International Hydrogen Ramp-up Programme – H2Uppp

Green Hydrogen for Decentralized Energy Applications in Nigeria

Advisory Report

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

Imprint

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EXECUTIVE SUMMARY

The International Hydrogen Ramp Up Program (H2Uppp) is sponsored by the German Federal Ministry for Economic Affairs and Climate Action (BMWK) and implemented by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) in collaboration with the German Chambers of Commerce Abroad (AHKs).

The project supports the market ramp-up for green hydrogen and Power-to-X (PtX) technologies and products in developing countries and emerging economies through public-private partnerships (PPPs). In Nigeria, the program is working on early market-enabling activities to develop the local market for green hydrogen and other PtX derivatives, with a particular emphasis on private sector support. This complements other programs supported by the German Federal Government, including the German-Nigerian Hydrogen Diplomacy (H2-Diplo) office and the Export Initiative Environmental Protection. The German-Nigerian Hydrogen Office (H2Diplo) facilitates dialogue with the Nigerian public sector and policymakers, engages the private sector, and supports the development of green hydrogen and PtX initiatives. The Export Initiative Environmental Protection analyses hydrogen and fuel cell opportunities in off-grid energy supply.

Nigeria's reliance on fossil fuel exports and the potential decline in demand necessitates a shift toward sustainable energy models, with green hydrogen playing a crucial role. Nigeria has taken steps towards its energy transition and decarbonization, and green hydrogen can support the country's efforts towards a climate-neutral energy system and diversify its markets, however, the creation of PtX markets in Nigeria requires regulatory and technical frameworks, investment in renewable energy, and infrastructure upgrades.

H2Uppp supported German and Nigerian companies in understanding business opportunities related to decentralized applications of green hydrogen and fuel cells, particularly in replacing diesel generators with renewable energy-based hydrogen/fuel cell modules for increased energy access and security; this report is a compendium of the main technical solutions and their associated business models as well as relevant insights.

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LIST OF ABBREVIATIONS

AHKs	German Chambers of Commerce Abroad
BMWK	German Federal Ministry for Economic Affairs and Climate Action
C&I	Commercial and Industrial
ETP	Energy Transition Plan
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
H_2-Diplo	Global Hydrogen Diplomacy Programme
H_2Uppp	International Hydrogen Ramp Up Program
HT	High-Temperature
Kg	Kilogram
L	Litre
N	Naira
PEM	Proton Exchange Membrane
PPPs	Public-Private Partnerships
PtX	Power-to-X
PV	Photovoltaic
REA	Rural Electrification Agency
SHS	Solar Home Systems
SPV	Special Purpose Vehicle
TWh	Terra Watt-hour
USD	United States Dollars

1. INTRODUCTION

Nigeria has been intensifying its efforts towards implementing the energy transition and decarbonization to achieve its net-zero emissions target by 2060. The Energy Transition Plan (ETP) further lays out the path to achieve this and highlights the need to build out a hydrogen market post-2030, holding potential for both local consumption and export. Considering these developments, renewable hydrogen utilization can contribute towards a climate-neutral energy system given the expected drastic reduction in the demand for fossil fuels.

The upgrade of the electricity grid and a ramp-up of renewable energy generation are prerequisites for the build-up of a local green hydrogen market. However, along with developing hydrogen comes the conundrum of prioritizing energy access over the production of hydrogen using renewable energy sources. On another hand, large renewable energy systems such as commercial and industrial (C&I) solar Photovoltaic (PV) solutions and off-grid solar hybrid mini-grids rely heavily on diesel generator sets for backup power.

Recent developments in the country indicate that such applications of renewable energy can be achieved complementarily using electrolysers and fuel cells in decentralised settings, thus achieving the threefold objective of providing energy access, producing green hydrogen and displacing diesel generator sets. Several project developers are already designing and planning the implementation of pilot green hydrogen projects for decentralized energy applications.

