Centre for Energy, Petroleum
and Mineral Law and Policy
University of Dundee

The Emergence of Hydrogen Legal Frameworks in the Global Energy Transition: What can South Africa learn from the US and Germany?

Author: Priscilla Brandt *

Dissertation

CEPMLP Annual Review 2022

Abstract

This study provides an in-depth look at two of the most robust and prominent hydrogen energy-friendly jurisdictions, namely Germany and the United States of America (USA), and compares their situation to that of an emerging economy nation, South Africa, and its nascent embrace of this form of energy in the context of its own energy transition, in particular away from coal-fired thermal power generation. As new technologies emerge, in countries where governance structures are sufficiently responsive, State strategies, policies and regulation can adapt and change to reflect new realities and possibilities. This study focuses on one case study: hydrogen energy regulation in South Africa, as informed by German and USA experiences.

The author notes that it may be remiss to believe that hydrogen can be facilitated by the State similarly to natural gas or alternative energy sources. Indeed, there is a slew of additional variables to consider when developing a robust regulatory strategy, and the situation of hydrogen energy may be different than for natural gas or coal. The vibrancy of a new hydrogen energy economy is already evident in many nations, as is the abundance of innovations associated with the hydrogen economy. However, this study also underlines the reality that development is not uniformly distributed around the world. Fledgling levels of hydrogen energy development and nascent legislative and regulatory frameworks continue to be the norm in many nations, whereas other jurisdictions are rapidly transitioning into an enabling environment that would provide a stable investment climate for the hydrogen economy.

The first five chapters of this dissertation consist of: an introduction; the hydrogen phenomenon; a Germany case study; a case study of the USA; and consideration of South Africa's hydrogen energy landscape. The sixth chapter comprises discussions on the challenges related to the hydrogen economy and recommendations for the countries concerned. The last chapter contains a conclusion that seeks to give a brief exposition on the study's findings.

The research methodology applied for this dissertation aimed to comparatively examine whether exemplary national hydrogen strategies formulated by leading economies such as Germany and the US could serve as models for an emerging economy such as that of South Africa. The examination was illustrated through the analysis of various national hydrogen acceleration efforts deployed by the aforementioned countries, such as inter alia, available *regulatory frameworks and financial pledges generated towards adopting a hydrogen economy.*

This study further examines future commercialisation prospects and the barriers that must be addressed in an effort to accomplish regional and global targets. It finds that hydrogen energy lies at a complex confluence of energy and climate regulations, a nexus of competing and complementary global energy futures.

* Priscilla graduated with an LLM in International Oil and Gas Law and Policy (with Distinction) from the Centre for Energy, Petroleum & Mineral Law and Policy under the University of Dundee. She holds an LLB from the University of the Free State (South Africa) and a half-year specialisation certificate in European Governance and Integration from the University of Agder (Norway).

Priscilla previously served as the President of the AIPN (Association of Petroleum Negotiators) Dundee Student Chapter as well as the Secretary of the Energy Institute - Dundee Student Chapter. During her studies at the University of Dundee, she drafted various country profiles and presented a video on "The Road to a Diversified Energy Mix in Power Generation: The Constraints and Challenges Attached to a South African Perspective" under the Extractives Hub.

She is currently serving her articles of clerkship as a candidate attorney at Cliffe Dekker Hofmeyr Inc, one of the Big Five law firms in South Africa and Africa at large.

Dedication

To my dear grandmother and mother, thank you for teaching me the importance of values and prayers. Your love has sustained me through the ebbs and flows.

**Kumakhulu nakumama ndiyabulela ngokundifundisa ukubaluleka kweenqobo ezisemgangathweni kunye nemithandazo. Uthando lwenu lundixhasa kwiindawo eziphakamileyo nezisezantsi.*

Acknowledgements

First of all, I would like to thank God Almighty for His grace and protection during the course of my studies. In addition to giving me the strength and fortitude to continue even on my darkest days.

I would like to thank my esteemed supervisor Professor Stephen Dow for his invaluable guidance, patience, and support throughout the duration of my studies. Your insight encouraged me to improve my thinking and raise the quality of my work.

My gratitude further extends to all the Professors, lecturers, and administrative staff at the CEPMLP for their continuous support, financial contribution towards my scholarship and making it possible for me to acquire such a profound academic experience.

I would like to thank the Chevening Secretariat and the Foreign and Commonwealth Office (FCO) for having actualised this dream come true for me through the receipt of the prestigious Chevening Scholarship.

I would like to thank my matriarch; my dear grandmother Ma Lingiwe Mvelase, my mother Vuyelwa Brandt and Tombzodwa Mei and the rest of my family for their constant encouragement, prayers and lending a sympathetic ear throughout the course of this journey.

I would like to thank my partner for his love, continuous support and patience.

Lastly, I would like to thank all the friends who walked this journey with me.

May the Almighty God richly bless all of you.

Figures, Abbreviations, Legislation and Policies

Abbreviations

ATR	Autothermal Reforming
BMVI	Bundesministerium für Verkehr und digitale Infrastruktur
BMWi	Bundesministerium für Wirtschaft und Energie
CAP	Climate Action Plan
CAPEX	Capital Expenditure
CCS	Carbon Capture Storage
CCUS	Carbon Capture Usage and Storage
CFR	Code of Federal Regulations
CoC	Centers of Competence
CO2	Carbon Dioxide
DMR	Department of Mineral Resources
DoE	Department of Energy
DSI	Department of Science and Innovation
DST	Department of Science and Technology
ECOWAS	Economic Community of West-African States
EIA	Energy Industry Act
EISA	Energy Independence and Security Act
EPA	Energy Policy Act
ERA	Energy Regulation Act
EU	European Union
FCEV	Fuel Cell Electric Vehicle
FERC	Federal Energy Regulatory Commission
GGE	Gasoline Gallon Equivalent
GHG	Greenhouse Gas
GH2	Gaseous Hydrogen
GWh	Gigawatt hours
GWe	Gigawatt of Electric Energy
H2	Hydrogen
HRS	Hydrogen Refuelling Station
IEA	International Energy Agency

IRENA	International Renewable Energy Agency
IRP	Integrated Resource Plan
ISO	International Organisation for Standardisation
LH2	Liquid Hydrogen
m	million
MENA	Middle East and North Africa
MBtu	Million British Thermal Units
NOW	Nationale Organisation Wasserstoff- und Brennstoffzellentechnologies
P2X	Power-to-X
PGM	Platinum Group Metals
PHMSA	Pipeline and Hazardous Materials Safety Administration
R	Rand
R&D	Research and Development
RES	Renewable Energy Sources
SMR	Steam Methane Reforming
SADC	Southern African Development Community
TWh	Terawatt hours
USA	United States of America
VRE	Variable Renewable Energy

Figures

Legislative and Policies

Jurisdiction	Legislation and Policies
Germany	*Electric Mobility Act of 2015*
Germany	*Energy Industry Act of 1998*
Germany	*National Hydrogen Strategy 2020*
South Africa	*White Paper on Energy Policy of 1998*
South Africa	*Energy Regulation Act (ERA) 4 of 2006*
South Africa	*Integrated Resource Plan (IRP) of 2009*
South Africa	*National Hydrogen and Fuel Cell Technologies Research, Development, and Innovation strategy (HySA)*
USA	*2001 National Energy Policy*
USA	*Energy Policy Act of 2005 (the "EPA")*
USA	*Energy Independence and Security Act of 2007 (the "EISA")*
USA	*Hydrogen Program Plan*

Contents

1. Introduction

1.1 Chapter Overview

This chapter aims to introduce the various facets of the dissertation, outlining a background analysis of the research subject, serving as a framework for defining the research problem to be addressed in this study. It explores the research questions, delimiting a study structure in the form of research questions (including primary and secondary questions), research aims, and objectives. A brief introduction of the research methodology employed in this study is presented, illustrating guidelines, and processes used to achieve the research aims throughout the study. Finally, research limitations are provided in order to provide a comprehensive understanding of the research breadth.

1.2 Research Problem

In the current global energy transition period, the necessity for hydrogen regulation and legislative restrictions on the element's procurement, trade, use, and related operations in both liquid and gaseous form is underlined. The transition from traditional energy sources to more environmentally conscious options has not been abrupt; rather, it may be seen as a global collaborative effort to create a more sustainable environment for the entire world's population. Hydrogen has been shown to influence this sustainability effort significantly, and its application is expected to increase in the near future, worldwide. Various nations and regions throughout the globe have begun to implement sustainable industrial processes. This process typically entails creating a set of objectives and putting a strategy into action on a large scale.[1] Notwithstanding, hydrogen regulation is also essential, particularly regarding safety, procurement, trading, and consumption.[2]

The regulation of this chemical energy will further ensure that hydrogen is utilised as an environmentally sustainable alternative in contrast to the existing traditional fossil fuels and allows for a more dynamic approach to industrial growth. In the current global energy

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[1] Shane D. Stephens-Romero and others, 'Systematic Planning To Optimize Investments In Hydrogen Infrastructure Deployment' (2010) 35 International Journal of Hydrogen Energy.

[2] Michal Nachmany and others, 'The GLOBE Climate Legislation Study: A Review Of Climate Change Legislation In 66 Countries' (*https://www.lse.ac.uk/granthaminstitute/wp-content/uploads/2014/03/Globe2014.pdf*, 2021) <https://www.lse.ac.uk/granthaminstitute/wp-content/uploads/2014/03/Globe2014.pdf> accessed 4 August 2021.

transition period, several nations have adopted distinct strategies and structures for hydrogen regulation.[3] The USA's and Germany's national hydrogen strategies, both innovative, are considered as outstanding examples of a sustainable and methodical framework.[4]

On the other hand, several countries have yet to properly assess their capability to contribute to the global sustainability agenda due to an overt lack of appropriate legislative frameworks and legal safeguards. South Africa, for example, despite its growing economy, currently lacks the requisite legislative framework and long-term pathways needed for effective hydrogen deployment.[5] To remediate this situation, strategies adopted in other countries, such as the USA or Germany, can usefully critically examined and evaluated in accordance for potential adaptation and use in South Africa, and in light of its specific national context. Moreover, the introduction of efficacious hydrogen energy regulation, and the promotion of that industry, in emerging nations like South Africa is required to enhance ecological sustainability globally.[6]

1.3 Research Questions

The twin research questions to be answered throughout this study is "Can foreign national hydrogen regulation strategies formulated in Germany and the United States serve as models for South Africa? How can hydrogen regulation be implemented in South Africa through effectively relevant strategies, laws and policies?" These twin questions have been divided into the following secondary questions pursuant to generating a thorough research base:

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[3] ibid.

[4] James Prest, Joshua Woodyatt and Jordie Pettit, 'Comparing The Hydrogen Strategies Of The EU, Germany, And Australia: Legal And Policy Issues' (*Papers.ssrn.com*, 2021) <https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3875170> accessed 4 August 2021; Ertuğrul Yildirim, Şenay Saraç and Alper Aslan, 'Energy Consumption And Economic Growth In The USA: Evidence From Renewable Energy' (2012) 16 Renewable and Sustainable Energy Reviews <https://www.sciencedirect.com/science/article/pii/S1364032112005011> accessed 5 August 2021.

[5] Phillimon M. Modisha and others, 'The Prospect Of Hydrogen Storage Using Liquid Organic Hydrogen Carriers' (2019) 33 Energy & Fuels <https://www.semanticscholar.org/paper/The-prospect-of-hydrogen-storage-using-liquid-Modisha-Ouma/86dd57ebadf08d36c563ee1ddfc53b6921466688> accessed 5 August 2021.

[6] Davide Astiaso Garcia, 'Analysis Of Non-Economic Barriers For The Deployment Of Hydrogen Technologies And Infrastructures In European Countries' (2017) 42 International Journal of Hydrogen Energy.

1. what are the current uses of hydrogen within different industrial sectors?;
2. how is hydrogen beneficial for environmental sustainability in the global energy transition era?;
3. what are the hydrogen regulation strategies, legal and regulatory frameworks within Germany during the global energy transition era?;
4. what are the hydrogen regulation strategies, legal and regulatory frameworks within the United States during the global energy transition era?; and
5. what type of hydrogen regulation system and relevant legislation is implemented within South Africa?

1.4 Research Aim and Objectives

The primary aim of the study is to generate a detailed level of understanding regarding the currently implemented hydrogen regulation policies, laws, and processes within significant countries in the world (namely, the US and Germany), in order to form a fundamental and strategic model which could potentially be implemented within South Africa. For this purpose, the research will obtain the following objectives, namely to:

- identify the current uses of hydrogen within different industrial sectors;
- determine the benefits of using hydrogen and its impact on environmental sustainability in the global energy transition era;
- assess the hydrogen regulation strategies, laws and policies implemented within Germany during the global energy transition era;
- assess the hydrogen regulation strategies, laws and policies implemented within the US during the global energy transition era;
- comparatively analyse the national hydrogen regulation strategies currently implemented in the US and Germany; and
- form a basis of a hydrogen regulation system and relevant legislations implementable within South Africa.

1.5 Research Methodology

The study will apply a legal deductive research method, incorporating a critical examination of the US' and Germany's national strategies for hydrogen usage and regulation individually. The qualitative and critical analysis of the available literature on the research area will be carried out through the researcher's observations and interpretations of the subject.

Subsequently, a comparative research method will be applied to present a critical analysis of the USA, Germany and South Africa's national strategies for hydrogen regulation.[7] Analysis of USA and German case studies is conducted pursuant to identifying lessons for South African adaptation and implementation. The overall goal is to generate a comparative understanding regarding the current trends and legislation for the application and regulation of hydrogen, its potential benefits, implications on the global environmental sustainability agenda[8] and the necessity for them to be enforced globally.[9]

1.6 Limitations of the Study

As a result of the deductive method employed in this study, it entails a specific limitation regarding the foundation for hydrogen regulation in South Africa. The limitation is primarily owing to the fact that only the theoretical evidence available on the national strategies and legislations for hydrogen regulation in the US and Germany could be interpreted and aligned within the South African national system. Furthermore, only two major countries have been selected for the study: the US and Germany. These countries differ in terms of the national structure, social systems and industrial operations within them.[10] As a result, while this will provide an ideal juxtaposition, it may also lead to disparities in the implementation of hydrogen regulation techniques that are unique to the demands of their national operations. Here, the question arises if these findings from the comparative analysis are transferable to South Africa. The importance of specific national context is therefore emphasised.

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[7] Prest, Woodyatt and Pettit (n 6).

[8] María Liliana Ávalos Rodríguez and others, 'The Legal Regulation Of The H2 As A Strategy For Public Policy In Mexico From The Consolidation Of The National Council Of The Hydrogen' (2019) 44 International Journal of Hydrogen Energy.

