A Research Proposal

On

TOWARDS CONTINUOUS NATURAL GAS USAGE – *A Study of the Technical Implications of Generating Hydrogen from Natural Gas and using it in the Future Green Energy Economy.*

By

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Chapter 1 - Introduction

A) Background of the Study

Global energy demand is projected to continuously rise until 2050 in line with the steady growth in the global population while energy generation from fossil fuel resources is on a steady decline as renewable and less carbon-intensive energy sources, such as hydrogen, are favoured over fossil fuels as the energy of the future[1]. The prospect of replacing natural gas with hydrogen in the race to net zero is also being largely considered amongst both local and international stakeholders in the energy industry[2–5]. This is not an unlikely outcome considering that the share of renewables in global power generation has witnessed a continuous increase over the last two decades; rising from 0 to 13% between 2001 and 2021[6]. So, if renewables were to replace fossil fuels in the aftermath of the energy transition, what will the world do with her 7,257 trillion cubic feet (tcf) of proven natural gas reserve[7]?

Fortunately, natural gas can still be indispensable in a world with hydrogen as the leading source of energy because hydrogen can be generated from natural gas. However, doing that releases a lot of CO_2 into the environment and opens plenty of other questions including the challenge of capturing, sequestering and valorising the greenhouse gas and the cost of building hydrogen infrastructures. This study will address some of those questions to promote continuous natural gas relevance in the future energy mix.

Specifically, the study will investigate some of the challenges associated with adopting existing natural gas infrastructure for hydrogen transportation and storage and assess the effect of geologic uncertainties on the underground storage of the greenhouse gases which accompany hydrogen production from natural gas through a combination of empirical studies, molecular modelling and reservoir simulations.

B) Research Problem

Natural gas usage in the future as a leading energy resource is contingent on two crucial conditions: (i) its ability to be used as the major source for hydrogen production and; (ii) our ability to repurpose existing natural gas infrastructure for hydrogen. To meet these conditions, some of the questions that must be addressed include (1) what infrastructure would we need and how much would it cost to construct hydrogen processing and transportation facilities?; (2) what modifications must be made to the current natural gas infrastructure to repurpose them for hydrogen transportation and combustion to reduce the expenses that would otherwise be incurred in constructing entirely new facilities for hydrogen?; (3) how do we meet consumers' energy needs without exceeding pipeline erosional velocity limits considering that a given amount of hydrogen only delivers one-third of an equivalent amount of energy as the same amount of natural gas, and hydrogen would need to be transported at three times the flow rate of natural gas to deliver an equivalent amount of energy as natural gas[2]?; (4) how would blends of hydrogen and natural gas burn if we were to solve the high-velocity problem by blending hydrogen with natural gas; (5) how do we minimise the effect of geologic uncertainties to perfect the geologic storage of CO_2 which is largely associated with hydrogen production from natural gas? Following a systematic and comprehensive literature review on this subject matter (a summary of which is presented in Chapter 2), this study will focus on answering the parts of these questions that are yet to be addressed by previous researchers.

C) Significance of the Study

This study will contribute to ensuring the continued relevance of natural gas as a leading energy source following the era of the energy transition by providing solutions to three major hindrances to the use of natural gas for the production and utilisation of hydrogen – a widely advocated future energy source: (i) The study will alleviate the cost of building new infrastructure for hydrogen storage and transportation by investigating and proffering solutions to the exceeding of pipeline erosional velocity limits and high embrittlement of steel pipelines that happen when adopting conventional natural gas pipelines for the storage and transportation of hydrogen and blends of hydrogen and natural gas; (ii) The study will also recommend structural modifications to existing gas pipelines to make them suitable for hydrogen storage and transportation; (iii) Finally, the study will also make the geologic storage of CO_2 (which is a by-product of hydrogen production from natural gas) more efficient by investigating and highlighting the effects of major uncertainties inherent in the use of depleted gas reservoirs and salt caverns for CO_2 storage. **This way, countries (like Nigeria) that generate a significant proportion of their national revenue from natural gas can continue to benefit from their fossil fuel resources without failing to meet their net zero emissions goals.**

D) Aim and Objectives of the Proposed Study

This study aims to investigate some technical implications of generating hydrogen from natural gas and adopting natural gas infrastructure for hydrogen transportation and storage; thereby, promoting continuous natural gas usage for energy generation in a future with net zero greenhouse gas emissions. To achieve this, the study objectives are to:

i. explore the effect of increased hydrogen gas velocity on the lifetime and integrity of conventional gas pipelines;
ii. explore the effect of increased internal pressure on the lifetime and integrity of conventional gas pipelines;
iii. recommend design modifications that should be made to conventional gas pipelines to repurpose them for hydrogen transportation and storage;
iv. evaluate the uncertainties associated with the modelling of underground sequestration of the enormous CO_2 that is generated when hydrogen is produced from natural gas.

