macrothink Institute™

International Journal of Global Sustainability
ISSN 1937-7924
2023, Vol. 7, No. 1

Mobile Modular Hydrogen Power Generation a Zero Carbon Energy System

Marc Abbott

Future Energy Innovations

5834 Dusty Heath Ct, Katy, Texas, 77450, USA

Tel: 1-713-505-6795 E-mail: Marc.Abbott@Gmail.com

Received: May 15, 2023 Accepted: June 14, 2023 Published: June 29, 2023

doi:10.5296/ijgs.v7i1.21120 URL: https://doi.org/10.5296/ijgs.v7i1.21120

Abstract

The transition to a zero-carbon energy system is inevitable if society is to negate CO2 emissions associated causes of Climate Change and replace the usage of our finite hydrocarbon resources. The transition to a zero-carbon energy system will take decades to not only replicate the scale and efficiency of our existing energy system but to also develop the technologies needed that on a like for like basis will provide society with at least comparing with today a zero-carbon energy system that is efficient and cost effective. This short communication puts forward a potential solution that is efficient, cost effective and most importantly zero-carbon emissions. The intent is to give an overview of the technologies that can achieve this with their respective current technical readiness and timeline to full scale public deployment.

Keywords: zero, carbon, hydrogen, electrolysis, energy, turbine, battery

1. Introduction

1.1 Maintaining Status Quo

Our current fossil fuel energy system functions on an enormous scale, in 2018 global electricity generation stood at 26614.8 Terawatt-hours of electricity of which fossil fuels (Oil, Natural Gas and Coal) was 17086.1 Terawatt-hours (Michaux, 2021a) or 64.2% of total electrical generation, renewables accounted for 9.3% and the remainder 26.5% was Nuclear and Hydro-Electric. Our primary global electrical consumption is also enormous, in 2018 it stood at 13864.9 Terawatt-hours with fossil fuel primary energy consumption accounting for 11743.6 Terawatt-hours or 84.7% (Michaux, 2021b). Insee define primary electrical consumption as “equal to all the economy’s energy consumption in primary form (that is, not transformed after extraction) and marginally in the form of non-energy derivatives (tar, asphalt, lubricant, etc.)."

It is not an understatement to state that maintaining the status quo, i.e., replacing the existing residential fossil fuel energy system on a like for like basis will be a monumental undertaking never mind the phasing out the ICE (Internal Combustion Engine) with electrically powered vehicles and its associated infrastructure, and the electrification of our complex industrial system coupled with the demand for projected population growth.

This short communication will discuss at a high level a solution for using mobile and modular hydrogen production as a feedstock for zero-carbon power generation and for use in heavy duty mobility applications.

For intellectual property reasons technical details of the AEM Electrolysis and Hydrogen Gas Turbine cannot be presented in detail.

1.2 What problems need to be solved?

Fundamentally two problems exist for society, the first being: "Finding the lowest true energy cost of generating zero-carbon electricity" As previously mentioned replacing our existing fossil fuel electrical generation system with zero-carbon electrical generation will be extremely difficult not just because of the scale of the capacity to be replaced but also by the differing global geopolitical landscapes, public acceptance of the costs associated with zero-carbon electricity, technical readiness of new energy technologies and the differing pace with economic development. The second problem is: "Replacing our existing fossil fuel energy system with one where the Energy Returned on Energy Invested (ERoEI) does not result in a less efficient and more expensive system". The Energy Returned on Energy Invested ratio is explained further in 2.1 Energy is needed 24/7.

There are inevitably some countries that will simply proceed with their own agenda for example China. (China is the benchmark as it dominates the manufacturing of global goods and the consumption of raw materials) In 2022 the Chinese government approved 106 Gigawatts of additional coal generated electrical capacity, approximately equal to starting two additional coal generating plants each week (CNN, 2023). Their counter argument is, and not unreasonably, that they are using their resource rich cost-effective coal deposits.

This short communication focuses on the first problem by discussing the technologies we should pursue and how on their own merit they are a critical piece of the solution for achieving a zero-carbon energy system through establishing Hydrogen as a feedstock that provides sinusoidal quality electricity to industry and residential consumers.