[9] Jingzheng Ren and others, 'Hydrogen Economy In China: Strengths–Weaknesses–Opportunities–Threats Analysis And Strategies Prioritization' (2015) 41 Renewable and Sustainable Energy Reviews.

[10] Prest, Woodyatt and Pettit (n 6).

2. The Hydrogen Phenomenon

2.1 What is Hydrogen?

Hydrogen is as an abundant, lightweight and simple element, abundant in the earth's structures of water and organic composites.[11]It is a combustible, odourless, colourless gas containing only one proton and electron.[12] The 8th of October is celebrated as "National Hydrogen and Fuel Cell Day" in the USA.[13] The Fuel Cell and Hydrogen Energy Association has acknowledged this day as it aims to raise awareness about hydrogen technologies and fuel cells and their future relevance in the global energy transition.[14] Hydrogen is considerably lighter and non-toxic compared to alternative split fuels since it dissipates rapidly when discharged. Thus, it serves as a safer fuel in the event of a fuel tank leakage.

The major safety risk with hydrogen energy is if a leak goes unnoticed and builds up in a restricted space, it may then ignite and potentially trigger an explosion.[15] Hydrogen is thus one of a number of fuels that carries a degree of danger, and its safe use primarily focuses on avoiding situations where the three primary combustion variables such as ignition, oxidant, and fuel are present.[16] Several properties of hydrogen, such as a wide range of flammable concentrations in air (4% to 75%) and reduced ignition energy (just one-tenth of the energy required to ignite gasoline), would almost certainly necessitate additional engineering controls to ensure its safe use.[17]

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[11] Dolf Gielen and others, ‘The Role of Renewable Energy in the Global Energy Transformation’ (2019) 24 Energy Strategy Reviews 38; Editha Kötter and others, ‘The Future Electric Power System: Impact of Power-to-Gas by Interacting with Other Renewable Energy Components’ (2016) 5 Journal of Energy Storage 113.

[12] C Rivkin, R Burgess and W Buttner, 'Hydrogen Technologies Safety Guide' (*Nrel.gov*, 2015) <https://www.nrel.gov/docs/fy15osti/60948.pdf> accessed 3 August 2021.

[13] Eric L. Miller and others, 'U.S. Department Of Energy Hydrogen And Fuel Cells Program: Progress, Challenges And Future Directions' (2016) 1 MRS Advances.

[14] Furat Dawood, Martin Anda and G.M. Shafiullah, 'Hydrogen Production For Energy: An Overview' (2020) 45 International Journal of Hydrogen Energy.

[15] M. W. Melaina, O. Antonia, and M. Penev, 'Blending Hydrogen Into Natural Gas Pipeline Networks: A Review Of Key Issues' (*Nrel.gov*, 2013) <https://www.nrel.gov/docs/fy13osti/51995.pdf> accessed 10 August 2021.

[16] Furat Dawood, Martin Anda and G.M. Shafiullah, 'Hydrogen Production For Energy: An Overview' (2020) 45 International Journal of Hydrogen Energy.

[17] Firooz Tabkhi and others, ‘A Mathematical Framework for Modelling and Evaluating Natural Gas Pipeline Networks under Hydrogen Injection’ (2008) 33 International Journal of Hydrogen Energy 6222; Andrew L Dicks, D. A. J Rand and James Larminie, *Fuel Cell Systems Explained* (3rd edn, John Wiley & Sons Ltd 2018).

The hydrogen-based energy network comprises four interrelated and interdependent phases (otherwise referred to as corners). These four stages include hydrogen production, storage, safety, and utilisation, and a four-cornered model called Hydrogen Square (HydS) is depicted in Fig.1, below. The novel HydS model depicted illustrates considerable interdependence between these stages (e.g. safety and storage), a fact salient to hydrogen energy pathway choice.[18]

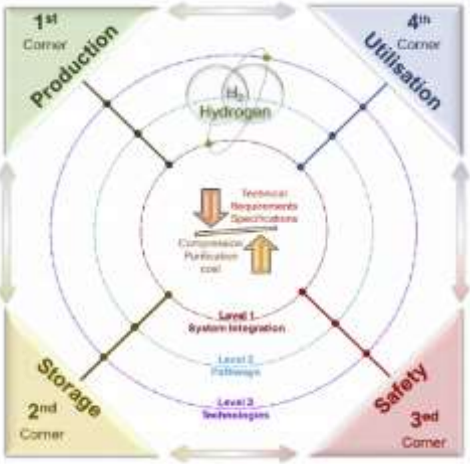

Figure 1. Hydrogen square four corner model[19]

Source: Dawood, Anda and Shafiullah

The critical factors in safe hydrogen usage comprise a thorough understanding of the properties of hydrogen and the integration of safety features inside hydrogen systems for safe hydrogen storage and transportation. As it is expressed as follows by the (USA) Department of Energy: “As more and more hydrogen demonstrations get underway, hydrogen’s safety record can grow and build confidence that hydrogen can be as safe as the fuels in widespread use today.”[20]

2.2 The Hydrogen Phenomenon

The application of hydrogen is gaining unprecedented political and commercial notoriety, with a growing number of regulations and initiatives being implemented worldwide. Thus,

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[18] Detlef Stolten and Bernd Emonts, *Fuel Cell Science And Engineering* (John Wiley & Sons 2012) ; Dicks and Rand (n 24); Kazunari Sasaki and others, *Hydrogen Energy Engineering* (Springer 2016).

[19] Dawood, Anda and Shafiullah (n 2).

[20] Dawood, Anda and Shafiullah (n 3).

ensuring a transition, relies upon the adoption of near zero-emission hydrogen to develop various technological instruments aimed at generating energy from low-carbon sources.[21]

Following the COVID-19 global crisis, hydrogen technologies are currently being viewed as a potential possibility for the growth of industrial economies.[22] Different colour schemes (notably grey, blue, green, turquoise, and yellow) have been used to codify hydrogen production technologies.[23] Grey hydrogen (sometimes termed dark or black hydrogen) is generated from fossil fuels such as coal or natural gas and emits carbon dioxide as a by-product.[24] Blue hydrogen is generated by combining carbon capture and storage (CCS) with grey hydrogen, eliminating greenhouse gas production. Green hydrogen is generated solely using either renewable electricity-generating electrolysers or through the application of bioenergy-based routes such as solid biomass gasification or bio-methane reforming.[25]

Pyrolysing fossil fuels generate turquoise hydrogen with solid carbon as a by-product. Finally, electrolysers delivering energy from nuclear power plants create yellow hydrogen.[26] Presently, green and blue hydrogen are the leading competitors, particularly in Europe. The main distinction is that, whereas blue hydrogen promotes natural gas extraction and the CCS sector, green hydrogen promotes renewable energy generation. Furthermore, green hydrogen, which is created by the electrolysis of water, necessitates large quantities of freshwater, therefore rendering it a challenge to produce in dry locations regions such as the Middle East and North Africa (MENA).[27]

Furthermore, different terms such as low-carbon hydrogen and clean hydrogen have been adopted to denote the aforementioned-colour groupings. These colour codified expressions may appear ambiguous; however, they can easily be described as low-carbon hydrogen,

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[21] Dolf Gielen, Emanuele Taibi and Raul Miranda, 'Hydrogen: A Renewable Energy Perspective' (*Irena.org*, 2021) <https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Hydrogen_2019.pdf> accessed 4 August 2021.

[22] Michel Noussan and others, 'The Role of Green and Blue Hydrogen in the Energy Transition—a Technological and Geopolitical Perspective' (2021) 13 Sustainability 298.

[23] Marcus Newborough and Graham Cooley, 'Developments in the Global Hydrogen Market: The Spectrum of Hydrogen Colours' (2020) 2020 Fuel Cells Bulletin 16; Alex Ivanenko, 'Council Post: A Look At The 'Colors' Of Hydrogen That Could Power Our Future' (*Forbes*, 2021). <https://www.forbes.com/sites/forbestechcouncil/2020/08/31/a-look-at-the-colors-of-hydrogen-that-could-power-our-future/?sh=65193fc05e91> accessed 6 August 2021.

[24] ibid.

[25] ibid.

[26] Noussan and others (n 2).

[27] Ibid.

inclusive of blue, yellow, green, and turquoise hydrogen. Nonetheless, because of the broad diversity of factors, it is crucial to remember that each colour is also connected to considerable carbon intensity variations. Certain hydrogen generation methods, such as those that combine CCS with bioenergy, do not discharge any carbon by-products. [28]

Alternative approaches exist; however, these alternatives remain in the research phase and have not been commercially implemented. As a further caveat, it is noted that new technologies are likely to comprise demerits as well as merits. Notably, when States adopt various remedies targeted towards a particular domain or sector (in this case, the energy sector, due regard needs to be taken for the respective variables concerned). These variables have implications on the State's national regulatory models, which relate to resource accessibility, energy security issues or giving priority to a specific industry.[29] Furthermore, given the critical need for energy infrastructure decarbonization in the foreseeable future, cross-border hydrogen trading may become a turning point in the world's geopolitical energy landscape.[30]

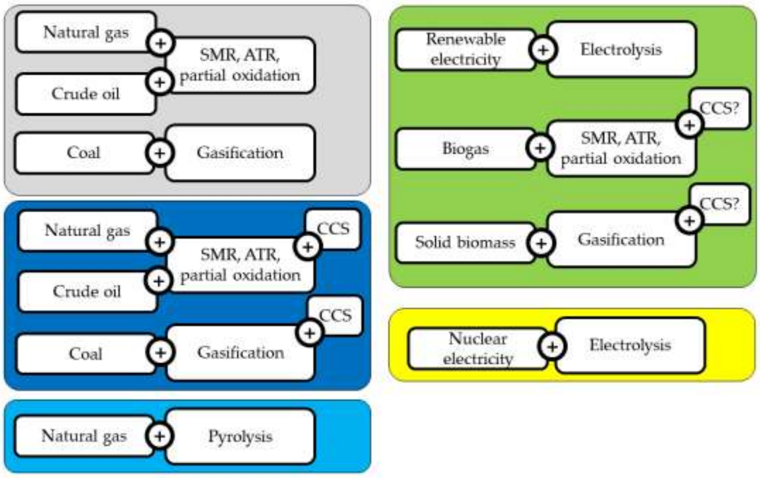

Figure 2. Colour coded various hydrogen generation pathways; CCS: carbon capture and sequestration, ATR: auto-thermal reforming, Steam Methane Reforming[31]

Source: Noussan and others

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[28] Noussan and others (n 3).

[29] Rossana Scita, Pier Paolo Raimondi and Michel Noussan, 'Green Hydrogen: The Holy Grail Of Decarbonisation? An Analysis Of The Technical And Geopolitical Implications Of The Future Hydrogen Economy' [2020] SSRN Electronic Journal.

[30] Thijs Van de Graaf and others, 'The New Oil? The Geopolitics and International Governance of Hydrogen' (2020) 70 Energy Research & Social Science 101667.

[31] Noussan and others (n 4).

Hydrogen's probable function is analogous to electricity since it is an energy vector rather than an energy source. Multiple energy sources and technology platforms can produce hydrogen and electricity. They may be utilised in a variety of operations since they are both adaptable.[32] The usage of hydrogen or electricity emits no carbon emissions, particulates, sulphur oxides, or ground-level ozone. When hydrogen is utilised in a fuel cell, it releases only water. However, if it is produced from fossil fuels such as coal, oil, or natural gas, hydrogen, and electricity it could result in a high carbon dioxide intensity output. Solely employing renewables or nuclear as the original energy source, or replacing fossil fuel facilities with Carbon Capture Usage and Storage (CCUS), may mitigate this limitation.[33]

Hydrogen differs from electricity in that it is a molecular energy carrier made up of molecules rather than just electrons. The above contrast is at the core of all the theories for why hydrogen may outperform electricity in some circumstances (and *vice versa*).[34] Hydrogen is appealing as, like oil, coal, biomass, and natural gas, it may be stored and delivered securely. Given its molecular structure, hydrogen may be mixed with several elements such as carbon and nitrogen to produce hydrogen-rich fuels that are simpler to manage and could be utilised as feedstock in various industries, consequently lowering emissions.[35]

If hydrogen is not accessible, a decarbonized energy system based on electricity will be heavily flow-based. The demand and supply of flow-based energy systems require close coordination over long haul distribution. They are, nevertheless, subject to supply interruptions.[36]As hydrogen holds more energy per unit of mass compared to natural gas or gasoline, it serves as a smart alternative for transportation fuel. On the other hand, hydrogen is the lightest element; thus, its energy density per unit volume is minimal.[37]This means that, in contrast to other fuels, considerable quantities of hydrogen would be delivered to meet the required energy demands. Larger pipes with a faster flow rate, for example, are capable of achieving the abovementioned. Although hydrogen may be compressed, liquefied, or

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[32] IEA, 'The Future Of Hydrogen: Seizing Today's Opportunities' (2019).<https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf> accessed 10 August 2021.

[33] ibid 32.

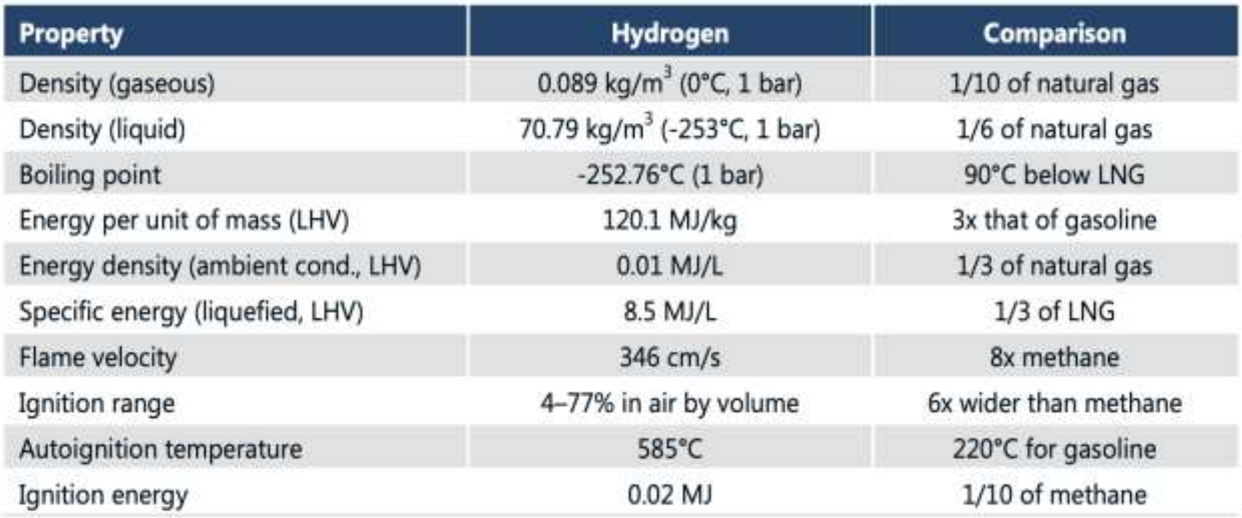
[34] ibid.