E) Scope of the Work

The proposed research will involve a detailed literature review of current global practices and challenges related to producing hydrogen from natural gas and adopting existing natural gas infrastructure for hydrogen transportation and storage. This will be followed by a series of experiments, including laboratory studies, molecular modelling, pipeline flow modelling, and reservoir simulations to address the study objectives. The experiments' results will be analysed and used to recommend solutions to the challenges associated with generating hydrogen from natural gas and using existing natural gas infrastructure for hydrogen transportation and storage.

Chapter 2 - Literature Review (Summary)

Recently, the international community synergised in their commitment to reduce carbon emissions and increase investments and interests in alternative energy sources[8–10]. Unfortunately, although relatively cleaner than fossil fuels, renewable energy resources are neither fully developed, sufficiently available nor cheap enough to meet current or projected global energy demands[11]. Consequently, the World faces the challenge of meeting rising energy demands with sources of energy that are not only clean but also reliable and affordable. To solve this, nations and stakeholders in the energy industry have ranked hydrogen, which has been almost entirely generated from natural gas, crude oil and coal over the last decade[12,13], preferentially among the options being considered for the energy source of the future in the aftermath of the energy transition[2,5,12,14]. For instance, The United Kingdom plans to switch from natural gas to hydrogen for domestic and industrial applications by progressively blending the former with hydrogen, starting from 20 to 30% in the short term and up to 100% hydrogen in the long term[2,14]; Canada and Germany entered an agreement on August 23, 2022, to begin shipping hydrogen across the Atlantic as early as 2025[15]; in June 2021, the World's biggest oil firm, Saudi Aramco, outlined its plans to invest in blue hydrogen as they forecast a full global market for the energy source in 2030[16]; and Natural gas which is currently the major source of blue hydrogen[17] is at the heart of Nigeria's energy transition strategy[9]. Sadly, making and generating energy from hydrogen comes with a plethora of technical, economic and environmental challenges including the high cost of production, adverse environmental footprint, lack of hydrogen infrastructure for transportation and storage and high cost of building new ones.

As of October 2021, it is estimated that a whopping \$30.0375 trillion is required to construct hydrogen infrastructure that will replace the existing natural gas network in the US[2]. To minimise this, investigations were done on the idea of using existing natural gas infrastructure for hydrogen transportation and the major setbacks to that were found to include hydrogen embrittlement of steel pipes, low energy contents of hydrogen relative to natural gas and the high compressibility characteristic of hydrogen relative to natural gas[2,18]. Abbas et al (2021) looked into the low energy and high compressibility challenges by using numerical modelling of hydrogen flow in natural gas pipelines to study the implications of generating the same amount of energy from hydrogen as you would from natural gas. The study revealed that, because natural gas possesses three times more energy value than hydrogen, the latter would need to be delivered at about three times the volumetric flow rate of natural gas to deliver an equivalent amount of energy. Regrettably, doing that endangers the integrity of the pipeline as the erosional velocity limits are exceeded when hydrogen blends exceed 60%[2]. The study, however, did not consider the mechanism and severity of the threat of exceeding this limit. In other words, the effect of increased hydrogen gas velocity on the lifetime and integrity of conventional pipelines was not investigated. There is a paucity of information on hydrogen penetration behaviour/rate in conventional gas pipelines, the erosional behaviour of pipeline internals under a high flow of hydrogen and the interaction of hydrogen and iron oxide molecules. Since low-carbon steel pipelines are coated with iron oxides[19], a good understanding of the role of iron oxides against hydrogen entry is, therefore, expedient to the use of existing natural gas pipelines for hydrogen transportation.