Figure 1.0 illustrates a potential zero-carbon energy system known as Mobile Modular Hydrogen Power Generation. Anion Exchange Membrane (AEM) Electrolysis is used for Hydrogen production and a Hydrogen gas turbine for power generation. Note: 30 Megawatt electrolysis in theory produces enough Hydrogen to power 1,000 residential homes.

International Journal of Global Sustainability
ISSN 1937-7924
2023, Vol. 7, No. 1

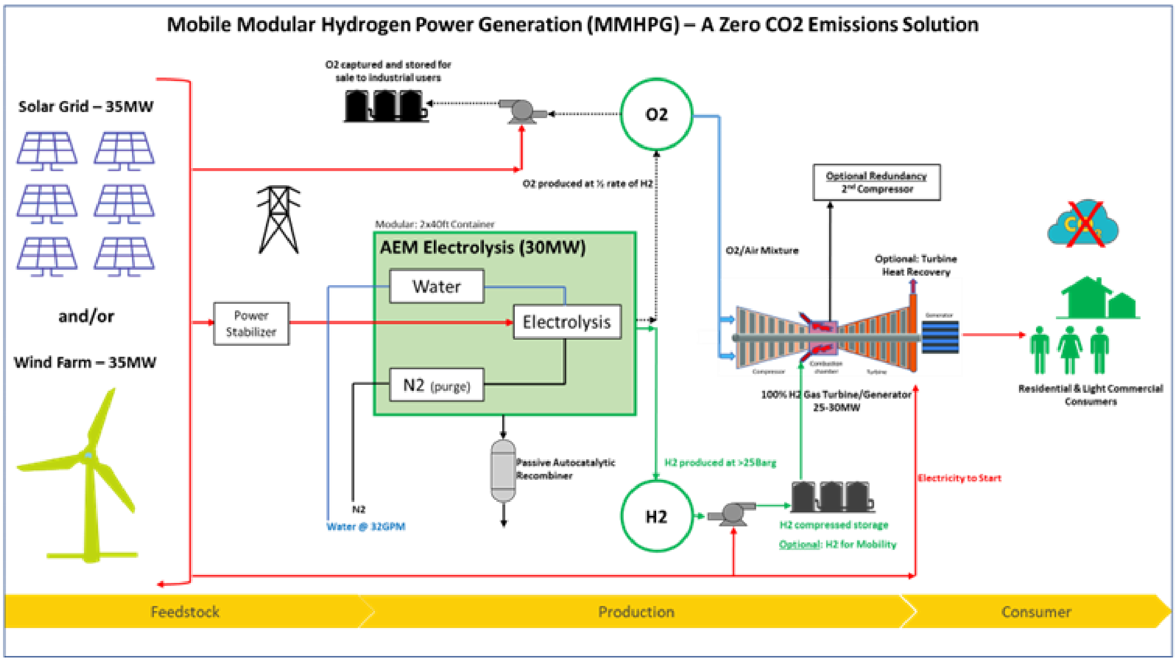

Figure 1. Mobile Modular Hydrogen Power Generation - a Zero-Carbon Energy System

2. Analysis of the Solution

2.1 Energy is needed 24/7

Today energy production and consumption are taken as a given, very few completely understand what it takes to 'keep the lights on' or provide hot water or cook your food, the scale of our existing global energy system including infrastructure is immense, as of 2018 there were 12,848 global power plants operating 24/7 to maintain society as we know it (Michaux, 2021c). More importantly though is the efficiency of the fossil fuel energy system that created modern day standards of living, if it is to be replaced by a future zero-carbon fuel system, even at par with today the challenge is monumental and will take many decades to implement. Why is this? Simply put crude oil, natural gas, and coal (excluding nuclear) were and are the most concentrated sources of energy we have ever had and subsequently powered and transformed our way of life for the last 100 years. Critically the energy returned on the energy invested (ERoEI) to extract and utilize these resources has always exceeded a ratio of 11:1 that is the minimum ratio a complex modern society needs to function (Michaux, 2021d).