[35] ibid.

[36] ibid.

[37] ibid 34.

converted into higher-energy-density hydrogen-based fuels, this (and any future re-conversion) requires energy.[38]



Property	Hydrogen	Comparison
Density (gaseous)	0.089 kg/m^3 (0°C, 1 bar)	1/10 of natural gas
Density (liquid)	70.79 kg/m^3 (-253°C, 1 bar)	1/6 of natural gas
Boiling point	-252.76°C (1 bar)	90°C below LNG
Energy per unit of mass (LHV)	120.1 MJ/kg	3x that of gasoline
Energy density (ambient cond., LHV)	0.01 MJ/L	1/3 of natural gas
Specific energy (liquefied, LHV)	8.5 MJ/L	1/3 of LNG
Flame velocity	346 cm/s	8x methane
Ignition range	4–77% in air by volume	6x wider than methane
Autoignition temperature	585°C	220°C for gasoline
Ignition energy	0.02 MJ	1/10 of methane

Figure 3. Physical properties of hydrogen[39]

Source: International Energy Agency (IEA)

2.3 Hydrogen in the Global Energy Transition Era

The energy transition will not occur over the next several years. We are, on the contrary, already heavily involved in the process.[40] The deployment of renewable energy sources (RES) as fossil fuel substitutes is the preliminary measure towards creating a carbon-free future. Considering renewable energy is intermittent, the storage of energy features as a critical component of the transition process.[41] Hence, hydrogen has been identified as the most viable technology option due to the numerous innovations attached to it.[42] During recent years the potential application of hydrogen has gained wide attention and popularity. This is because the climate agenda is expanding, as well as concerns related to the carbon emission target set in the Paris Agreement. The year 2016, is inscribed as a watershed moment in history. It saw the coming together of more than one-hundred and seventy-six nations, in a concerted effort of collectively undertaking the mammoth task of reducing carbon emissions through the ratification of the Paris Agreement. The Paris Agreement's

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[38] ibid 35.

[39] ibid.

[40] Ankica Kovač, Matej Paranos and Doria Marciuš, 'Hydrogen In Energy Transition: A Review' (2021) 46 International Journal of Hydrogen Energy.

[41] ibid.

[42] ibid.

goal of lifting the lid on the reduction of carbon emissions is a laudable effort. However, it is laden with many uncertainties as to how States would go about reaching their respective mandates. Notably, even though a variety of hydrogen technologies have only been recently investigated, the technology is still in the early stages of development and is not yet ready for grand-scale deployment.[43]

According to a growing number of authoritative studies and launched programs, the exploitation of hydrogen's substantial carbon-neutral characteristics is foreseen in the next several decades. Hydrogen technology, which encompasses hydrogen generation, storage, delivery, and use, is gaining traction across many industries.[44] Technological advancements in a constantly evolving environment prompt public debates that determine if civilians would conform and welcome innovations or refute the abovementioned advances.[45]

At present, hydrogen is directly correlated with fuel cell electric vehicle (FCEVs), wherein only water vapour and warm air are discharged and do not emit hazardous exhaust emissions.[46]To date, hydrogen is widely utilised as a feedstock material in many industrial processes, including the manufacture of methanol, the production of ammonia and refineries. Globally, hydrogen consumption had grown from less than twenty megatons in 1975 to more than seventy megatons in 2018.[47] Conversely, the current demand for hydrogen has been met by fossil fuels, which cost between $1[48] and $3 per kilogramme and are therefore considered the most cost-effective option, which comprises coal, oil, and natural gas.[49]

Historically, there were three distinct periods of interest in hydrogen technologies' potential for industrial and scientific applications.[50] The first instance was in the 1970s, throughout most of the oil crisis when researchers looked for an alternative fuel to address future oil shortages as well as environmental concerns such as acid rain and environmental degradation.[51] However, all of these research operations and initiatives were futile owing

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[43] ibid.

[44] ibid.

[45] ibid.

[46] ibid.

[47] Michael Ball and Martin Wietschel, 'The Future of Hydrogen–Opportunities and Challenges (2009) 34 International Journal of Hydrogen Energy 615.

[48] All $ quoted are United States Dollars

[49] Noussan and others (n 5).

[50] Ball and Wietschel (n 2).

[51] ibid.

to the discovery of untapped oil reserves, which led to a reduction in lower oil prices and the concerns related to a lack of oil supply. The 1990s and the 2000s saw the rise of two other waves of enthusiasm; these two waves arose in response to the growing concerns surrounding climate change and oil peak forecasts.[52] The fall in oil prices and the financial and economic crises stifled the proliferation of hydrogen technology during the end of the 2000s.

By combining RES with electrolysis, which was previously discontinued due to excessive production costs in water electrolysis, green hydrogen may be utilised to produce electricity. Although the current cost of an electrolyzer and RES electricity production remains expensive when compared to fossil-based alternatives. Given the projected cost of production, electrolyzer and RES electricity generation might be a feasible alternative in the coming decade. Figure 4, below, shows the projected variation in blue and green hydrogen generation cost premised on Bloomberg New Energy Finance data.[53] The International Renewable Energy Agency (IRENA) predicted the cost of hydrogen to be 0.95 $/kg until 2050, and 1.2 $/kg if it is derived from wind or solar energy.[54]

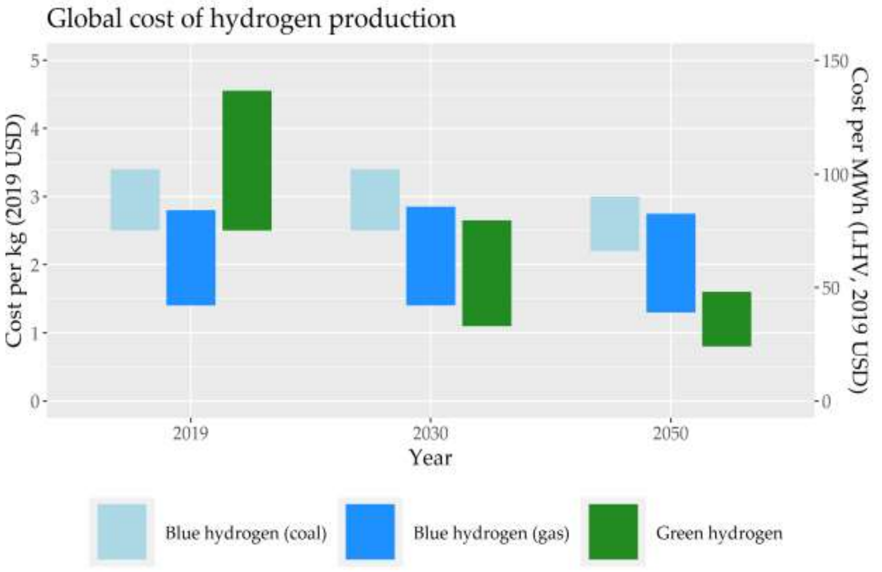

Figure 4. Future estimation of hydrogen cost by different pathways[55]

Source: Noussan and others

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[52] ibid.

[53] NP Brandon and Zeynep Kurban, 'Clean Energy and the Hydrogen Economy' (2017) 375 Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 20160400. Noussan and others (n2).

[54] Irena (n 2).

[55] Noussan and others (n 2).

Furthermore, alternative methods and the pathways for blue and green hydrogen generation across certain locations or states must be considered. Although nuclear electricity produced from hydrogen is rarely discussed in European plans, it appears as a feasible option in some parts of the world, notably both Russia[56] and China.[57] Other methods, such as biomass gasification or steam methane reforming (SMR)-based biogas feedstock, could potentially generate renewable hydrogen, but scaling up these methods may be comparatively more arduous.

2.4 The Need for Hydrogen Legislation

The energy system is transitioning to technological innovations that seek to lower greenhouse gas (GHG) emissions to address the climate change threat. Many countries have regarded hydrogen as a viable fuel source in various industries such as energy, transportation, and industrial application in recent years. This recognition has been captured in numerous international and local plans and models. Germany, fellow national Member States of the European Union (EU), Japan, and Australia are amongst those nations that have created hydrogen strategies and action plans.[58] Presently, there is a lot of momentum across the whole world to design and implement hydrogen strategies. The hydrogen economy's long-term viability depends on several variables, including the advancement of current technology and the reliable supply of hydrogen to consumers. The usage of hydrogen is not the only goal; the current energy infrastructure must also be replaced with low-carbon alternatives.

As a result, future hydrogen strategies and their deployment in conjunction with alternative options are critical.[59] Notwithstanding, due to the numerous processes involved in the supply chain to end-users, hydrogen production requires a robust supply chain. While the cost of production is a significant concern, hydrogen storage and distribution also present a substantial challenge in terms of potential energy losses which could be incurred. The aforementioned necessitates the development of robust legal frameworks as well as secure infrastructure. It is also worth noting that the establishment of coherent and unambiguous regulatory frameworks is one of the two critical factors for the adoption of the hydrogen

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[56] S.Z. Zhiznin, V.M. Timokhov and A.L. Gusev, 'Economic Aspects of Nuclear and Hydrogen Energy in the World and Russia' (2020) 45 International Journal of Hydrogen Energy 31353.

[57] Zhang Ping and others, 'Progress of Nuclear Hydrogen Production through the Iodine–Sulfur Process in China' (2018) 81 Renewable and Sustainable Energy Reviews 1802.

[58] Scita and others (n 2) 6.

[59] ibid.

economy.[60] Regulatory frameworks and strategies in different countries are frequently influenced by political and socioeconomic priority areas and barriers they encounter, along with accessible resources and infrastructure. Whether a government decides to adopt a different policy option or not, its indicators will be more effective if various countries degrees of aim, scheduling, and international reach are coordinated.[61]

2.5 The Production of Hydrogen

Hydrogen is capable of being produced from petroleum-based fuels and biomass, water electrolysis or a combination of the two.[62] Presently, natural gas is considered the essential source for the generation of hydrogen globally. It accounts for roughly three-quarters of the yearly international production of hydrogen, which is approximately 70 million tonnes (MT).[63] Around 6% of the world's natural gas is consumed in this way. Owing to coal's supremacy in China, gas is preceded by coal, with oil and electricity accounting for a minor portion of the total. [64] Various technical and economic aspects influence the cost of producing hydrogen from natural gas, with gas pricing and capital expenditures considered the two most critical. Costs for fuel are the most expensive feature of the production.[65] They make up roughly 45% to 75% of total expenditures. Lower gas prices in various countries such as the Middle East, Russia, and North America have led to some of the most cost-effective hydrogen. Production. [66]Increased gas import prices affect gas importers such as Japan, Korea, China, and India, resulting in increased expenditure for hydrogen production.[67]

2.5.1 Hydrogen Produced from Natural Gas

Although ATR is also used, SMR has been the most commonly used process for sizable hydrogen generation using natural gas. [68]Natural gas is used as both a fuel and a feedstock in SMR (together with water). The process usually burns 30-40% of it to power the process,

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[60] ibid.
[61] IEA, 'The Future Of Hydrogen: Seizing Today’s Opportunities' (2019).<https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf> accessed 10 August 2021.
[62] IEA (n 2) 38.
[63] ibid.
[64] ibid.
[65] ibid.
[66] ibid.
[67] ibid.
[68] IEA (n 8) 39.

resulting in a “diluted” CO2 stream, while the remaining volume is split into hydrogen and more concentrated “process”.[69] SMR is likely to operate as the primary technology for sizable hydrogen generation. It is an appealing alternative for producers due to its attractive and promising economics and the availability of many SMR units that are presently in use.[70]

2.5.2 Hydrogen Production Costs Derived from Natural Gas

A myriad of technical and economic variables impact the cost of producing hydrogen from natural gas; however, the two that hold the most prominence are gas pricing and capital expenditure (CAPEX).[71] Across all geographies, fuel prices are the most significant expense, accounting for approximately 45% to 75% of the total costs of production (Figure 5, below).[72] Reduced gas costs in the Middle East, Russia, and North America result in several of the lowest hydrogen production costs in the world.[73] Increased gas import prices affect gas importers such as Japan, Korea, China, and India, resulting in increased hydrogen production expenditure.[74]

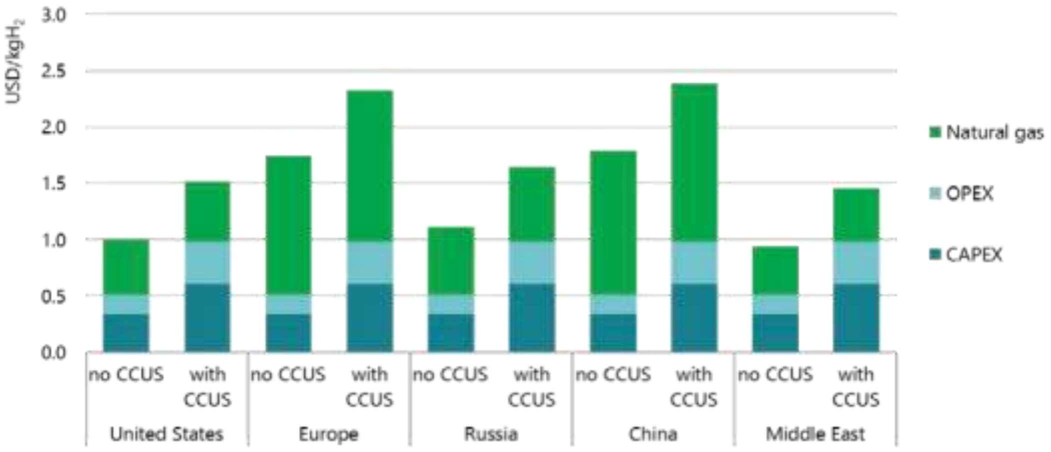

Figure 5. Hydrogen production costs derived from natural gas in different regions, 2018[75]

Source: IEA 2019. All rights reserved.

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[69] ibid.
[70] ibid.
[71] ibid 42.
[72] ibid.
[73] ibid.
[74] ibid.
[75] ibid.