Green hydrogen research has advanced significantly to the point that some scholars consider it the future‘s clean energy solution. Multiple applications within the transport, electricity and storage sectors have been envisaged, however, the objective of this report is to help stakeholders (project developers, off-takers, financing institutions, and local governments) better understand the business case for using green hydrogen in decentralized energy applications in Nigeria, and also learn from global experience. Therefore, based on global experience, a report on the main technical solutions, business cases and first lessons learned on green hydrogen solutions in decentralized energy supply in Nigeria (and Africa) is provided.

1.1 Renewable Hydrogen Production

Hydrogen is the most abundant element in the known universe. Yet despite its cosmic abundance, molecular hydrogen (H_2) on earth is rare. However, hydrogen can be produced from compounds containing bound hydrogen, e.g., by splitting the constituents of water (H_2O), or from hydrocarbons such as methane (CH_4), and others. Hydrogen is a fuel. This means that hydrogen is a chemical energy carrier, similar to fossil fuels, which are chemical energy carriers as well. Renewable hydrogen can be produced from the electrolysis of water, from woody biomass and photo-related processes.

1.1.1 Hydrogen from the electrolysis of water: There are three (3) main types of electrolysis, namely alkaline electrolysis, proton exchange membrane electrolysis (PEM electrolysis) and high-temperature (HT) electrolysis. Alkaline electrolysis is a mature process to produce hydrogen on industrial scales and has been applied for many decades. PEM electrolysis has niche applications, while the maturity of HT electrolysis remains to be demonstrated. It is noted, however, that HT electrolysis appears to be well-suited for variable operating conditions, as would be the case when powering electrolysis using intermittent renewable energy sources. Further development is needed to enhance the durability and cost-effectiveness of contemporary electrolysers.

1.1.2 Hydrogen from woody biomass: A large variety of woody biomass raw materials are suitable for hydrogen production. The gasification of biomass, e.g., in the form of wood, wood chips or agricultural residues, results in syngas, which is a mix of gases consisting of hydrogen, carbon monoxide, and CO_2. Other biomass-related production processes entail the use of biogas in steam reforming and the use of bacteria to induce the fermentation of feedstock and splitting water by way of photo-biological approaches.

1.1.3 Hydrogen from photo-related processes: For a sun-drenched country, such as Nigeria, concentrated solar thermal plants could eventually be used to split water into its constituents. In addition, processes such as photo-electrochemical and photocatalytic splitting allow the direct use of solar radiation to produce hydrogen. However, these approaches have not yet reached the technical maturity that is necessary for their large-scale commercial application. In photo-biological water-splitting processes, solar radiation is used to produce hydrogen from water. This is a special type of photosynthesis, resulting in hydrogen as a by-product of the metabolic processes of microorganisms used in the process. However, to date, the process efficiencies remain low, thus necessitating considerable additional research and development before their large-scale roll-out.

1.2 Economics of Hydrogen Production

The economics of producing hydrogen from intermittent renewables, such as solar or wind is improved as the number of full production hours per year are increased. It is for this reason that solar and wind resources that complement each other, for example with the sun being available when the wind does not blow and vice versa, are important prerequisites in the design of efficient green hydrogen production facilities powered by renewable energy resources.

Generally, producing, conditioning, transporting and using fuels leads to energy losses. Such losses can be expensive and sometimes render a fuel non-viable. To minimise losses, energy supply systems deliberately minimise the number of conversions required, from production to its end-use. In the case of hydrogen production from electrolysis, present day electrolysers are about 67 % efficient[1]. This means that about one-third of the input energy required to produce hydrogen is lost during the electrolysis process alone. In other words, more than 1.5 units of energy are needed to produce one energy unit of hydrogen[1]. For illustration, it takes some 50 kWh of electrical energy to electrolytically produce 1 Kg of hydrogen, the latter having an energy content of some 33.3 kWh[2].