Figure 1.1 illustrates simplistically the concept of Energy Returned on Energy Invested.

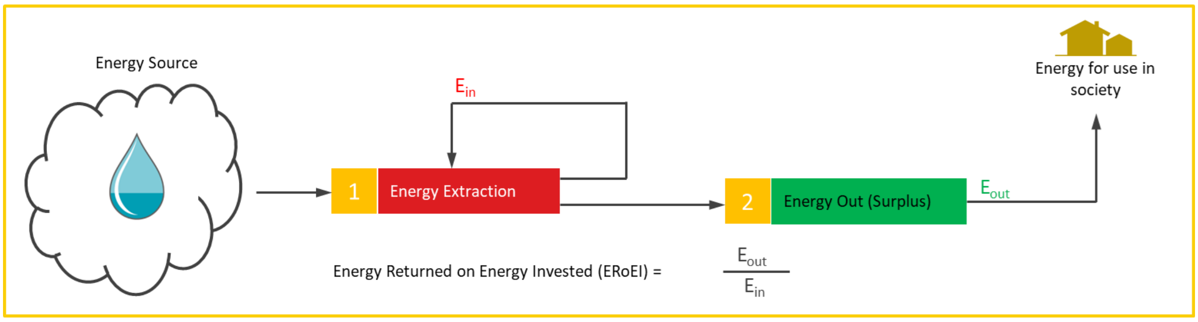

Figure 1.1 – Energy Returned on Energy Invested Ratio

Fossil fuels are a finite resource and over time have depleted and become more difficult to extract thus the ERoEI ratio reduces and couple this with the need to eliminate carbon emissions and we need to not only singularly replace our existing fossil fuel energy system but with a zero-carbon energy system that has at the very worst an ERoEI >7:1 (minimum for a modern basic society needs to function) but at least an ERoEI>11:1 (minimum for a modern complex society needs to function) (Michaux, 2021d).

Figure 1.2 The Net Energy Cliff (Michaux, 2021e) illustrates that a declining ERoEI ratio will exacerbate the problem of fossil fuels and that if we are to continue to function as we have been used to then the key will be on how the energy transition out of fossil fuels is done and that should not be considered as time based but by using the right technologies on their merit and not following trends or making reactive decisions based on short term strategies.