2.5.3 Blending

Many studies are exploring the possibility of injecting hydrogen into existing gas networks because the worldwide natural gas network boasts significant transport and storage facilities (>100 Gigawatt hours (GWh)).[76] A further notable advantage of blending hydrogen with natural gas is a reduction in GHG emissions, particularly if the result is green hydrogen. A practical method to increase the output of renewable energy systems such as solar parks by blending hydrogen into the natural gas pipeline.[77] Along the same lines as the previous theme, releasing pure hydrogen is considered as a technique of extracting hydrogen from a natural gas mixture at the point of consumption.[78] The existing pipeline infrastructure presents a lower investment risk compared to the construction of new ones.

Therefore, repurposing infrastructure would ensure that costs are kept down, which is especially important at this early stage of the energy transition. Additional costs to consider include system network upgrades, risk assessments, safety protocols, hydrogen purification, mixing, and extraction.[79] Blending as a means of delivering hydrogen to end-users is highly dependent on natural gas and pipeline properties and ought to be extensively examined on a case-by-case basis. An additional factor to consider is the quantity of hydrogen added to natural gas, since this may influence safety. [80]The establishment of a new hydrogen value chain is dependent on a number of factors, such as ensuring the successful construction and integration of all components linked to the infrastructure of the hydrogen network.

These components comprise generation, transmission, transportation, storage and production.[81]The preceding would require financing from a broad spectrum of market players, which might be challenging to obtain. However, by blending hydrogen in the existing natural gas infrastructure, considerable capital expenditures associated with the construction of novel transmission and distribution facilities would be averted.[82] Moreover, low-level blending would reduce CO_2 emissions; however, it would drive up the natural gas supply price to end-users.[83] If measures are undertaken to clarify current national legislation

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[76] IEA, 'The Future Of Hydrogen: Seizing Today’s Opportunities' (2019).<https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf> accessed 10 August 2021.

[77] ibid.

[78] ibid.

[79] ibid.

[80] ibid.

[81] IEA (n 8) 70.

[82] ibid.

[83] ibid.

on the injection of hydrogen in natural gas pipelines and the consolidation of regulations across borders, blending would be much easier to execute.

2.6 Hydrogen Infrastructure

The layout and development of hydrogen supply infrastructure in different countries are influenced by various variables such as the availability of feedstock, regulatory frameworks, and population size, which ought to be examined on a country-by-country level.[84] The large-scale manufacturing of fuel cell electric automobiles and the emergence of improved infrastructural systems have all contributed towards a considerable increase in hydrogen-related transportation in recent years.[85]

Commonly in the transportation industry, hydrogen-focused infrastructure includes many of the crucial features and facilities required to meet the hydrogen fuel demand of FCEVs.[86] Hydrogen infrastructure concerning Hydrogen Refuelling Stations (HRSs) denotes a value chain which comprises of the production, storage, distribution and supply of hydrogen to end-users (in this instance, it relates to the owners of automobiles). [87] The HRS is an integral feature of the hydrogen transportation infrastructure. The nature of hydrogen production technology utilised and the geographic area where the fuel is produced, either on-site or generated and transported from the main production plant, may be used to categorise the station structure.[88]

- **Hydrogen Generated Off-site**

The very first version of HRSs includes stations, whereby hydrogen is supplied by road freight or dedicated pipelines from a centralised production facility. “Heavy-duty trucks transport hydrogen via road, where it is kept as a compressed gas (GH2) in tube trailers at pressures of more than 180 bar, or as liquid (LH2) in specialised tanks at cryogenic temperatures of -253 °C over long hauls.”[89] Notwithstanding, due to the sheer volume of energy required to liquefy hydrogen, this form of H2 distribution is substantially more

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[84] M Ball and M Wietschel, 'The Future Of Hydrogen – Opportunities And Challenges☆' (2009) 34 International Journal of Hydrogen Energy.
[85] D. Apostolou and G. Xydis, 'A Literature Review On Hydrogen Refuelling Stations And Infrastructure. Current Status And Future Prospects' (2019) 113 Renewable and Sustainable Energy Reviews.
[86] ibid 2.
[87] ibid.
[88] ibid.
[89] ibid 4.

expensive than that of gaseous H2 distribution and hence is not yet commonly utilised for supplying hydrogen refuelling stations.[90]

- **Hydrogen Generated On-site**

In relation to the operating phases, the second version of HRSs is comparable to the first; however, the hydrogen required to refuel the FCEVs is produced on-site.[91] Steam methane reforming (SMR) and water electrolysis are the two most commonly utilised methods for on-site hydrogen generation. In comparison to off-site HRSs, on-site stations have technical capacity restrictions that are contingent on the H2 generators' production volume, which generally varies from 100 kg/day to 1000 kg/day.[92] Existing on-site HRSs, on the other hand, do not have daily H2 production capacities exceeding 400 kg, as the most frequent applications produce less than 100 kgH2/day.[93]

- **Contrasting features between the two HRSs**

The hydrogen source utilised to provide the fuel throughout refuelling operations determines the fundamental distinctions between the two primary modes of HRSs.[94] In terms of the HRSs hydrogen storage infrastructure, off-site stations are practical, and the infrastructure is more focused on compression-refuelling operations, which is distinct from the relevant infrastructure utilised for the uptake of the hydrogen provided.[95] Against this backdrop, it is noteworthy to cite that the capacity of off-site HRSs might differ and it is scaled in accordance with the demand, which is subject to the storage infrastructure available.[96]In comparison to off-site stations, on-site hydrogen production refuelling stations integrate the technology required for the production and management of the H2 gas ahead of its primary storage.[97] The primary apparatus utilised for off-site HRS consists of a hydrogen generator (either a methane steam reformer or a water electrolysis unit) and a purification system to enhance the purity of hydrogen fuel to acceptable standards (i.e. fuel index more than 99.97%) under International Organization for Standardization (ISO) requirements.[98]

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[90] ibid.

[91] ibid.

[92] ibid.

[93] ibid 5.

[94] D. Apostolou and G. Xydis (n 10) 5.

[95] ibid.

[96] ibid.

[97] ibid.

[98] ibid.

3. Germany's Hydrogen Landscape

3.1 Germany Heeding the Clarion Call

Germany is considered one of the most advanced countries in the world when it comes to the development of hydrogen and fuel cell technology. In 2006, it joined hands with various key actors and established a coalition to create an innovation program named the National Innovation Program Hydrogen and Fuel Cell Technology. This National Innovation Program was aimed at accelerating the development of hydrogen and fuel cell technology. The National Innovation Program is categorised by a three-pronged approach, which seeks to (1) elevate Germany's position as the leading hydrogen technology centre, (2) accelerating market development for hydrogen, and (3) bolstering the hydrogen sector in Germany.[99]

3.2 The Evolution of Hydrogen in Germany

Christian Friedrich Schönbein, a German-Swiss scientist, disclosed electricity generation through a reaction between oxygen and hydrogen in 1839.[100] A year later, Werner von Siemens created a device in the form of a dynamo that transposed a rotary whirling action derived from the vapour of water into electrical power.[101] Further, conducting extensive studies on electrical power generation acquired from simplified processes such as fuel cells utilising hydrogen and oxygen for power generation. In 1875, the aforesaid fuel cell innovations brought upon a prediction made by French scientist, Jules Verne that hydrogen derived from water would substitute coal as a preferred energy source for the future.[102] It is worth citing that electricity production derived from hydrogen has been the subject of various research efforts over a centennial period.

The National Organization Hydrogen and Fuel Cell Technology, otherwise referred to as Nationale Organisation Wasserstoff- und Brennstoffzellentechnologies (NOW) in Germany,

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[99] Muhammad Asyraf Azni and Rasyikah Md Khalid, 'Hydrogen Fuel Cell Legal Framework In The United States, Germany, And South Korea—A Model For A Regulation In Malaysia' (2021) 13 Sustainability.

[100] Michael Fuhrmann, 'Germany's National Hydrogen Strategy - Serious Efforts To Realize A Decarbonized Society; Development Of Green Hydrogen Supply Infrastructure Is The Challenge -' (*Mitsui.com*, 2020) <https://www.mitsui.com/mgssi/en/report/detail/__icsFiles/afieldfile/2021/02/19/2012_fuhrmann_e.pdf> accessed 6 August 2021.

[101] ibid.

[102] ibid.

came into existence in 2008.[103] The FFG Ministry of Transport and Digital Infrastructure (Bundesministerium für Verkehr und digitale Infrastruktur (BMVI)) is regarded as NOW's only shareholder.[104] The premise of NOW's establishment is at the wheel of devising, arranging and implementing national strategies and schemes in both public and private branches of the country.[105] The aforementioned serve as blueprints aimed towards driving requisite upward mobility in the technology sector in an effort to bolster green transportability and reliable energy delivery mechanisms. The BMWi is a key component alongside the BMVI, the BMWi (*Bundesministerium für Wirtschaft und Energie*) is referred to as the Federal Ministry for Economic Affairs and Energy. It is premised on enhancing the political considerations applicable to Germany's economic and energy objectives.

As a point of distinction between the BMWi and the BMVI, it is necessary to note that the role of the BMWi is constrained to conducting applied research and development.[106] In contrast, the BMVI's area of concentration relates to piloting various projects and market development. The Federal Government of Germany (FGG) contributed released the Energy Concept in 2010, a dossier that encapsulates the state's modes of intervention to provide a low-cost, credible, and environmentally sound energy supply.[107] The electric transport plan in Germany purports to obtain financing to the tune of €6 million (m) by 2030.[108] FCEV is envisaged as the car of the future through the strict instrumentality of green hydrogen. The expressions 'electric mobility' or 'eMobility' has engendered the plates labelling of FCEV vehicles with an 'E' which falls within the purview of the Electric Mobility Act of 2015.[109]

The FGG has played a strong interventionist role towards granting the requisite support for electric mobility and deploying strategies that would garner public support towards the adoption of hydrogen technologies. To realise the above, the FGG a sum of €5 billion (bn) and a diverse range of regulatory regimes.[110] Through the National Innovation Program, the BMWi and BMVI have funded over 750 research and development programs. These Research and Development (R&D) programmes were equivalent to the sum of approximately €710m cumulatively from 2006 up to 2016.[111] It has been reported that the

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[103] Azni and Khalid (n 2) 5.
[104] ibid.
[105] ibid.
[106] ibid.
[107] ibid.
[108] ibid.
[109] ibid.
[110] ibid.
[111] ibid.

grantees made investments of €690m and the receipt of €20m of the aforesaid Program. The National Innovation Program was established to support innovative technologies related to hydrogen production, transportation, and heat and power applications.[112] As a result of the program, Germany climbed to the top as the third leading jurisdiction to finance Hydrogen Fuel Cell development, following Japan and the USA.[113]

3.3 Germany's Commitment to the Paris Agreement

In 2015, a collective of nations were signatories to the Paris Agreement, which was premised on limiting global temperature increases to less than 2°C. In view of the foregoing, great impetus for the adoption of hydrogen as a low-carbon energy source has garnered considerable attention over the preceding years. The rise of awareness about the EU's long-term vision for a Clean Planet has increased. In 2018, the Commission launched their long-range policy document titled "A Clean Planet for All", which sets out Europe's decarbonising agenda to be achieved by 2050.[114] Furthermore, the EU's decarbonising plan is accompanied by the European Green Deal published in 2019.[115] It seeks to drive the buoyancy of the EU's socio-economic landscape and focuses on achieving this through various initiatives such as the construction of hydrogen networks in smart infrastructure.[116] Germany is at the helm of the expansion of hydrogen in Europe. The country's transport sector is at the head of its greenhouse gas emissions, estimated at approximately 20% (see figure 1 above).

In curtailing the rise of carbon emissions, the state put the National Innovation Programme Hydrogen and Fuel Cell Technology (NIP) (NIP I: 2007-2016, NIP II: 2017-2026) into effect from 2006.[117] In remedying its greenhouse gas emissions, the FGG contributed €1.65bn towards R&D and marketing hydrogen technology up to 2019.[118] However, despite this support, the greenhouse gas emissions from the country's transport segments continue to increase.[119] By the same token, in 2016, Germany furnished its Climate Action Plan (CAP),

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[112] ibid.
[113] ibid.
[114] Michael Fuhrmann, 'Germany's National Hydrogen Strategy - Serious Efforts To Realize A Decarbonized Society; Development Of Green Hydrogen Supply Infrastructure Is The Challenge -' (*Mitsui.com*, 2020)
[115] ibid 2.
[116] ibid.
[117] ibid.
[118] ibid.
[119] ibid.

which outlines ambitious goals in an effort to minimize the discharge of carbon emissions.[120] A weighty goal of 80-95% to be achieved by 2050 has been set. Further, incorporating a more significant portion of energy generated from the renewable resources has also been prioritised in the CAP.[121] However, the FGG has stressed that due to the intermittent nature of renewable energy due to varying climate and environmental factors, the storage capability of renewable energy requires enhancement.[122]

Note: Sector classification is based on the German Climate Protection Act (KSG)
Source: Prepared by Mitsui & Co. Global Strategic Studies Institute, based on data from the German Environment Agency (March 9, 2020)

Figure 6. German Greenhouse Gas Emissions[123]

Source: Mitsui & Co. Global Strategic Studies Institute, based on data from the German Environment Agency (March 9, 2020).