Today, producing hydrogen from natural gas costs between N25.3/kWh H_2 (€0.03/kWh H_2) and N50.6/kWh H_2 (€ 0.06/kWh H_2)[3]. In contrast, producing green hydrogen by electrolysis costs between N84.32/kWh H_2 (€0.10/kWh H_2) and N126.48/kWh H_2 (€0.15/kWh H_2)[3]. Further cost reduction potentials exist and are estimated to range between 50 % and 60 %[4]. As the scale of hydrogen production increases, and individual component costs decrease, green hydrogen costs are expected to decrease. The Hydrogen Council estimates that costs between N14.33/kWh H_2 (€0.017/kWh H_2) and N42.16/kWh H_2 (€0.05/kWh H_2) will be achievable by 2050[4].

2. GREEN HYDROGEN IN DECENTRALIZED ENERGY APPLICATIONS

Decentralized energy systems use renewable-based small/modular power generation and energy storage units to generate electricity off the main grid to be consumed in load centres close to the electricity source. These systems can also be grid-connected to provide an extra level of reliability through their capability to receive electricity from the grid. A decentralized energy system allows for more optimal use of renewable energy and combined heat and power, reducing fossil fuel use and increasing eco-efficiency.

Decentralized energy systems are a relatively new electrification approach in the electricity sector, especially in developing countries with energy access challenges. This approach reduces transmission and distribution inefficiencies and related economic and environmental costs for such infrastructure. A decentralized energy system relies on distributed generation, energy storage and demand response.

The energy supply for decentralized applications is mostly provided by so-called mini-grids, which are electric power grids that are powered mostly using renewables and can function as stand-alone to provide electricity connections in remote areas. They are locally delimited and self-contained power grids that supply several households or businesses with electricity and can be fed by various renewable energy sources.

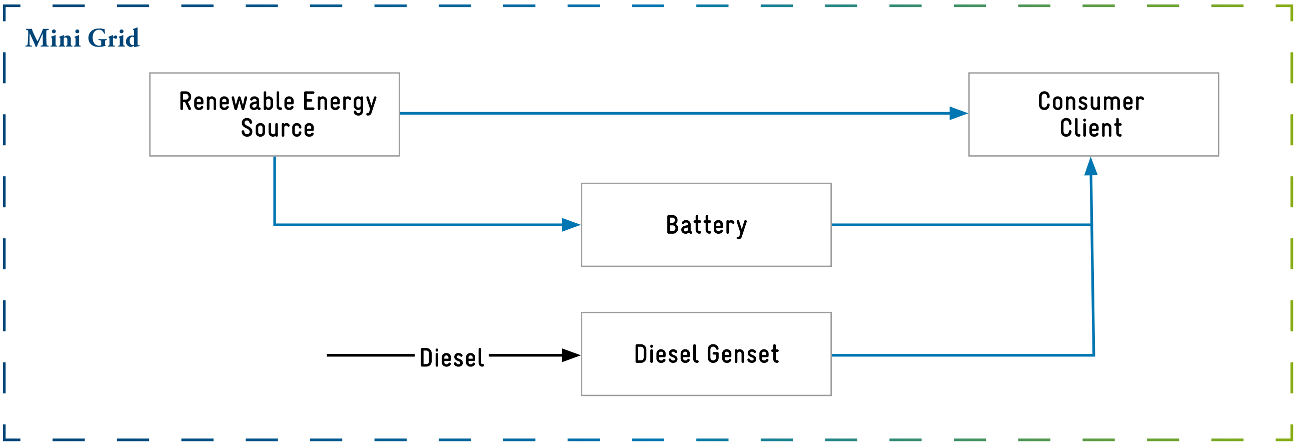

Figure 1: Concept of commercial setup of mini-grids

In the last decade, new storage systems for variable renewable energy sources have been transforming the mini-grid landscape, leading to further reducing or even eliminating the need for costly fossil fuels. This has been made possible using batteries and hydrogen. Introducing storage to the problem of seasonal generation and fluctuations in detached mini-grid systems, is a crucial factor for achieving 100 % green microgrids. A typical microgrid is often oversized with an average of 30 % excess solar being lost as it cannot be stored for a time when needed.