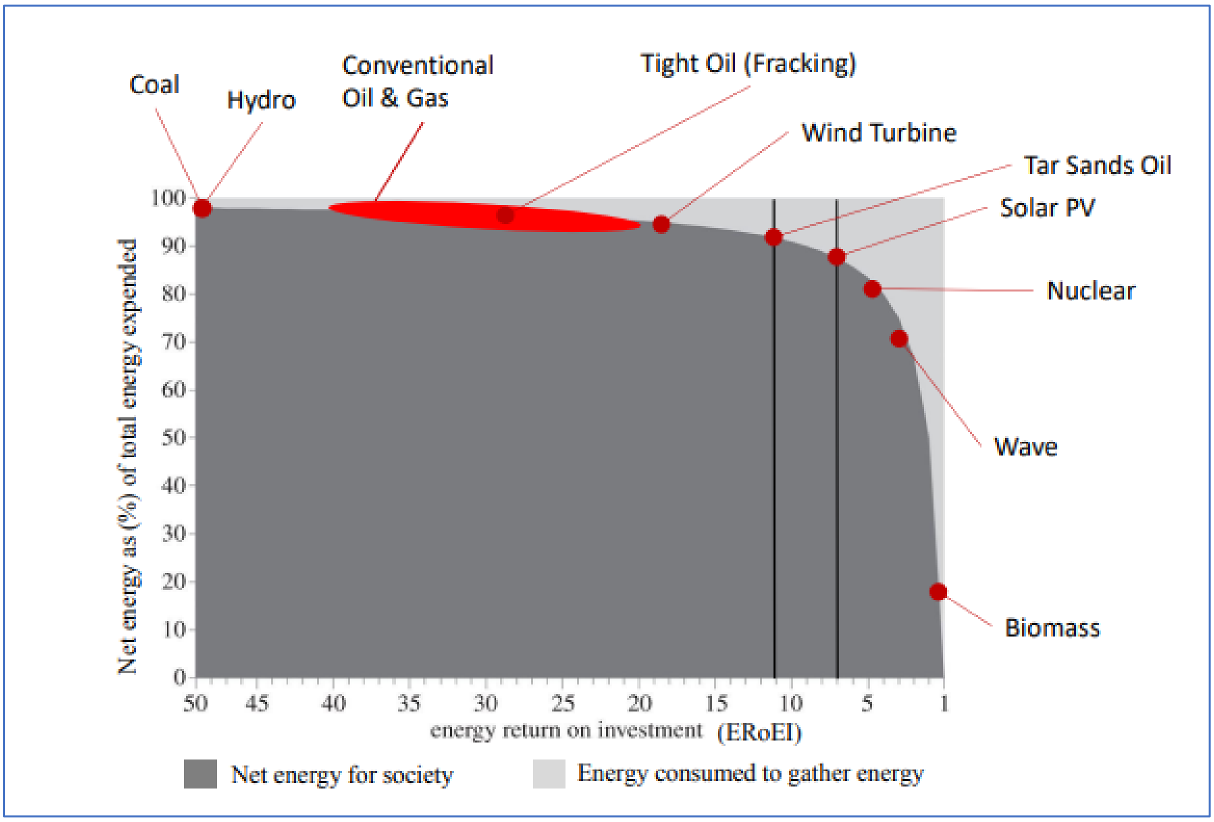

Figure 1.2. The Net Energy Cliff

2.2 Why not battery storage?

Wind and solar are intermittent sources of power meaning they cannot produce on demand as we cannot control when the sun shines or the wind blows. To make wind or solar a consistent source of electricity and meet the demand cycles of consumers a storage medium is required, the most common is battery storage. In the proposed zero-carbon energy system the obvious decision would be to use battery storage instead of an AEM Electrolyzer and Hydrogen gas turbine, or would it be?

There are some obvious and not so obvious reasons as to why battery storage was not proposed, lets briefly look at four key reasons that 'rule out' battery storage as part of a practical zero-carbon solution.

2.2.1 Energy required to make a lithium-ion battery

Lithium-ion battery production is exceptionally energy intensive, as part of the Environmental Impact Assessment into battery manufacturing at Northvolt Ett (a battery manufacturer in Sweden) the assessment estimated that the annual electricity consumption for their 8 Gigawatt hours production line to be 400 Gigawatt hours, the estimated annual electricity consumption to produce 32 Gigawatt hours of lithium-ion battery is 2 Terawatt hours (IOP Science, 2019). Consider just the 8 Gigawatt hour production line and the ERoEI ratio is -50:1. Furthermore how is the electricity generated? What is the impact on grid loading? These are reasonable questions that need to be answered.

2.2.2 Lithium-ion battery production and associated environmental concerns

Lithium-ion battery production requires the mining and processing of Lithium, this process is CO2 intensive. The CO2 cost of producing a lithium-ion battery is around 73kg CO2 equivalent per kWh (Changeit.App, 2021). In the Northvolt Ett example the production of 8 GWh of lithium-ion batteries results in 584 million tonnes of CO2 equivalent emissions, as a comparison the United Kingdom's total CO2 equivalent emission between 2021 and 2021 was 505 million tonnes (ONS, 2022).

The environmental impact of lithium mining is highly negative to extract 1 ton of lithium requires 500,000 litres of water (CCS, 2023), and once past their useful lifecycle are either disposed or recycled. Today only 5% of the world's lithium-ion batteries are thought to be recycled this environmental impact is huge with a projected 8 million tons of waste disposed to landfill (CAS, 2022). Lithium-ion waste contains metal toxins from Cobalt, Nickel and Manganese which are used in lithium-ion batteries, these metal toxins have the potential to contaminate water supplies and the wider eco-system if not recycled.