3.4 Existing Legal Frameworks in Germany

In Germany, the government has endorsed the development of the hydrogen economy by creating a national policy denoted as the Energy Concept. Notwithstanding, the Energy Concept constitutes solely a policy that holds no legal validity compared to existing legislation.[124] The emergence of the Energy Concept serves as a roadmap for Germany's energy security. This policy ensures that the State undertakes measures that give

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[120] ibid.
[121] ibid.
[122] ibid.
[123] ibid.
[124] Muhammad Asyraf Azni and Rasyikah Md Khalid, 'Hydrogen Fuel Cell Legal Framework In The United States, Germany, And South Korea—A Model For A Regulation In Malaysia' (2021) 13 Sustainability.

precedence to achieving its respective energy security objectives and sets out environmental protection measures. In Section 3.2, the policy recognizes FCEVs as the preferred vehicles of the future.[125] However, this is contingent on hydrogen generated from renewable forms of energy.[126] Additionally, adopting the *Electric Mobility Act of 2015* and the provision of subsidies allocated to FCEV acquisitions signifies Germany's endorsement of its Hydrogen sector.[127]

Through this law, the government is encouraged to provide various means of support to encourage the development of electric vehicles. This is further supported by establishment of policies and regulations that aim to promote the Hydrogen Fuel Cell sector. Through the aforementioned legislation, it is indicative of Germany's steps toward reducing GHG emissions. Conversely, it has been cited that private entities within Germany are more inclined to participate in developing the Hydrogel Fuel Cell field.[128] This is evidenced by the creation of various programs such as the National Innovation Program, which is aimed at promoting the Hydrogen industry.[129] Through the National Innovation Program, Germany became the third-largest funding contributor towards HFC technology worldwide.[130]

3.4.1 Germany's National Hydrogen Strategy

Germany is the leading proponent in Europe for heeding the clarion call for hydrogen deployment. In June 2020, Germany's government proclaimed its National Hydrogen Strategy, which is fundamental to its decarbonization efforts. It underscores the entirety of the value chain insofar as it concerns technologies linked to the generation, storage, network structures, etcetera.[131] The strategy is designed to foster radical changes in the country's socio-economic status. This policy intervention has enabled the state to furnish €9bn towards the advent of green hydrogen. The strategy is accompanied by various elements that are compatible with the cardinal tenet of ensuring the security of supply, accessibility and the preservation of environmentally sound measures.[132] The preceding is sought to be achieved by integrating smart climate action and innovative supply and demand

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[125] ibid 8.
[126] ibid.
[127] ibid.
[128] ibid.
[129] ibid.
[130] ibid.
[131] ibid 3.
[132] Ankica Kovač, Matej Paranos and Doria Marciuš, 'Hydrogen In Energy Transition: A Review' (2021) 46 International Journal of Hydrogen Energy.

management strategies. As a result of the aforementioned, it is indicative that the strategy aims to achieve a balanced energy transition that is both economical and environmentally sound.[133]

The aims and objectives of Germany's national strategy highlight the incorporation of hydrogen in its socio-economic fabric. Thus, the capacity of the production of hydrogen is recognized as a major economic driver. Thus, against the backdrop of its energy transition scheme, the strategy's primary aim is to employ hydrogen as a green energy storage component[134]and utilise it as a fuel for the transport sector and convert it into an eminent feedstock element for respective branches of the industrial sector.[135] A sum of €12.36bn by 2026 was pledged by the Federal German Government, in addition to €9bn, that would be deducted from its coronavirus economic stimulus package and generated towards its hydrogen promotion budget. This approach was adopted prior to the announcement of Germany's National Hydrogen Strategy.[136]

There are thirty-eight measures within this strategy, grouped as per the following taxonomy: "(1) Production of hydrogen: four measures, (2) Utilization of hydrogen (transportation: nine measures, industry: four measures; buildings and heat utilization: two measures), (3) Hydrogen supply infrastructure: three measures, (4) Promotion of education and R&D: seven measures, (5) Hydrogen diffusion in the EU: four measures, (6) Global market development and coordination: five measures."[137]

Germany envisages a low-carbon future accompanied by effective policies that would not impede the state's economic status but rather strives to propel the country's progress and fiscal expansion.[138] It can be inferred from the aforementioned aims included in the strategy that hydrocarbons presently employed would be substituted by renewable energy sources.[139] Notably, this mainly relates to gas and liquid energy resources, which Germany relies on for its continued energy supply.[140]Given the foregoing, hydrogen is a vital component of the energy transition and is expected to play a leading role in meeting the

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[133] ibid.

[134] ibid.

[135] ibid.

[136] Furhmann (n 16) 3.

[137] ibid.

[138] ibid.

[139] 'The Promise Of Hydrogen: An International Guide' (2021) <https://cms.law/en/int/expert-guides/cms-expert-guide-to-hydrogen> accessed 11 August 2021.

[140] ibid.

Energy Transition goals. The Hydrogen strategy comprises two stages of implementation in achieving the aforesaid outcomes. During the first stage, which is to be carried out through to 2023, the Government has sought thirty-eight arrangements that take into account, *inter alia*, the production of hydrogen, transport, industrial branches, etcetera.[141]

The Federal Government has planned to formulate a set of measures to promote hydrogen production, transport, and industrial branches the first stage.[142] Additionally, making attempts to explore the possibilities of establishing alliances within the European Union.[143]

The second stage aims to set the national market in equilibrium, consequently forging exemplary hydrogen development scales in Europe that would shape the German Hydrogen industry's internationalisation.[144] It is worth citing that, in order to promote the development of hydrogen, various systems and infrastructures must be put in place. These include the requisite delivery and distribution networks. Additionally, surveys linked to pipeline systems designed to handle the flow of freight traffic are also needed to be included in the study to present varying remedies.[145]

The following components underpin Germany's strategy: In 2030, Germany's Federal Government has estimated that the country will need up to 110TWh of hydrogen.[146]To meet this demand, Germany intends to build up to 5GW of new generation capacity through offshore and onshore energy plants.[147] This figure assumes that total green hydrogen production is equivalent to 14TWh and that 20TWh of renewable electricity is required.[148] A supplementary 5GW of capacity is to be considered for addition between 2035 and 2040.[149] Through the imposition of carbon dioxide pricing levies placed on hydrocarbons employed by the transport and heating industries, the clampdown of hydrocarbons indicates the government's endorsement for the production of green hydrogen. Moreover, the lowering of the EEA surcharge would be in accordance with the aforesaid endorsement.[150]

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[141] Kovač and others (n 2).
[142] Kovač and others (n 3).
[143] ibid.
[144] ibid.
[145] ibid.
[146] 'The Promise Of Hydrogen: An International Guide' (2021) <https://cms.law/en/int/expert-guides/cms-expert-guide-to-hydrogen> accessed 11 August 2021.
[147] ibid 77.
[148] ibid 77.
[149] ibid.
[150] ibid.

The industrial sector is expected to be one of the main factors that accelerate the market's hydrogen uptake; this is due primarily to the industrial sector's growing importance.[151] With the increasing demand for carbon-neutral steel production in Germany by 2050, the need for hydrogen has become more significant as an excess of 80TWh of hydrogen would be required to actualise this lofty undertaking.[152] Contrary to the feasibility of electric heat generation being widely explored, there will be a long-lasting necessity for the utilisation of gas.[153] In the long-term, hydrogen and its downstream outputs are instrumental in decarbonising segments of the heat market in a myriad of modes.[154] It is noteworthy that between 2020-2024, an estimated €700m would be allocated towards financing fuel-cell heating schemes.[155]

3.4.2 Draft Amendment to Energy Industry Act of 1998

The 10th of February 2021 saw the passing of a draft amendment to the *Energy Industry Act of 1998* (otherwise referred as the *Energy Act*) by the German government. The *Act* sets outs provisions governing the regulation of hydrogen networks. The amendment is premised on the incremental construction of a hydrogen network within the country.[156]The new legislative provisions contained in the *Energy Act* serve as a stopgap measure, pending the development of suitable norms and standards by the EU. A pronouncement by the European Union Commission stated that relevant propositions regarding the regulation of hydrogen would be tabled at the close of 2021.[157]

Upon receipt and adoption of the aforesaid propositions, from 2025, the integration of provisions within German law is projected to commence. The draft outlines that hydrogen wholly denotes its status as an independent energy vector adjacent to gas; this is under the expression of "energy" contained in Section 3. no.14 of the *Energy Act.*[158] Notwithstanding, the applicability of the aforementioned provision is exclusive to unhomogenised hydrogen pipelines. As long as electrolysis produces hydrogen through its blending with the natural gas network, it constitutes gas and therefore remains governed under the legislation in

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[151] ibid.
[152] ibid.
[153] ibid.
[154] ibid
[155] ibid 78.
[156] ibid 78.
[157] ibid.
[158] ibid.

force.[159] The draft legislation amassed vehement dissent by various network operators due to the proposed differentiation of natural gas and hydrogen networks. Network operators denounced the disunion of the aforesaid as an impediment to the development of a swift and functional hydrogen framework.[160]

As a result of the differentiation of the networks, tariffs would be imposed on the networks separately. Moreover, in the case of hydrogen tariffication, excessive subsidies imposed during the inception period would increase aggregated network tariffs.[161]According to experts, the concept of preventing cross-subsidisation between the aforesaid networks is highly debatable. However, the imposition of separate tariffs was favoured by multiple network user associations. They stated that natural gas buyers ought not to be billed for the construction of hydrogen facilities as their use is limited to industrial operations.[162] The draft legislation provides an opaque provisional remedy, wherein network operators are expected to exercise discretion in selecting their preferred network. This appears to be improbable and denotes the formulation of the draft as a comprehensive regime that would be utilised over the mid-term period.[163] Detaching gas conduits from hydrogen is improbable, as hydrogen is likely to assume the function of natural gas in due course. Thus, it is imperative for gas networks to be incorporated into hydrogen infrastructure.[164] Modifications made to current gas pipelines are expected to constitute a critical element for the future of hydrogen infrastructure.[165] The incumbent network operators will administer the facilitation of gas pipeline modifications. Additionally, the draft has not elucidated adequate justifications regarding the disassociation of gas and hydrogen networks during the phase-out duration.[166]

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[159] 'The Promise Of Hydrogen: An International Guide' (2021) <https://cms.law/en/int/expert-guides/cms-expert-guide-to-hydrogen> accessed 11 August 2021.

[160] ibid.

[161] ibid.

[162] ibid.

[163] ibid.

[164] ibid.

[165] ibid 79.

[166] ibid 79.

4. The USA’s Hydrogen Energy Landscape

4.1 Shifting Energy Networks

Energy networks in the US are undergoing significant shifts, largely owing to the global energy transition. Processes impacted by the aforesaid changes include, but are not limited to *inter alia*, electricity generation, transport, etcetera. Corporations are bearing the brunt associated with the impending road to a decarbonised future which is further exacerbated by the conservation of natural resources, ageing infrastructure, the storage of energy, a changing legal environment and emerging consumer needs.[167] Hydrogen has been identified as a remedy to the aforementioned barriers. This is due to its status as an energy vector that functions in a plurality of industries and contains numerous advantages.[168]Furthermore, it provides capabilities of storing energy for extended durations and can undergo long-range environmental transportation.

For instance, in the case of FCEVs, irrespective of the vehicle’s duty, hydrogen does not emit gaseous emissions due to its ability to be produced with practically nil emitted carbons. The power of hydrogen in the US is believed to sustain the country’s energy hegemony and security of supply, provide employment opportunities, the substantial truncation of gaseous emissions and spurring the advancement of the economy.[169] Due to the advances made by countries such as Japan and Germany regarding their hydrogen acceleration plans, the USA is in a race against time in ensuring it follows suit.[170]

With respect to expediting the deployment of hydrogen in the country, the USA Department of Energy provided financing close to $100m to $280m annually during the preceding decade.[171] By way of illustration, it was recorded since 2017 that the government contributed $150m.[172] Comparatively, jurisdictions have made sizeable investments in the hydrogen

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[167] 'ROAD MAP TO A US HYDROGEN ECONOMY: Reducing Emissions And Driving Growth Across The Nation' (2020) <https://cafcp.org/sites/default/files/Road%2BMap%2Bto%2Ba%2BUS%2BHydrogen%2BEconomy%2BFull%2BReport.pdf> accessed 13 August 2021.

[168] ibid

[169] ibid.

[170] ibid.

[171] ibid.

[172] ibid.

sector. For instance, Germany has invested over $100m on annual basis to further hydrogen energy research and development for commercial end use.[173] Lastly, China serves as a relevant example, wherein funding above $17bn has been allocated up towards 2023.[174]

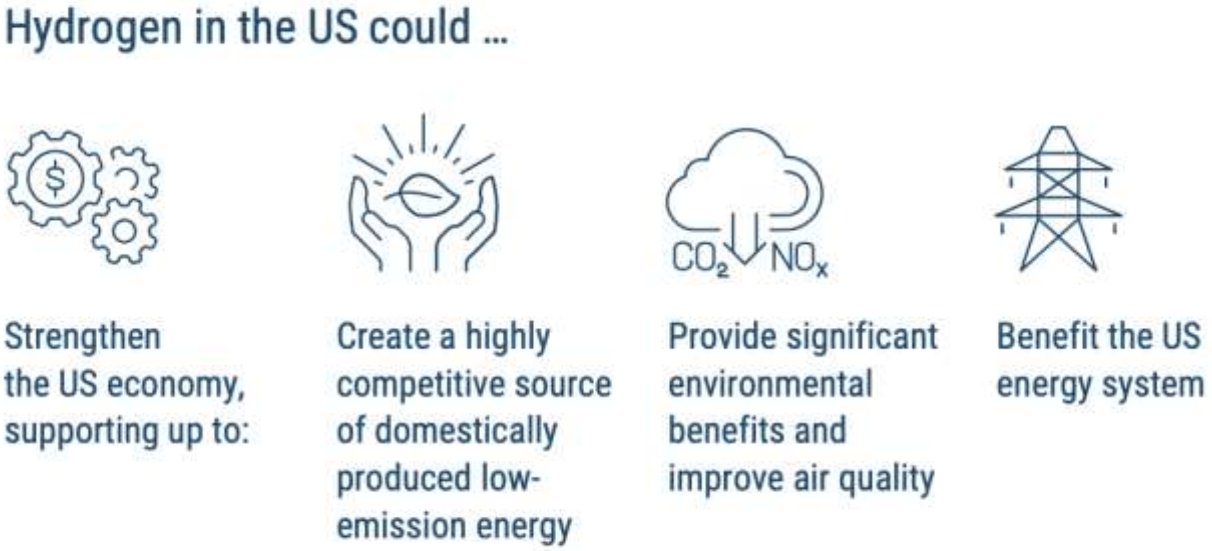

Figure 7. Potential benefits of hydrogen in the US in the ambitious scenario [175]

Source: Roadmap to a hydrogen economy

4.2 Current US Hydrogen Landscape

The US is among the key producers of both natural gas and oil globally. The role of hydrogen is that of a significant technological emergence, accompanied by its fiscal gain. Albeit, despite the potential profitability of low-carbon hydrogen and due to the varying political stances surrounding the development of low-carbon hydrogen, it is not yet clear whether the USA will continue with its fossil fuel-based energy transition.[176] Despite the preceding factors, hydrogen holds the ability to contribute substantially to the country's energy mix. Its capability is supported by its profitability, categorised by an income-earning potential of approximately $130-170bn annually.[177] In realising the link associated with the aforementioned fiscal projections, it is essential to refer to the annual income of the US' petroleum sector. The oil and gas sector managed to obtain an aggregate income of $181bn

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[173] ibid.
[174] ibid.
[175] ibid.
[176] 'The Promise Of Hydrogen: An International Guide' (2021) <https://cms.law/en/int/expert-guides/cms-expert-guide-to-hydrogen> accessed 11 August 2021. Pg 190.
[177] ibid.

in 2018.[178] For hydrogen to gain the earning potential associated with the petroleum industry, additional assistance towards further research and development and the formulation of adequate legal regulations are required. The USA is endowed with various economically priced renewable sources of energy required to produce green hydrogen.[179]

By way of illustration, renewable energy sources such as solar, wind, and hydropower can produce green hydrogen through electrolysis. Additionally, natural gas reforming which produces carbons that are captured and subsequently stored produces blue hydrogen. The aforementioned serve as examples of the US' diverse energy source potential.[180] With abundant natural resources, the US is adequately equipped to produce affordable, low-carbon hydrogen. However, due to the country's abundance of resources, it may choose to pursue other avenues of energy production excluding hydrogen.[181]

The development of hydrogen infrastructure in the USA is confronted with difficulties on account of the country's varying internal and state strategies. It is commonplace for states to set out individual state-specific strategies and work plans as instruments for the satisfactory execution of their hydrogen development benchmarks.[182] The West Coast has been an exemplary region in the US in terms of its expeditious modus operandi concerning hydrogen infrastructure development and its robust policies concerning the reduction of carbon emissions in the transport sector.[183] Predictions surrounding the scaling up of vehicles powered by hydrogen, mainly in California have been made.[184]

Various industry professionals have noted that aside from reducing greenhouse gas emissions, hydrogen alongside greener energy sources can augment or replace traditional power sources as a reliable power source for communities that experience frequent power interruptions due to seasonal weather conditions wildfires.[185]

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[178] ibid 190.
[179] Ibid.
[180] ibid.
[181] ibid.
[182] ibid.
[183] ibid.
[184] ibid.
[185] 'ROAD MAP To A US HYDROGEN ECONOMY: Reducing Emissions And Driving Growth Across The Nation' (2020) <https://cafcp.org/sites/default/files/Road%2BMap%2Bto%2Ba%2BUS%2BHydrogen%2BEconomy%2BFull%2BReport.pdf> accessed 13 August 2021.