In the case of hydrogen, the excess from the generated renewable capacity is converted to green hydrogen via water electrolysis. The hydrogen is stored and used during periods of low renewable electricity supply and high electricity demand. While batteries are great at load shifting, they cannot provide for efficient long-term storage. Here hydrogen is the perfect partner as it can be stored with a very high energy density and low carbon footprint – a major advantage when land availability is restricted. With the help of a fuel cell, the stored hydrogen produces electricity when needed. Thus, introducing green hydrogen to mini-grids solves the problem of seasonal or long-term storage in a way that batteries cannot.

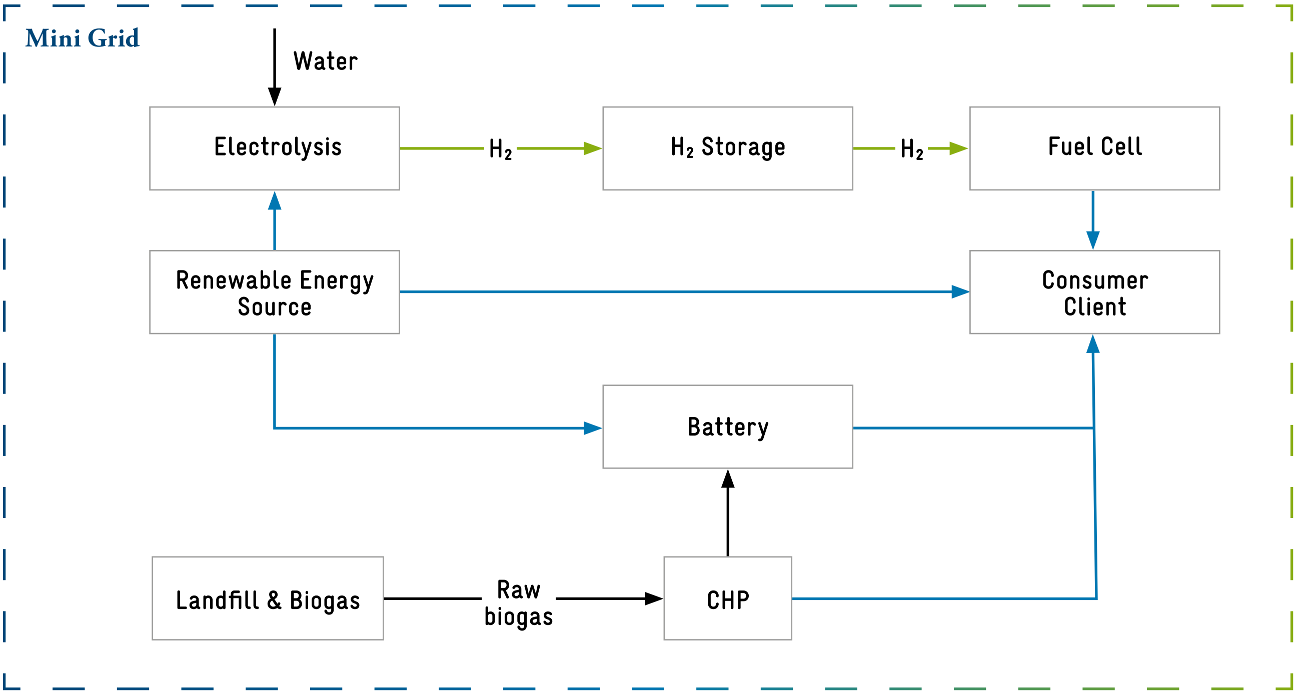

Figure 2: Optimizing the energy supply of mini-grids with additional sources, like green hydrogen and biogas

2.1 Comparing hydrogen, battery and diesel scenarios

The Enapter report (2020)[5] demonstrates this using the case study of Koh Jik – a small off-grid island in Thailand, as a case study in which 100 households of 300 inhabitants living on the island have been powered by a solar, diesel, and battery mini-grid. The initial plan was to upgrade to solar and add new batteries. This would increase the renewable share to a whopping 85 %. However, 15 % of power would still need to be covered by a diesel generator, with the battery system lacking the capacity to power 30 % of solar generation throughout the year.