2.2.3 Energy curtailment and battery performance

Energy curtailment is a stop order on producing energy from either wind or solar for a specific period by the grid operator. Curtailment is driven by economics or grid capacity. Grid operators try to balance supply with demand to maintain specific prices for electricity should supply outstrip demand then prices fall making electricity generation uneconomical at this point curtailment is usually enforced and wind or solar production is shut down. Curtailment is again enforced when grid capacity reaches or gets close to its maximum, at this point it is not uncommon for grid operators for example to stop purchasing electricity from residential consumers who have excess supply from their own solar or wind installations.

Battery performance encompasses a wide range of variables for this discussion the considerations are the effects of the operating environment and number of charge and discharge cycles over the expected battery lifetime. Temperature is the major factor in the operating environment and has a major effect on battery performance. In colder environments performance is greatly reduced whereas in warmer environments the performance reduction is not as noticeable, but cooling becomes an issue. Ultimately the less variance in temperature the better the performance of battery storage. The more charge and discharge cycle a battery is exposed to the greater the capacity fade and reduction in battery life. Capacity fade is unavoidable in lithium-ion batteries the technical reasons are not discussed here but it is an important factor as the impact of replacing spent batteries and recycling them if practicable not only has a major environmental impact but significant cost implications. It has been estimated to install battery storage to backup all wind and solar in a net zero energy system in the US would cost $23 Trillion (Zero hedge, 2023), never mind replacement and recycling.

2.2.4 The intermittency problem

With wind and solar being intermittent energy sources the renewables industry turned to, the most common is battery storage.

However, using battery storage, in addition to the forementioned, presents two further problems that are not within our control: 1. What are the implications if you cannot recharge the battery storage due to no sun nor wind being available? and what if the battery storage is at capacity and there is no room for further charge? These cannot be overcome and place limitations on battery storage and including the other concerns they are not a realistic solution for providing 24/7 zero-carbon energy.

2.3 Hydrogen production and anion exchange membrane electrolysis

Steam Methane Reforming and Water Gas Shift is the most used process today in industry to produce Hydrogen, 48% of all global hydrogen production uses this process (Michaux, 2021f). In this process Methane CH_4 is converted into a mixture of CO, CO_2 and H_2, the reaction equations are noted below for information, detailed analysis is widely available on the internet.

Steam Methane Reforming: $CH_4 + H_2O \Longrightarrow CO + 3H_2$

Water Gas Shift: $CO + H_2O \Longrightarrow CO_2 + H_2$

The obvious problem with using this process is the production of the Greenhouse Gas CO_2 the process also requires a vast amount of heat to produce the super-heated steam and if the CO_2 is to be captured further electrical capacity is required. Steam Methane Reforming is a mature hydrogen production process but with a CO_2 to H_2 ratio of 6:1 it surely has a limited future as a hydrogen production method in any zero-carbon energy system.

Other popular methods to produce hydrogen (excluding electrolysis) include Plasma Reforming, Coal, and Petroleum Coke Gasification, however none of these are Zero Carbon solutions as they either consume hydrocarbons or produce problematic climate gases and should not be considered.

Water Electrolysis or as it is more commonly known Electrolysis is a disassociation reaction that produces elemental oxygen and hydrogen gases. Electrolyzers can be generally classified as either Liquid Electrolyte or Solid Electrolyte systems, with the former only able to operate effectively at lower temperatures (<200C).

Liquid Alkaline Electrolyzers (AEC Systems) are well established technologies that have been used for many decades the alternative liquid system an Acid System are extremely uncommon and only mentioned for reference.

Solid electrolyte systems are the focus of much research technology today, the most common commercially and technologically advanced system today is the Proton Exchange Membrane (PEM) system. The Anion Exchange Membrane better known as AEM will be discussed further. The high temperature systems Solid Proton Conducting Electrolysis Cells (SPCEC) and Solid Oxide Electrolysis Cells (SOEC) are noted for reference but not discussed as they are out of scope.

Anion Exchange Membrane Electrolysis is a rapidly developing technology and is more and more seen as a preferred solution for not only improving the performance of water electrolysis but also producing green hydrogen. Current proof-of-concept testing on the durability of membranes and electrodes looks promising along with positive current density and degradation performance.

Figure 1.3 illustrates a typical AEM Electrolysis Cell.

Table 1.0 compares the key differences between AEC, PEM and AEM Electrolysis.