Besides the problems created by the discrepancy in the energy contents and compressibility factors of hydrogen and natural gas, another hindrance to the prospect of utilising blue hydrogen (and hence, natural gas) as a major energy source in the future is the immaturity of the technology and global practices in hydrogen storage[20]. One practicable solution is line packing: storing hydrogen under high pressure in pipelines. Unfortunately, storing hydrogen gas in this form presents the threat of embrittlement and catastrophic failures[18]. To adopt existing natural gas pipelines for line packing of hydrogen and save the cost of building new infrastructure for that, the physical chemistry of hydrogen atoms occupation of iron oxides matrices, absorption of hydrogen molecules on iron oxide interfaces and the diffusion of hydrogen into gas pipeline sublayers under high, static pressures need to be well understood. Another solution to the hydrogen storage challenge, which has been widely investigated, is the use of underground, geological formations (such as depleted hydrocarbon reservoirs, aquifers and salt caverns) for hydrogen storage[20–22]. Unfortunately, previous studies on this subject greatly ignored the high uncertainties associated with modelling and simulating reactive flow in different underground porous media except for depleted oil reservoirs[21,23].

Since the major stakeholders and influencers in the energy industry have favoured the use of hydrogen for energy generation during and after the transition to a net zero emissions economy, natural gas will become a major energy source in the aftermath of the energy transition if these hindrances to the use of natural gas for hydrogen production are obliterated. Nigeria, for instance, which has a proven natural gas reserve of 206.5tcf made an estimated \$41.378 billion from petroleum exports in 2022[24] (with natural gas contributing the lion's share in this figure[25]). Considering that global energy demand is projected to rise significantly over the next three to four decades[1] and Nigeria is a major exporter of crude oil, the country's oil and gas earnings should also increase in the future. But Nigeria ratified the 2016 PARIS Agreement and announced the target to achieve net zero emissions by 2060 at the COP 26 climate summit in Glasgow during which natural gas was adjudged to be essential in the country's energy transition plan[8,9]. For countries like Nigeria to achieve their energy transition goals and also maximise the use of their abundant oil and gas reserves, they must embrace alternative and less carbon-intensive means of utilising their fossil energy resources. This study proffers solutions to the challenges of exploring one of such alternatives – the use of natural gas and its infrastructures for hydrogen production, transportation and storage.

Chapter 3 - Proposed Research Methodology

A) Proposed Experimental Workflow

[1] **Carry out a detailed literature review** on current global practices and challenges facing the production of hydrogen from natural gas and the adoption of existing natural gas infrastructure for hydrogen transportation and storage.

[2] **Laboratory experiments:** Conduct Low Energy Electron Diffraction (LEED), Scanning Tunnelling Microscopy (STM) and X-ray Photoelectron Spectroscopy (XPS) on both bare iron oxides specimens and those under conditions of varying hydrogen dosages and analyse the rate/behaviour of hydrogen penetration with Time-of-Flight Secondary Ion Mass Spectrometry (ToF-SIMS).

[3] **Molecular modelling:** Use density function theory to (thermodynamically and kinetically) describe hydrogen adsorption and absorption into the subsurface of pipelines internal under varying flow and static conditions.

[4] By an extension of Step [3], **explore hydrogen adsorption and absorption behaviour for different gas pipeline doping materials** to recommend suitable design modifications to contemporary gas pipelines for hydrogen transportation and storage.

[5] Use CMG tools to **conduct dynamic simulations of CO_2 storage with an evaluation of the effects of geologic uncertainties on underground CO_2 storage** in depleted gas reservoirs, aquifers and salt caverns.

B) Required Apparatus and Materials

- ***Required Apparatus and Software***: (i) LEED, STM and XPS apparatus; (ii) Hypercube molecular modelling software; (iii) CMG CoFlow and CMOST reservoir simulation and uncertainties modelling tools; (iv) statistical simulation and data analysis tools such as Microsoft Excel, Python and Design Expert; (v) access to research products and resources including textbooks, journal articles and conference proceedings, Scopus, Science direct, etc.
- ***Required Materials*****:** (i) industrial hydrogen gas; (ii) gas pipeline steel specimens; (iii) pipeline doping materials.

C) Mode of Data Collection and Data Sources

- Data collection will be mainly by **direct observations** of the experimental outcomes and **data mining** from case studies and published literature.
- Data sources for the systematic literature review will include major peer-reviewed scholarly databases like Scopus, Science Direct and EBSCO.
- Data for the molecular modelling will be sourced from the LEED/STM/XPS experiments and the ToF-SIMS analysis (Step [2], Section 3A).
- Data for the geologic modelling and uncertainty analysis will be sourced from underground hydrogen storage projects worldwide and literature in scholarly databases like Scopus, Science Direct and EBSCO.