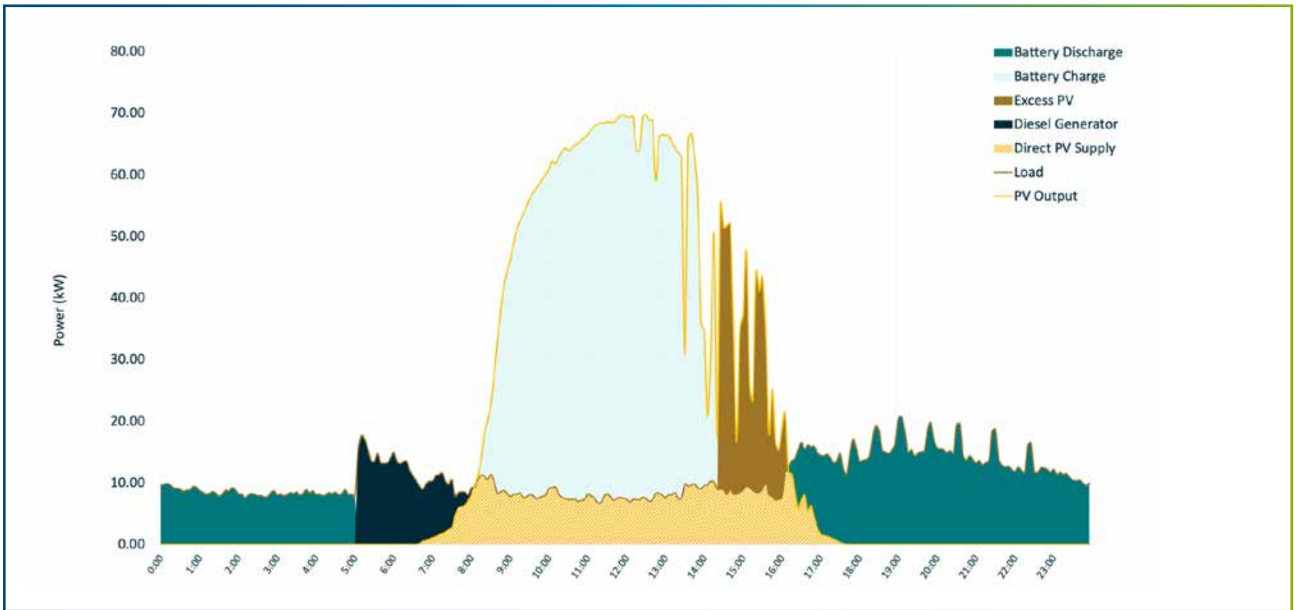

Figure 3: Initial plan for community household using solar, diesel, and battery mini-grid – scenario 1[5]

Instead of wasting the excess solar, a modular electrolyzer turns it into green hydrogen in the case of Figure 4 below. The stored hydrogen can then be used to generate electricity on days when there is not enough energy in the batteries. To achieve a renewable microgrid without hydrogen requires significantly oversized batteries and PV panels. This would be challenging due to the restricted land availability. With the new setup in Figure 4 below, there is a limited curtailment of solar, all renewable energy is used and diesel is no longer required.