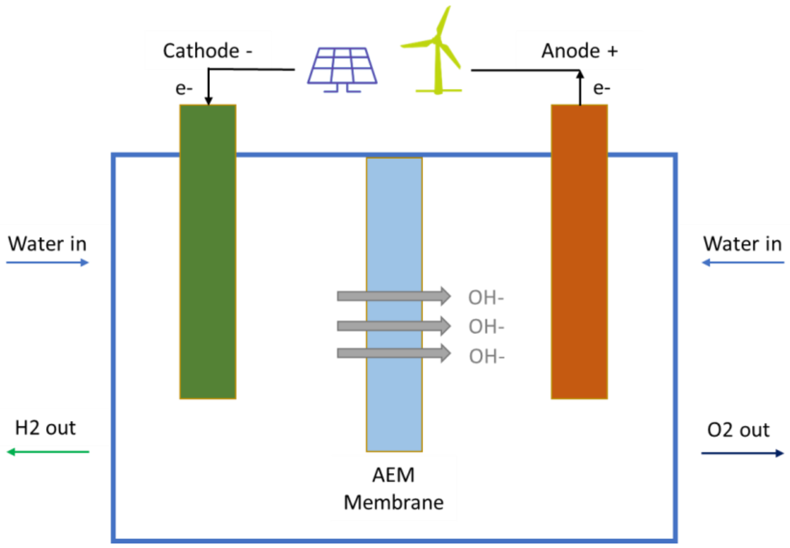

Figure 1.3. Typical AEM Electrolysis Cell

Table 1. Comparison of AEC, PEM and AEM Electrolysis

	Alkaline	Proton Exchange	Anion Exchange
Cost per Kilowatt	Higher	Highest	Lowest
Benefit 1	Abundant materials	High performance	Abundant materials
Benefit 2	High stability	Dynamic operation	Dynamic operation
Benefit 3			Smallest footprint
Benefit 4			No PFA's
Issue 1	Produces low pressure H2	Sensitive to supply chain issues and high cost due to rare materials: Iridium & Platinum	Durability not proven
Issue 2	Slow response (not dynamic) restricts compatibility with solar and wind	Toxic membrane	Long term performance not proven
Issue 3	Low overall efficiency		
Issue 4	Large footprint, not mobile with future cost reductions difficult		

* PFA's: Poly-fluoroalkyl substances

Solid Oxide Electrolysis has been omitted from the comparison as its technology has yet to still overcome some fundamental issues, such as difficulties in manufacturing result in very high-cost systems and the high temperature operation makes it difficult to dynamically operate with wind and solar.

2.4 Hydrogen and oxygen use cases

In the zero-carbon energy system scenario (Figure 1.0) there are two use cases for hydrogen that can significantly help reduce GHG (Greenhouse Gases) and one for oxygen that monetizes at the current stage of AEM electrolysis development for what is considered a by-product.

The first use case for produced hydrogen is as a fuel for a gas turbine to generate electricity. Electricity generation in the US in 2021 accounted for 25% of all GHG emissions (EPA, 2021). Section 2.5 will explain further the technology development of gas turbines to allow hydrogen as a pure fuel. The second use case is hydrogen for transportation, in this context transportation can be considered all modes except aviation but primarily passenger cars and heavy-duty vehicles.

Transportation is the largest source of GHG emissions in the US in 2021 transportation accounted for 28% (EPA, 2021) of all GHG emissions add that to electricity generated GHG emissions and you have the potential to reduce, using the US as an example, approximately 50% of its GHG emissions by using hydrogen for electricity generation and transportation.

Hydrogen as a fuel for transportation is a unique opportunity to decarbonise this sector of the economy with technology to design and develop hydrogen internal combustion engines accelerating rapidly. Hydrogen internal combustion engines have already been developed with validation expected in 2024 and planned mass production in 2025 these engines will be classified as zero emissions by the EU (Hyundai Doosan Infracore, 2023).