Several states have expressed that their need to decarbonise the gas grid has prompted the application of hydrogen as a fuel. Whereby, through the process of blending hydrogen in gas grids, the production of low-cost hydrogen-based fuel in regions that are decarbonizing their gas grids would encourage the adoption of hydrogen as a feedstock.[186] However, other states have different priorities in relation to the usage of hydrogen. The foregoing statement particularly relates to hydrogen being undertaken as a panacea for concerns associated with electric grids, its capacity to enable the employment of green energy sources and its ability to prop up nuclear energy as a contending power source. [187] A large number of hydrogen ventures are primarily affiliated with the country's transport industry. It has been reported that the industrial industry emits 10% of the country's total greenhouse gas emissions as it is the primary energy user.[188]Currently, grey hydrogen is the most commonly utilised form of hydrogen in the industrial industry. As a result of the environmental impact of grey hydrogen, the US is looking to the future of a decarbonised industrial industry by virtue of adopting low-carbon hydrogen.[189]

4.3 The USA's Pole Position

The US is laden with ample and affordable power sources that have the wherewithal to generate near-zero carbon-hydrogen. As an illustration, substantial and low-carbon energy sources found within the US, such as wind, hydro energy and nuclear, are qualified to generate electrolytic hydrogen.[190] According to projections, in 2030, power consumption costs will be set at $20 per MWh.[191] Additionally, the substitution of aged conventional nuclear reactors by a fleet of modular nuclear reactors is expected to commence from the 2030s.[192] Modular nuclear reactors are expected to yield substantial hydrogen output at fixed rates, further accompanied by its increased capacity element and reducing greenhouse gas emissions.[193] Moreover, the US boasts a copious supply of affordable natural gas and carbon storage capacity, enabling hydrogen production through natural gas reforming with carbon capture and storage (CCS). Notably, gas reserves within the US are

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[186] ibid 3.

[187] ibid.

[188] 'The Promise Of Hydrogen: An International Guide' (2021) <https://cms.law/en/int/expert-guides/cms-expert-guide-to-hydrogen> accessed 11 August 2021. Pg 190.

[189] ibid 194.

[190] ibid.

[191] 'ROAD MAP To A US HYDROGEN ECONOMY: Reducing Emissions And Driving Growth Across The Nation' (2020)

[192] ibid.

[193] ibid.

likely to set their prices from a minimum value of \$2 to \$3 per MBtu.[194] The country offers a latent storage scope of approximately 3,000 metric gigatons of carbon dioxide of technically available storage capabilities; however, this is contingent on the public's approval for hydrogen technology deployment.[195]

The production of hydrogen from the various energy sources found within the USA holds prospects of augmenting the country's energy security and would reduce energy imports significantly. Due to the flexibility linked to hydrogen generation, customers are likely to benefit from low-cost energy derived from various power sources. This benefit would further encourage the expansion of the US economy. Four key stages of the roadmap have been outlined, and they are as follows: 2020 to 2022, 2023 to 2025, 2026 to 2030.[196] Contained within the various stages are high-priority targets, which speak to the mobilisation of hydrogen in different sectors. The requisite primary drivers are divided into (i) policy facilitators and (ii) hydrogen supply and end-use equipment facilitators.[197] Policy enablers are primarily required to generate the appropriate incentives to retain investments from the private sector and essentially seek to foster the hydrogen economy's growth.

4.4 Current Legal and Regulatory Instruments

In the USA, all states have their own distinct energy policies, including for hydrogen energy where extant. However, for the purposes of this study, the state of California serves as the primary example for this chapter. At the federal level, the *Energy Policy Act of 2005* (EPA) governs energy generation in the United States, notably renewable energy. *Title VIII of the EPA* (otherwise referred to as the Spark M. Matsunaga Hydrogen Act of 2005) seeks to: "enable and promote comprehensive development, demonstration, and commercialisation of hydrogen and fuel cell technology in partnership with industry; build a mature hydrogen economy that creates fuel diversity across the massive transportation sector in the US."[198] The EPA is further supplemented by the 2001 National Energy Policy and the *Energy Independence and Security Act of 2007* (EISA) which sets out the following: "Increased production of clean, renewable fuels; promotion of research on and deployment of

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[194] ibid 11.
[195] ibid.
[196] Ibid.
[197] ibid.
[198] Energy Policy Act of 2005; ibid.

greenhouse gas capture and storage options; and improved energy performance of the Federal Government.,"[199]

In the USA, overarching legislation governing the hydrogen economy presently does not exist. However, several state entities such as the Federal Energy Regulatory Commission (FERC), the Environmental Protection Agency (EPA) and Pipeline and Hazardous Materials Safety Administration (PHMSA) have the powers to drive an imprint on the development of hydrogen and the requisite infrastructure.[200] Notwithstanding the absence of a legal framework governing the hydrogen industry, the State acknowledges the prospects of hydrogen within the energy sector.

The country's federal government has endorsed research and development efforts towards hydrogen as a potential fuel source. This is inclusive of funding earmarked for the implementation of schemes within the various state entities. The $100m commitment by the USA Department of Energy is a major step toward advancing hydrogen and fuel cell technologies.[201]It has been indicated that one consortium will focus on developing low-cost electrolysers through electrical power, which would essentially convert water into oxygen and hydrogen.[202] In contrast, the other will focus on developing fuel cells for vehicles, focusing on long-haul trucks.[203]

4.4.1 US Hydrogen Program Plan

The DOE launched its revised Hydrogen Program Plan in November 2020. The DOE demonstrates its ministry-specific undertaking to create an enabling environment for the hydrogen as a dual source and sets out a "strategic framework for the Department's hydrogen [R&D] activities."[204]The creation of the Hydrogen Program Plan is indicative of the country's commitment in pursuing its hydrogen economy. However, an essential facet of growing the hydrogen economy, is contingent on the inclusion of hydrogen in the country's overarching legal framework. The federal government is armed with authority to institute and facilitate the aforementioned, ensuring that hydrogen forms an integral

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[199] Energy Independence and Security Act of 2007; Ibid.

[200] Damien Lyster and others, 'Federal Hydrogen Regulation In The United States: Where We Are And Where We Might Be Going | JD Supra' (*JD Supra*, 2020)

[201] ibid.

[202] ibid.

[203] ibid.

[204] ibid.

component of the USA energy infrastructure. However, many of the regulations concerning hydrogen are already being addressed by other federal agencies.[205] This includes FERC, EPA and other USA Department of Energy agencies. By way of illustration, many environmental regulations on hydrogen are focused on its scientific properties, which includes its flammable and explosive nature. Notably, the properties of hydrogen are some of the factors that determine its classification as a hazardous substance.[206]

The aforesaid regulations are contained in the Code of Federal Regulations (CFR). Despite the existence of the CFR, it does not provide a coherent framework for hydrogen. Regulations subsumed in the CFR focus on the scientific properties of hydrogen, and the hazards attached and do not address hydrogen in its entirety.[207] At present, federal-state entities such as the Occupational Safety and Health Administration, EPA, and PHMSA set out the majority of comprehensive regulations regarding hydrogen. Although hydrogen regulations do not form part of the agency's main functions, the agencies mentioned above, will serve as key actors as hydrogen becomes more widely used and technology evolves.

4.5 The Future of the US's Hydrogen Regulation

Following the above, although many federal agencies have roles in the nascent hydrogen economy, most have not fully integrated hydrogen into their regulations. Therefore, prompt action towards the formation of hydrogen regulatory frameworks into federal regulation must be put into effect. Several federal agencies have regulations that could affect the use or commercialization of hydrogen. These regulations could serve as the basis for developing a regulatory regime for the hydrogen industry. If hydrogen becomes mainstream, then agencies will have to consider whether they should focus more on this emerging fuel under existing legal frameworks or foster new regimes mainly focused on hydrogen.[208]

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[205] ibid.
[206] ibid.
[207] ibid.
[208] ibid.

5. South Africa’s Hydrogen Energy Landscape

5.1 The Status of Hydrogen in South Africa

In 2007, the South African government launched a 15-year hydrogen research initiative. The Department of Science and Technology (DST) leads this project, which is being carried out through the Hydrogen South Africa (HySA) programme. HySA is charged with carrying out DST's research, development, and innovation (RDI) plan, first announced in September 2008 [1]. Aside from the HySA programme, various research agencies in South Africa are also involved in developing hydrogen-related technologies.[209] The hydrogen economy is an essential component of South Africa's future energy strategy.

Through the adoption of hydrogen energy, the country is capacitated to produce dependable, alternative energy sources, which are in contrast to hydrocarbons. Hydrogen is classified as an energy vector with many functions. As an energy vector, it can store and distribute energy. In tandem, by blending it with other fuel cell technologies, it generates electricity.[210] The rising popularity of fuel cell and hydrogen technologies has been attributed to South Africa’s plentiful platinum group metals. The vast reserves of platinum group metals (PGM) in South Africa are considered as one of the main catalysts that fuel cell and hydrogen technologies can rely on in the future.[211] PGMs are the primary catalytic minerals often utilised in fuel cells and commands a hefty price. These catalysts account in total for approximately a third of the total cost of a fuel cell at current technological levels (as of the time of writing, September 2021).[212]

To date, an estimated 90% of discovered concentrated platinum deposits are located in South Africa and Zimbabwe. The broad deployment of fuel cells would provide the countries with significant socio-economic advantages.With the abundance of platinum in South Africa, it is logical for the country to start producing fuel cell catalytic material and subsequently

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[209] 'Hydrogen Research Activities In South Africa: A Review' (*Giz.de*, 2016) <https://www.giz.de/en/downloads/giz2021_en_Report%20-%20Hydrogen%20Research%20Activities%20in%20SA%20for%20print.pdf> accessed 7 August 2021.

[210] ibid 17.

[211] ibid.

[212] Jonathan Metcalfe, Le Riche Burger and James Mackay, 'Unlocking South Africa’S Hydrogen Potential' (2020) <https://www.pwc.co.za/en/assets/pdf/unlocking-south-africas-hydrogen-potential.pdf> accessed 12 August 2021.

export the finished product to world markets.[213] South Africa's climate is suitable for solar and wind energy generation, which are the most commonly used renewable energy sources for green hydrogen generation.

High solar and wind availability variables enhance hydrogen electrolyser utilisation efficiency, lowering the high costs associated with green hydrogen generation and thus making investments more appealing to investors (Polity, 2019).[214] South Africa offers an ideal climate for wind and solar energy generation and storage utilising hydrogen as an instrument (figure 8, below).[215]

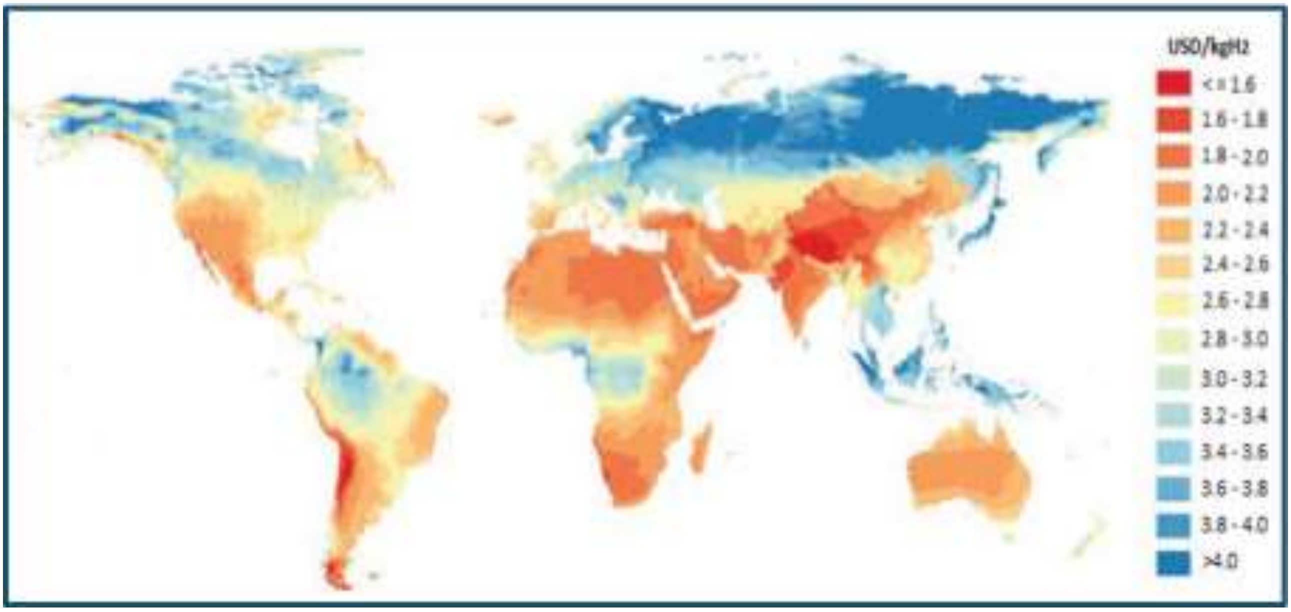

Figure 8. Hydrogen production costs by geography (with wind and solar generation) [216]

Source: (IEA, 2019)

2.4 Current Legal and Regulatory Frameworks

The present guiding document for energy policy in South Africa is the *White Paper on Energy Policy*, released in 1998.[217] Additionally, South Africa's *Energy Regulation Act (ERA) 4 of 2006* and the rules on new generation capacity established under the *ERA* necessitates

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[213] ibid.