D) Study Progression and Work Schedule

Table 3-1: Proposed Study Timeline and Work Schedule

S/N	TASK	START DATE	FINISH DATE	DURATION (MONTHS)
1.	**Literature Review** (to be carried out across the entire programme/study duration)	12/09/2023	30/08/2026	36
	• Problem Definition, Identification of Research Gaps, Formulation of Research Questions and Standardization of Research Objectives. • Writing and publishing a literature review article on current global practices in adopting natural gas for hydrogen transportation and storage.	12/09/2023	11/03/2024	**6**
2.	**Laboratory Experiments**: LEED, STM & XPS and ToF-SIMS analysis	13/03/2024	12/09/2025	**6**
3.	**Molecular modelling** of hydrogen adsorption and absorption into pipeline surface.	13/09/2025	11/03/2025	**6**
4.	**Testing of hydrogen interactions with different gas pipelines doping materials**	12/03/2025	11/09/2026	**6**
5.	**Modelling and uncertainty analysis of CO_2 geological storage**	07/04/2025	02/04/2026	**6**
6.	**PhD Thesis/Dissertation writing up and submission.**	02/04/2026	30/08/2026	**5**

Chapter 4 - Expected Outcomes and Contributions to Knowledge

Table 4-1: Research Outcome Presentation and Communications Plan

S/N	TITLE OF RESEARCH OUTCOME/RESULT	RESULT TYPE	RESULT COMMUNICATION PLAN/MEDIUM
1.	Repurposing Natural Gas Infrastructure for Hydrogen Transportation and Storage – A Review of Global Prospect and Challenges.	Review article.	To be published in Elsevier Journal of Natural Gas Science and Engineering or another high-ranking (Q1) journal in the field.
2.	An analysis of the effect of increased hydrogen velocity and internal pressure during hydrogen transportation and storage, respectively, in conventional gas pipelines.	i. Conference Paper.	To be presented in the 2025 SPE Nigerian Annual International Conference and Exhibition (NAICE) of the Society of Petroleum Engineers International
		ii. Journal Article.	To be published in Elsevier Journal of Natural Gas Science and Engineering or another high-ranking (Q1) journal in the field.
3.	Numerical Modelling Study of Hydrogen Permeation and Embrittlement Behaviour in Conventional Gas Pipelines	Journal Article	To be published in Elsevier Journal of Petroleum Science and Engineering or another high-ranking (Q1) journal in the field.
4.	Novel materials and design modifications for natural gas pipelines to make them fit for hydrogen transportation and storage.	Patent	Patent to be registered with the National Office for Technology Acquisition and Promotion (NOTAP) of the Nigerian Ministry of Science and Technology, Abuja.
5.	Dynamic Simulation Study and Uncertainty Analysis of Underground CO_2 Storage in depleted gas reservoirs, aquifers and salt caverns	Journal Article	To be published in Elsevier Journal of Petroleum Science and Engineering or another high-ranking (Q1) journal in the field.
6.	Towards Continuous Natural Gas Usage: A Study of the Technical Implications of Generating Hydrogen From Natural Gas and Using it in the Future Green Energy Economy.	PhD Dissertation	To be submitted to the engineering faculty of Robert Gordon University, Aberdeen.

Chapter 5 - Conclusion

This study promotes the continuous dominance of natural gas among the energy sources of the future (during and after the energy transition) by providing solutions to some of the challenges associated with producing hydrogen from natural gas and using existing natural gas infrastructure for hydrogen transportation. These objectives are important and feasible because hydrogen (which burns with zero greenhouse gas by-products) has enjoyed high advocacy as the energy of a future with net zero emissions amongst energy stakeholders including gigantic and influential international oil and gas corporations, governments of nations critical to the global energy industry and international organisations with momentous impacts on the global energy landscapes. The Literature review of Chapter 2 mentions these global energy influencers, their plans and investments in the future of hydrogen, and the research loopholes in the prospects of generating hydrogen from natural gas and repurposing current natural gas infrastructure for hydrogen transportation. Also provided in the second chapter are theories and reviews of past works in the research area. In Chapter 3, a concise description of the proposed research methodology, including the required apparatus and software, data sources and method of data collection are presented while Chapter 4 itemises relevant platforms and formats for the presentation of the research outcomes/results from the research objectives listed in the first chapter. With the findings from this work, countries (like Nigeria) that generate a significant proportion of their national revenue from natural gas can continue to benefit from the sale and usage of the resources without failing to meet net zero emissions targets.

References

1. BP. *Energy Outlook 2022 Edition*. *Outlook* https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/energy-outlook/bp-energy-outlook-2022.pdf (2022).