Oxygen is a useful industrial gas and by-product of water electrolysis being produced in half the quantity of hydrogen. By selling the oxygen rather than venting the overall operating cost of the system can be reduced common applications for oxygen include Medical, Steel and Metal Manufacturing and Chemical Manufacturing. In the proposed zero-carbon energy system there might also be an opportunity to use an oxygen/air mix for the gas turbine to further reduce emissions.

2.5 Hydrogen gas turbines

Gas turbines have been in use for decades whether in aero engines or industrial applications this is the result of them having four major benefits:

1) Durability – gas turbines have extremely low operational failures and low downtime for maintenance (think of the operational reliability of aero engines on passenger aircraft) as they do not need high levels of lubrication and have fewer moving parts than other engines.

2) Fuel Flexibility – gas turbines particularly industrial turbines often have dual fuel capability as a redundancy feature. A common set up in the oil and gas industry particularly offshore is the ability of gas turbines used to generate power to have the ability to switch instantaneously between natural gas and diesel back up in the event of an unexpected outage.

3) Waste Heat Recovery – gas turbines operate at high speeds, pressures, and temperatures. Unique to a gas turbine is that almost all the heat is discharged to the exhaust system giving an option for waste heat recovery and cogeneration.

4) Distributed Power Generation – gas turbines can either operate as a standalone unit or as part of an integrated system, both being a critical advantage in the energy transition.

As of 2020 there were approximately 1.6 terawatts of gas turbines installed globally (GE, 2022a) including the above four major benefits a logical conclusion is that gas turbines are a preferred choice for on demand power generation if we can use green hydrogen produced from AEM electrolysis as a 100% replacement for natural gas.

Development of hydrogen as a feedstock for gas turbines is well advanced with blended (50%/50%) natural gas and hydrogen fuel trials established (GE, 2022b). Technology advancements in the pre and post combustion phases suggest that 100% hydrogen gas turbines could be operational as early as 2028/2029, such a development achieves zero carbon fuel emissions. There are two combustion technologies that are subject to much research and development to enable 100% hydrogen fuel, diffusion flame and premixed flame.

Out with combustion technology there are other concerns that need to be resolved including safety and lowering the cost of hydrogen compared to natural gas as a feedstock today hydrogen is around four to eight times more expensive than natural gas however incentives and tax credits will eventually alleviate this problem.

Safety is always a concern and with hydrogen and its known difficulties with containment and embrittlement it requires special focus. In recent years safety standards for hydrogen and the associated technology have advanced significantly to ensure its production and containment are now comparable to that of natural gas. When compared to fossil fuels hydrogen has positive advantages that should not be discounted including non-toxic, rapid dispersion as it is fourteen times lighter than air and has a higher oxygen requirement for explosion than fossil fuels.

The future looks very promising for hydrogen gas turbines together with the technological advancements and high safety standards in place hydrogen gas turbines are a truly unique opportunity for zero-carbon energy systems.

3. Discussion

Establishing green hydrogen as a future fuel for society is a critical step out of fossil fuels and into a zero-carbon energy future. There is no doubt Anion Exchange Membrane electrolysis is still in development, but it is a promising breakthrough technology with zero toxicity and does not require rare and expensive materials such as those found in Proton Exchange Membrane (PEM) electrolysers. Multi megawatt and gigawatt AEM electrolysers in the future will be of modular design and small capacity, likely around 10 megawatts, and coupled together much like ‘Lego Bricks’ to achieve a desired output.’ At the present state of technical readiness it is not inconceivable that a 100 megawatt AEM electrolyser will be operational in the next five to ten years.

In any future energy system wind and solar should play an increasing and critical role, downsizing the current footprints particularly of solar grids on land is becoming a priority we now see the adoption of floating solar installations to help mitigate this. Advances in power electronics coupled with AEM electrolysis which has demonstrated good compatibility with wind and solar due to its wide turndown bandwidth can help establish wind and solar powered AEM electrolysis as a credible option.

Storing energy presents a huge problem but it is essential for the energy transition to be successful, battery storage is problematic as discussed and alternatives need to be found for large scale storage that has minimal environmental impact and supports a zero-carbon future. Hydrogen is challenging to store for power generation due to its low density, however technological advances in materials-based hydrogen storage that offer higher energy density look promising with their technology readiness timelines similar to that of AEM electrolysis.