[214] Polity. South Africa well placed to supply competitive hydrogen – _CSIR. 2019. <https://www.polity.org.za/article/south-africa-well-placed-to-supply-competitive-clean-hydrogen-csir-2019-08-28> accessed 4 September 2021.

[215] ibid.

[216] Ibid.

[217] White Paper on Energy Policy of the Republic of South Africa 1998

a long-term electricity sector plan at the national level, referred to as the Integrated Resource Plan (IRP).[218] One of the measures the IRP sets out to do is to create long-term planning simulations to satisfy power demand forecasts while considering state policy aspirations to achieve a diversified generation energy mix.[219]South Africa's National Hydrogen and Fuel Cell Technologies Research, Development and Innovation strategy [1], otherwise referred to as Hydrogen South Africa (HySA)[220]. The HySA is a policy that encourages and drives research in the hydrogen and fuel life cycle in South Africa. The goal is to equip South Africa to maximise domestic advantages from producing premium quality commodities (such as PGMs) to emerging hydrogen world markets.[221] Economic gains, such as the creation of employment opportunities, revenue, and emerging markets; the development of local content; and an adequate standard of living for all South Africans should all be included in these local advantages.[222]

Hydrogen R&D in South Africa is mainly conducted by the Department of Science and Technology (DST). South Africa's National Flagship Programme is a government-funded initiative aimed at stimulating intellectual property, human resources capital, and procedures for the rapid emergence and commercialization of fuel cell and hydrogen technologies.[223]

The HySA was adopted as part of the DST's multiple strategies and processes. These include the Department of Mining's (DMR) minerals beneficiation strategy, various innovation strategies, as well as the Department of Energy's (DoE) Integrated Resource Plan (IRP).[224] The framework is designed to bolster relevant expertise and innovation in tandem throughout all aspects of the hydrogen and fuel cell lifecycle. The diagram below indicates that the HySA programme is divided into three R&D Centers of Competence (CoC), see figure 9 below.[225]

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[218] Energy Regulation Act (ERA) 4 of 2006
[219] Integrated Resource Plan (IRP) 2019
[220] 'Hydrogen Research Activities In South Africa: A Review' (*Giz.de*, 2016) <https://www.giz.de/en/downloads/giz2021_en_Report%20-%20Hydrogen%20Research%20Activities%20in%20SA%20for%20print.pdf> accessed 7 August 2021.
[221] ibid.
[222] ibid 17.
[223] ibid.
[224] ibid.
[225] ibid.

Figure 9. HySA Centers of Competence (CoC).[226]

Source: Department of Science and Technology

Hydrogen South Africa is divided into three of the following competency centres:[227]

- HySA Catalysis, focuses on catalysts and membrane electrodeassemblies development (e.g., platinum group metals based catalysts as components of fuel cells) for fuel cells and hydrogen production;
- HySA Infrastructure, focuses on technologies for hydrogen generation/production, storage and distribution; codes and standards; and
- HySA Systems, focuses on hydrogen systems development and technology validation.

The three COCs have a common goal: to engender innovation and create the human capital needed to support and accelerate the commercialisation of fuel cell technologies.[228]Each CoC enlisted high-level foreign experts to provide specialist expertise and appropriate application systems and guarantee that the project and its outputs continue to maintain market relevance domestically and internationally.[229]Moreover, to fulfil the HySA strategy targets, the three HySA CoCs are responsible for implementing the strategy and disseminating the research findings and recommendations pertaining to hydrogen. They collaborate with various actors such as institutions of higher learning in the hydrogen R&D sector and industry.[230] The South African government has pledged Rand (R) 100m per year for the technology testing and validation phase, particularly relating to membrane electrode

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[226] ibid.
[227] ibid 18.
[228] ibid.
[229] ibid 18.
[230] ibid

assemblies derived from HySA CoCs. The DST has been funding hydrogen and energy-related R&D projects worth R130m to R150m annually over several years.[231] Through the creation of the HySA programme, the DST has managed to provide funding related to various hydrogen and energy R&D projects. The DST has allocated R75m to R80m annually to the HySA programme, which is shared among the several COCs based on project-specific needs and uses.[232]

HySA's main goals are as follows:[233]

"1. Wealth creation through value-added manufacturing (this will be achieved by developing the PGM catalysis value chain in South Africa). 2. Development of a hydrogen infrastructure (this will be achieved by developing local cost-competitive hydrogen production solutions based on renewable resources). 3. Equity and inclusion in sharing the economic benefit derived from South Africa's mineral endowment (this will be achieved through creating a viable industry for the finished products that will create jobs and boost economic growth for the benefit of all South Africans). 4. Stimulation of PGM (in particular platinum) demand."

5.3 South Africa and International Hydrogen Projects

South Africa is making progress in the hydrogen arena, with its first state-driven hydrogen roadmap (the HySA) and its participation in the Green Hydrogen Atlas-Africa (otherwise known as H2Atlas-Africa) project, which is promoting the country's hydrogen promise to the rest of the world.[234] The H2ATLAS-AFRICA project is the first phase of a collaboration between the FGG Ministry of Education and Research (BMBF) and African partners in the Sub-Saharan Africa region to continue investigating the prospects for green hydrogen generation deriving from renewable energy sources located with the sub-regions.[235] For purposes of clarity, SADC and ECOWAS are regional institutions in Africa which seek to bolster the economic growth and participation of States on the African continent. SADC comprises of countries in the Africa's Southern region and ECOWAS comprises of countries in West-Africa.

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[231] ibid.

[232] ibid 19.

[233] ibid 18.

[234] H2atlas-Africa' (*H2atlas.de*, 2020) <https://www.h2atlas.de/en/about> accessed 11 August 2021.

[235] H2atlas-Africa' (*H2atlas.de*, 2020) <https://www.h2atlas.de/en/about> accessed 11 August 2021.

It has been asserted by (Bhagwat S, Olczak M) that a local hydrogen economy can be created alongside current infrastructure channels such as roads, train lines, and shipping ports for usage inside and between regions.[236] Morocco, Egypt, Nigeria-Ghana, Ethiopia-Djibouti, Tanzania-Rwanda-Kenya, and South Africa are among the six probable landing zones determined through mapping by the African Hydrogen Partnership (see Figure 9 below).[237]

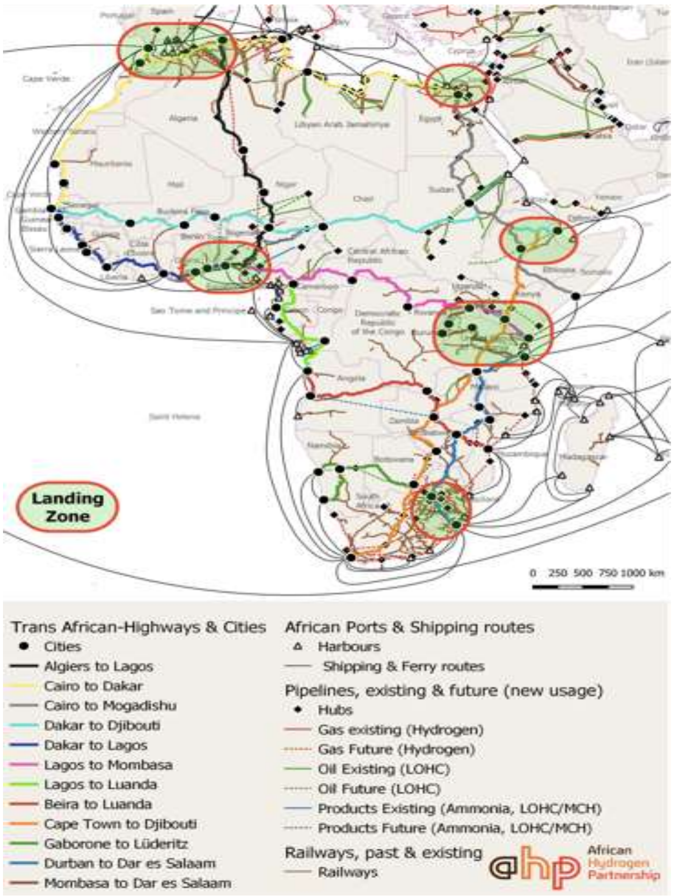

***Figure 10. Hydrogen infrastructure development potential in Africa*[238]**

Source: African Hydrogen Partnership

The aforesaid authors further state that the number of employment opportunities for every 1GWe of added power-to-x (P2X) capacity might vary from 300 to 700. Water is one of the

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[236] Florence School of Regulation (FSR), 'Green Hydrogen: Bridging The Energy Transition In Africa And Europe' (European University Institute 2020) <https://africa-eu-energy-partnership.org/wp-content/uploads/2020/10/AEEP_Green-Hydrogen_Bridging-the-Energy-Transition-in-Africa-and-Europe_Final_For-Publication.pdf> accessed 11 August 2021.

[237] ibid 22.

[238] African Hydrogen Partnership; ibid 22

most critical resources for hydrogen generation; one cubic metre of hydrogen may be produced from one litre of water. A map of Africa's water resources is shown in Figure 11.[239] With the potential to produce green hydrogen in Africa, European energy companies such as Enertrag are looking for opportunities to develop green hydrogen. They have identified South Africa as one of their potential locations, as the country has extensive experience in producing synthetic fuels at a rate of around 8bn litres per year. Enertrag's South African affiliate intends to implement twenty green hydrogen-powered fuel cell buses as its precursor into the country's hydrogen economy.[240]

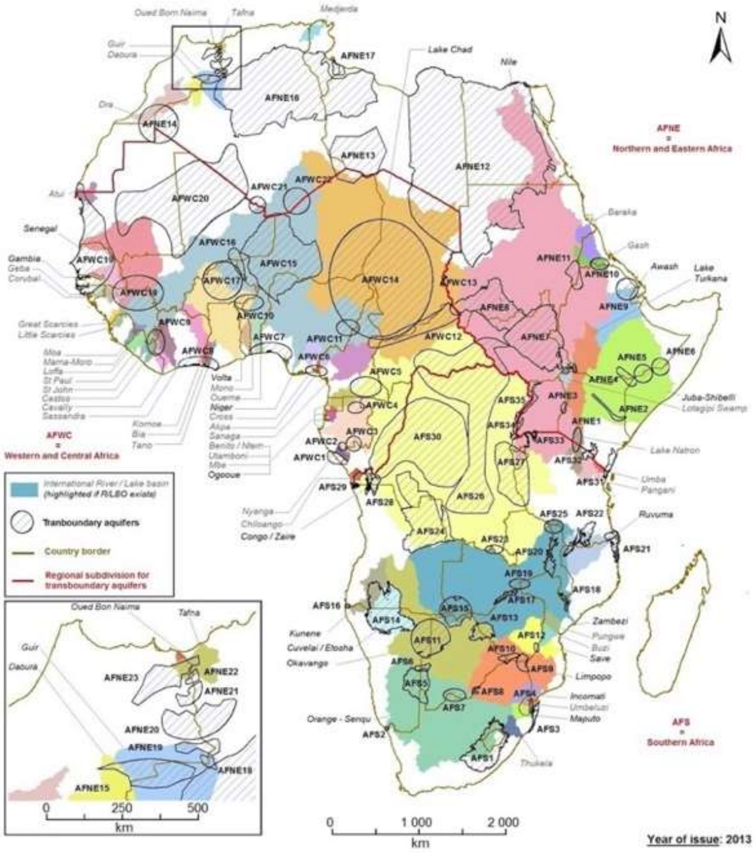

Figure 11. Water aquifers map of Africa[241]

Source: CGIAR Water, Land and Ecosystems

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[239] ibid.

[240] Jonathan Metcalfe, Le Riche Burger and James Mackay, 'Unlocking South Africa'S Hydrogen Potential' (2020) <https://www.pwc.co.za/en/assets/pdf/unlocking-south-africas-hydrogen-potential.pdf> accessed 12 August 2021.

[241] CGIAR Water, Land and Ecosystems; ibid 22.

6. Challenges

6.1 Introduction

Despite the significant surge and the variables favouring a substantial increase in hydrogen investment, many challenges remain. While the factors that have strengthened its resurgence are now well-aligned, more work needs to be done to address the various issues that have remained unresolved. It is critical to remove these roadblocks in order to create a favourable climate for the hydrogen economy and other clean energy technologies to grow. Germany, the US and South Africa are all subjected to the following three fundamental challenges:

6.1.1. Lack of Coherent Regulatory Frameworks and Technological Ambiguities

Legislative frameworks have not always kept pace with development aspirations, reflecting the fledgling but rapidly growing variety of hydrogen technologies. As a result, the lack of a defined legal and regulatory framework for hydrogen has emerged as a prominent problem for the jurisdictions selected (Germany, US and South Africa) in this paper.[242] In an effort to regulate hydrogen, a number of countries have expressed that they will draw guidelines for hydrogen from their existing gas regulations. Notwithstanding, such frameworks are often not suitable given hydrogen's diverse characteristics and functions, market participants would stand to gain from establishing a specified legislative framework that would support the implementation of a hydrogen economy.[243] Significant financial investments in hydrogen technology and infrastructure are far less appealing in the absence of unambiguous and preferably enforceable, long-term agreements that would promote reliable energy systems.[244] Contextually, although many countries have started implementing policies that support low-carbon hydrogen projects, many others have not undertaken the task. This reflects a deficit in broad, long-term energy policies, coupled with technological uncertainties rampant in some developing countries.[245] The absence of governmental support and political will would not yield competitive rates for implementing low-carbon hydrogen.

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[242] 'The Promise Of Hydrogen: An International Guide' (2021) <https://cms.law/en/int/expert-guides/cms-expert-guide-to-hydrogen> accessed 11 August 2021.
[243] ibid.
[244] IEA, 'The Future Of Hydrogen: Seizing Today's Opportunities' (2019).<https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf> accessed 10 August 2021.
[245] ibid.

Moreover, the comparable prices of generating hydrogen from various energy sources in various areas and how it could perform in the years ahead remain unknown.