2. Abbas, A. J., Hassani, H., Burby, M. & John, I. J. An Investigation into the Volumetric Flow Rate Requirement of Hydrogen Transportation in Existing Natural Gas Pipelines and Its Safety Implications. *Gases* **1**, 156–179 (2021).

3. Aminu, M. D. Nigeria's Prospects in the Hydrogen Economy. *Premium Times* 1 (2022).

4. Jones, D. R., Al-Masry, W. A. & Dunnill, C. W. Hydrogen-enriched natural gas as a domestic fuel: An analysis based on flash-back and blow-off limits for domestic natural gas appliances within the UK. *Sustain. Energy Fuels* **2**, 710–723 (2018).

5. Scherer, S. Canada says Hydrogen Better Than LNG for German Needs. *Reuters* 1 (2022).

6. BP. *Statistical Review of World Energy*. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2022-full-report.pdf (2022).

7. EIA. *International - U.S. Energy Information Administration*. *Natural Gas* https://www.eia.gov/international/data/world (2022).

8. Olurounbi, R. Africa's Biggest Oil Producer Commits to Net-Zero Emissions - Bloomberg. *Bloomberg Africa Edition: Green* (2021).

9. Esiedesa, O. Energy transition: NEITI to Unveil Roadmap on 2060 Net Zero Target. *Vanguard* (2022).

10. Speirs J *et al.* The Best Use of Natural Gas within Paris Climate Target. *Sustain. Gas Institute, Imp. Coll. London* **October 20**, (2021).

11. EIA. EIA Projects Nearly 50% Increase in World Energy Usage by 2050, led by Growth in Asia. *International Energy Outlook 2021 Narrative* 6–42 (2021).

12. IEA. The Future of Hydrogen: Seizing today's Opportunities. *IEA Publ.* 14, 37–64 (2019).

13. IRENA. Geopolitics of the Energy Transformation: the Hydrogen Factor. *International Renewable Energy Agency Publications* 28 (2022).

14. Jones, D. R., Al-Masry, W. A. & Dunnill, C. W. Hydrogen-enriched Natural Gas as a Domestic Fuel: an Analysis Based on Flash-back and Blow-off Limits for Domestic Natural Gas Appliances within the UK. *Sustain. Energy Fuels* **2**, 710–723 (2018).

15. Kestler-D'Amours, J. Environmentalists Welcome New Canada-Germany Hydrogen Pact | Oil and Gas News. *Al Jazeera, Economy | Oil and Gas* (2022).

16. Martin, M., Di Paola, A., E-Din, Y. G. & Ratcliffe, V. Saudi Aramco Bets on Blue Hydrogen Exports Ramping Up from 2030 - Bloomberg. *Bloomberg Business* (2021).

17. Howarth, R. W. & Jacobson, M. Z. How Green is Blue Hydrogen? *Energy Sci. Eng.* **9**, 1676–1687 (2021).

18. Abohamzeh, E., Salehi, F., Sheikholeslami, M., Abbassi, R. & Khan, F. Review of Hydrogen Safety during Storage, Transmission, and Applications Processes. *J. Loss Prev. Process Ind.* **72**, 104569 (2021).

19. Kim, Y. S. & Kim, J. G. Corrosion Behavior of Pipeline Carbon Steel under Different Iron Oxide Deposits in the District Heating System. *Metals (Basel).* **7**, 1–20 (2017).

20. Ugarte, E. R. & Salehi, S. A Review on Well Integrity Issues for Underground Hydrogen Storage. *J. Energy Resour. Technol.* **144**, 1–27 (2022).

21. Zivar, D., Kumar, S. & Foroozesh, J. Underground Hydrogen Storage: A Comprehensive Review. *Int. J. Hydrogen Energy* **46**, 23436–23462 (2021).

22. Valle-Falcones, L. M. *et al.* Green Hydrogen Storage in an Underground Cavern: A Case Study in Salt Diapir of Spain. *Appl. Sci.* **12**, (2022).

23. Heinemann, N. *et al.* Hydrogen Storage in Porous Geological Formations – Onshore Play Opportunities in the Midland Valley (Scotland, UK). *Int. J. Hydrogen Energy* **43**, 20861–20874 (2018).

24. OPEC. *Annual Statistical Bulletin: 2022 Edition*. http://www.opec.org/opec_web/en/publications/202.htm (2022).

25. Ndigew, C. & Ashinze, F. Nigeria Earns Twice More from Gas than Oil in Q1 - Businessday NG. *Energy - Oil and Gas* (2022).