Gas turbines are a proven technology that have many positive attributes, scalability, efficiency, reliability, and cost effectiveness that makes it difficult at this point in the energy transition to consider alternatives such as fuel cells. Technology development will continue to advance in this space with key players such as General Electric, Rolls Royce and SOLAR all being committed to 100% hydrogen gas turbines in the very near future.

If society is to be successful in transitioning from fossil fuels it will be how the transition is done and what technology will be ready to deploy, history has proven we are innovators and there are many reasons to believe that Mobile Modular Hydrogen Power Generation with its scalability, reliability and non-toxic attributes can play an important part in a future zero-carbon energy system.

References

Michaux, S. (2021a). Assessment of the Extra Capacity Required of Alternative Energy Electrical Power Systems to Completely Replace Fossil Fuels. *Geological Survey of Finland*, 31 Appendix B, p725.

Michaux, S. (2021b). Assessment of the Extra Capacity Required of Alternative Energy Electrical Power Systems to Completely Replace Fossil Fuels. *Geological Survey of Finland*, 30 Appendix A, p722.

Insee: Institut national de la statistique et des etudes economiques. https://www.insee.fr/en/metadonnees/definition/c1705

CNN: Cable News Network. https://edition.cnn.com/2023/02/27/energy/china-new-coal-plants-climate-report-intl-hnk/index.html

Michaux, S. (2021c). Assessment of the Extra Capacity Required of Alternative Energy Electrical Power Systems to Completely Replace Fossil Fuels. *Geological Survey of Finland*, p177.

Michaux, S. (2021d). Assessment of the Extra Capacity Required of Alternative Energy Electrical Power Systems to Completely Replace Fossil Fuels. Geological Survey of Finland, p128.

Michaux, S. (2021e). Assessment of the Extra Capacity Required of Alternative Energy Electrical Power Systems to Completely Replace Fossil Fuels. Geological Survey of Finland, p140.

IOP Science: Institute of Physics. https://iopscience.iop.org/article/10.1088/2515-7620/ab5e1e

Change It: Climate Change. https://changeit.app/blog/2021-03-26-environmental-impact-of-lithium-batteries/

ONS: Office for National Statistics

https://www.ons.gov.uk/economy/environmentalaccounts/bulletins/greenhousegasintensityprovisionalestimatesuk/2021

CCS: Columbia Climate School
https://news.climate.columbia.edu/2023/01/18/the-paradox-of-lithium/#:~:text=These%20side%20effects%20include%3A%20use,interests%20at%20stake%20are%20enormous.

CAS: Division of American Chemical Society
https://www.cas.org/resources/cas-insights/sustainability/lithium-ion-battery-recycling#:~:text=Today%2C%20only%205%25%20of%20the,8%20million%20tons%20of%20waste.

Zerohedge.com
https://zerohedge.com/political/net-zero-grid-batteries-alone-would-bankrupt-america

Michaux, S. (2021f). Assessment of the Extra Capacity Required of Alternative Energy Electrical Power Systems to Completely Replace Fossil Fuels. Geological Survey of Finland, p387-388.

EPA: Environmental Protection Agency
https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions

Hyundai Doosan Infracore
https://www.dieselprogress.com/news/hyundai-doosan-infracore-to-launch-hydrogen-engine/8026837.article

GE (2022a, p3): General Electric
https://www.ge.com/content/dam/gepower-new/global/en_US/downloads/gas-new-site/future-of-energy/hydrogen-for-power-gen-gea34805.pdf

GE (2022b, p11): General Electric
https://www.ge.com/content/dam/gepower-new/global/en_US/downloads/gas-new-site/future-of-energy/hydrogen-for-power-gen-gea34805.pdf

Notes

I have worked in the energy industry for over twenty-five years in many countries across the world and currently lead the deployment of new energy technologies for a large global technology company with a focus on hydrogen and carbon capture development. Aside from the references I have witnessed first hand the advances in AEM electrolysis and materials-based storage. Please feel free to contact me for further information.

Copyright Disclaimer