As a result, efforts to forecast comparable future hydrogen pricing relating to *inter alia* solid-state batteries, pumped-storage hydropower becomes increasingly challenging.[246] The frequency of cost reduction is a critical issue of contention for fuel cells. On the other hand, experts differ about the relationship between the size of the fuel cell market, pricing, and improving their efficiency.[247] Multiple dialogues surrounding the methods to be employed in transporting hydrogen across long haul distances have been expressed as a technological ambiguity and thus presents a barrier to the development of the hydrogen economy.[248]

6.1.2 Value Chain Ambiguities Coupled with Infrastructure Requirements

There are several barriers in constructing infrastructure suitable for the transportation of hydrogen and its distribution to dozens of potential local fuelling points. Due to the lower energy density of hydrogen, transportation, storage, and distribution to the end-consumer are associated with higher costs for each gasoline gallon equivalent (per-GGE) to alternative fuel.[249]The initial expenses of constructing a new hydrogen pipeline network are substantial, and the characteristics of hydrogen provide particular problems to pipeline polymers and the compressor structure.[250]Hydrogen value chains can take many distinct routes. Demand for low-carbon hydrogen can come from a variety of sectors, and there are many permutations of hydrogen supply and handling that could meet it. Furthermore, the best cost-competitive result will vary between geographies and applications.[251] If hydrogen is to be generated and delivered to end-users who are ready to consume it, investments and regulations must be coordinated in size and time for each potential value chain.

Establishing a rapport across the value chain to coordinate investments is a time-consuming process, and as a result, it would be prudent to put in place updated contractual arrangements.[252] Governments and businesses must devise and implement creative

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[246] ibid.
[247] ibid.
[248] ibid.
[249] IEA, 'The Future Of Hydrogen: Seizing Today's Opportunities' (2019).<https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf> accessed 10 August 2021.
[250] ibid.
[251] ibid 28
[252] ibid.

multidisciplinary methods in certain circumstances to fully harness hydrogen's adaptability. Since hydrogen well be generated domestically, it derives advantages from economies of scale in transportation and storage.[253] The present rate of infrastructure development is a stumbling block to the broad application of FCEVs within the context of hydrogen adoption for motorised vehicles, which would require a refuelling station system. In many jurisdictions and areas around the world, governments' capacity to undertake substantial (and essential) infrastructure expenditures are constrained; public-private investment models can assist, but they would also contribute to the complexities associated with the hydrogen economy.[254]

6.1.3 Codes and Standards

The present condition of existing rules and standards throughout the world today inhibits hydrogen consumption. Numerous laws are ambiguous or have not been established with consideration to updated hydrogen applications, thus preventing the maximum gains of hydrogen from being realised.[255] These laws address a number of complex, but critical issues; including the manner and location of how pressurised or liquefied hydrogen would be, how it would be managed, locations where motorised hydrogen vehicles would be employed and the fiscal regimes required to oversee energy modification.[256]

If hydrogen reaches a critical mass, regulatory frameworks must be amended to include the hydrogen economy. Regulations for hydrogen car refuelling, gas composition for trade across borders, safety precautions, licensing, the evaluation of materials and their implications on the environment are only a few of the essential standards that have yet to be agreed upon.[257]Since analogous hydrogen molecules could be generated and blended from sources with significantly varying CO2 concentrations, the problem of life-cycle effects presents a unique difficulty in the case of hydrogen. In comparison to electricity generation, hydrogen and hydrogen-based fuels may be combined with fossil fuels in unrecognisable combinations that consumers are unable to distinguish.[258]

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[253] ibid.

[254] ibid.

[255] ibid 28.

[256] ibid.

[257] ibid.

[258] ibid.

6.2 Recommendations

Governments serve as a critical component in shaping an enabling environment for a long-term investment policy framework, further forging joint resolutions regarding national hydrogen potential, driving market potential, eliminating regulatory impediments, steering research, and participating globally. However, flowing from the above, they are faced with critical challenges. In alleviating the existing challenges, several recommendations for governments to consider are as follows:

6.2.1 The Creation of a Uniform International Framework for Hydrogen

The lack of a uniform regulatory framework now curtails hydrogen uptake, limiting the benefits attached to its use.[259] As a result, governments around the world must establish a standardised production criteria and encourage international partnerships to develop uniform methods and benchmarks for determining the ecological effect of the projected life-cycle of hydrogen value chains.[260] The above-mentioned measure is necessary to ensure that the international hydrogen economy remains viable and efficient.

6.2.2 Encourage International Cooperation with Foreign States

Green hydrogen may be generated at relatively low costs in jurisdictions with ample renewable energy sources and minimal project development expenditures. Given their economic advantage, these economies can trade green hydrogen to countries where local hydrogen generation is not viable.[261]

6.2.3 Recommendations Particularly Concerning South Africa

In South Africa, the current legal and regulatory environment for hydrogen has not been sufficient to encourage widespread use. The DOE's HySA programme, for instance, has taken a leading role in the development and application of hydrogen in the country. However, this endeavour fails to satisfy a well-drafted strategy aimed at facilitating the acceleration and deployment of hydrogen.

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[259] Rossana Scita, Pier Paolo Raimondi and Michel Noussan, 'Green Hydrogen: The Holy Grail Of Decarbonisation? An Analysis Of The Technical And Geopolitical Implications Of The Future Hydrogen Economy' [2020] SSRN Electronic Journal.
[260] ibid.
[261] ibid.

Financial limitations on future R&D projects, inconsistent policies, a lack of legislative frameworks, and the absence of long-term planning contribute to an unfavourable regulatory environment for hydrogen investments.[262]Thus, the government must increase its funding obligations towards further R&D efforts to realise the hydrogen economy's full potential.

In fostering an enabling environment for local and foreign investors who are willing to participate in the use of the hydrogen, a more robust regulatory framework outlining policies and measures to stimulate the implementation of hydrogen energy systems is required. In order to effectively leverage the benefits associated with hydrogen, South Africa needs to develop a comprehensive hydrogen strategy and a coherent pathway plan to achieving its ambitions.[263] The pathway plan mentioned above should not only address South Africa's national strategy; instead, it should consider the country's international approach to hydrogen. [264] This is particularly concerning how the country should facilitate and incorporate its investments to assist the global hydrogen economy to expand more swiftly. This strategic plan must include explicit deadlines for achieving decarbonisation commitments and investing in hydrogen, as well as a steadfast commitment to attaining those objectives.[265]

The absence of an allotted timeframe would result in a lack of confidence to invest by investors. The state must foster transparent collaboration between the public and private sectors.[266] Collaboration of initiatives and sector-coupling hydrogen innovations will yield the most significant financial benefit.[267] From a legislative viewpoint, a proper combination of incentive schemes and punitive measures is critical in establishing a hydrogen market.[268] For instance, current strengths and advancements made possible by efforts like DSI and

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[262] Conrado Augustus de Melo, Gilberto de Martino Jannuzzi and Sergio Valdir Bajay, 'Nonconventional Renewable Energy Governance In Brazil: Lessons To Learn From The German Experience' (2016) 61 Renewable and Sustainable Energy Reviews.

[263] Jonathan Metcalfe, Le Riche Burger and James Mackay, 'Unlocking South Africa'S Hydrogen Potential' (2020) <https://www.pwc.co.za/en/assets/pdf/unlocking-south-africas-hydrogen-potential.pdf> accessed 12 August 2021.

[264] ibid.

[265] ibid.

[266] ibid.

[267] ibid.

[268] Muhammed Patel, 'Green Hydrogen: A Potential Export Commodity In A New Global Marketplace' (Trade and Industry Policy Strategies (TIPS) 2020) <https://www.tips.org.za/research-archive/sustainable-growth/green-economy-2/item/4006-green-hydrogen-a-potential-export-commodity-in-a-new-global-marketplace> accessed 7 August 2021.

HySA can be expedited with the requisite regulatory frameworks.[269] Collaborations between Sasol and PetroSA on significant carbon-intensive operations are critical for present decarbonising methods and maximising the use of existing facilities.[270] Incentives for the procurement and utilisation of hydrogen systems should be built into regulatory mechanisms.[271] In addition to encouraging the establishment of arrangements that allow investors to mitigate their risk. The breadth of the drafting process for sophisticated legal and regulatory instruments should be widened. Tariff levies, the deployment of modern technologies and infrastructure, technical certainty, and carbon reduction are all essential elements to consider during the policy formulation process.[272]

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[269] ibid 27.

[270] ibid.

[271] Conrado Augustus de Melo, Gilberto de Martino Jannuzzi and Sergio Valdir Bajay, 'Nonconventional Renewable Energy Governance In Brazil: Lessons To Learn From The German Experience' (2016) 61 Renewable and Sustainable Energy Reviews.

[272] ibid.

7. Conclusion

Several research findings throughout this study have demonstrated the influence of various policy incentives on the deployment and proliferation of the hydrogen economy undertaken by global markets such as the US and Germany. However, in emerging economies like South Africa, the efficacy and capacity of the relevant variables in specific countries necessitate primary quantitative and qualitative data collection. [273] The aforementioned data would give an exposition of socio-economic dynamics synonymous with emerging economies.

Allowing the State to build suitable regulatory frameworks suited to the political and socio-economic landscape of the country. It is worth noting that any country's ability to access world markets and expand its domestic trading prowess is inextricably tied to its political resolve to exploit modern technological innovations such as hydrogen. Additionally, the vigour, speed, and stability of a country's frameworks for innovation determines the uptake, integration, mastery, modification, and implementation of hydrogen advancements.[274]

In a growing economy like South Africa’s, the need for adequate governance and best practices to regulate hydrogen emanates from the notion that it is susceptible to various impediments and market volatility that may stifle its progression. By way of illustration, this study notes that the absence of robust legislative frameworks in South Africa impedes its hydrogen agenda. Well-drafted regulatory standards lay the groundwork for reducing immediate and long-term risks associated with novel technologies, resulting in the widespread adoption of the hydrogen economy. According to the World Energy Council's World Energy Issue Monitor, the Grand Energy Transition is an intricate and prominent concern throughout the many nations of the world which demands scalable solutions such as hydrogen.[275] Hydrogen is an adaptable energy carrier that may be used to remedy a variety of issues. These include, *inter alia*, supporting the colossal consolidation of

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[273] Neda Fereidounizadeh, 'Hydrogen Fuel In Sweden, A Comparative Study Of Five Countries' (Masters Thesis, Linnaeus University 2021).

[274] Vitor Ferreira and Radhika Perrot, 'Understanding The Emergence New Industries Building A Hydrogen Fuel Cell Industry In South Africa', *35th DRUID Celebration Conference*(2013) <https://www.semanticscholar.org/paper/Understanding-the-Emergence-New-Industries-Building-Ferreira-Perrot/7a348df3761b4405a3235f8c2285dfd11534a742> accessed 8 August 2021.

[275] World Energy Council, 'Hydrogen An Enabler Of The Grand Transition' (World Energy Council 2018) <https://www.worldenergy.org/assets/downloads/1Hydrogen-an-enabler-of-the-Grand-Transition_FEL_WEC_2018_Final.pdf> accessed 11 August 2021.

renewable energy sources and reducing greenhouse gas emissions during energy production.

In an attempt to devise a comprehensive implementation structure and enable the Grand Transition to proceed in the backdrop of unfair practices from conventional carbon-related facilities, various industries and sectors of society must work together to put in place measures for the deployment of hydrogen and renewable energy sources. [276]South Africa's HySA initiatives prove to be commendable, in terms of the aims they intend to accomplish and the method in which they are to be implemented. Given its significant potential, further measures are required to build and leverage emerging competencies as a mechanism for South Africa to play a prominent role in the growing international hydrogen economy. It is thus important for the state to invest considerably in the creation and procurement of the requisite interdisciplinary expertise to enable the successful growth of the local hydrogen economy.

The accelerating proliferation of hydrogen envisaged in national strategies and accompanying policy declarations require substantial legislative reform. According to Zillman and Smith, *"when the existing law was not written with new technologies in mind, lawyers are initially forced to see whether they can interpret the existing laws to reach a result that endorses the new technology"*.[277] In view of the foregoing, Zillman and Smith further assert that *"the more effective solution is for the appropriate law-making body to rewrite the existing law with the new technology in mind."*[278] Three key distinctions emerge as a result of examining the national strategies of the countries concerned: (i) aims relating to hydrogen production and generation capacity, (ii) funding for research and development, as well as financial incentives to encourage the growth of the hydrogen economy, (iii) as well as the meaning of the term "clean" hydrogen.[279] Furthermore, in the USA and Germany, hydrogen has successfully progressed from a series of experiments to a lucrative market.

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[276] ibid.

[277] Prest, James and Woodyatt, Joshua and Pettit, Jordie, Comparing the Hydrogen Strategies of the EU, Germany, and Australia: Legal and Policy Issues (February 1, 2021). (2021) 19(2) Oil, Gas and Energy Law Intelligence, ANU College of Law Research Paper No. 21.21, Available at SSRN: https://ssrn.com/abstract=3875170; Donald N Zillman & Don C Smith "The brave new world of energy and natural resources development, (2019) 37(1) *J Energy & Nat Res* L 3-45, DOI: 10.1080/02646811.2019.1557394

[278] ibid.

[279] ibid.

The aforementioned countries progress has been bolstered in part by their political will to improve the general public's understanding and application of hydrogen as an alternative energy source. Their unprecedented progress is further aided by the adoption of adequately drafted regulations and policies to govern and incentivize the market participants and customers involved. The 2001 National Energy Policy and the *Energy Policy Act of 2005* in the USA, and the *Electric Mobility Act* and the Climate Action Plan 2050 in Germany illustrate their existing legal frameworks. South Africa is committed to reducing its carbon emissions and has undertaken substantial climate mitigation efforts through its position as a signatory to the Paris Agreement.

Moreover, South Africa has ardently worked towards diversifying its energy mix through the development of renewable energy sources. However, the South African government has not managed to impose carbon levies on various energy and industrial industries as a measure to reduce carbon emissions. Therefore, South Africa would meet its Paris Agreement benchmark to reduce carbon emissions by 45% by 2030 by establishing a robust and legal environment that encourages buyers and sellers to participate in the hydrogen industry. As in the USA and Germany, the South African government must commit to hydrogen development more rigorously. Flowing from the study's findings, it can be deduced that the geopolitical characteristics, institutional arrangements, and industrial processes of the countries examined for this study are all distinct. As a result, while this study has provided a significant comparative contrast, it has also highlighted the disparities in the execution of national hydrogen regulation strategies unique to their respective national landscape.

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Centre for Energy, Petroleum
and Mineral Law and Policy
University of Dundee

Centre for Energy, Petroleum and Mineral Law and Policy
University of Dundee
Nethergate
Dundee
DD1 4HN

e: dundee.ac.uk/cepmlp