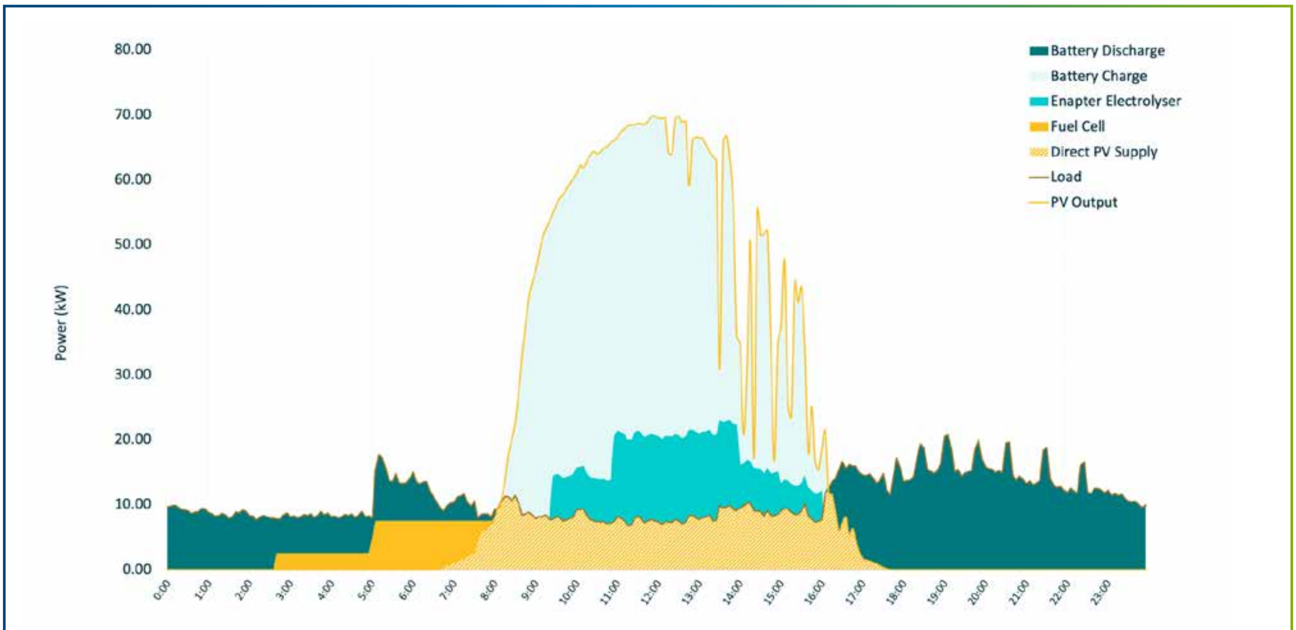

Figure 4: Initial plan for community household using solar, diesel, and battery mini-grid – scenario 2[5]

2.2 Cost-Effectiveness of hydrogen versus diesel scenario

The Enapter report (2020)[5] also compares the cost-effectiveness of the hydrogen scenario versus the diesel scenario, to establish that the hydrogen scenario is more effective. Using an average post-COVID-19 diesel price of N556.5 (€0.66) per litre, it established that the cost of operating a diesel genset, on top of fuel and logistics makes diesel more expensive from the outset. In this case, the cost of fuel in the diesel scenario amounts to N244.5 (€0.29)/kWh and another N244.5 (€0.29)/kWh for power generation. In total, the cost of electricity from diesel in this setup amounts to N489.05 (€0.58)/kWh. In comparison, the hydrogen solution costs use green electricity that would otherwise be curtailed, a modular electrolyzer, storage tanks, a hydrogen fuel cell and accessories. This constitutes to a fuel cost of N354.14 (€0.42)/kWh. For the power generation, a fuel cell is required which adds N101.18 (€0.12)/kWh. In total, the cost of electricity from hydrogen amounts to N489.05 (€0.58)/kWh. These results prove that for the past few years, hydrogen has proved itself in transforming mini-grids into a reliable, clean power source for everyday use. Now it has proven itself in making them more economical than diesel. This presents an even more compelling case for Nigeria, where the current diesel price is at N1300 (€1.54) per litre[6].

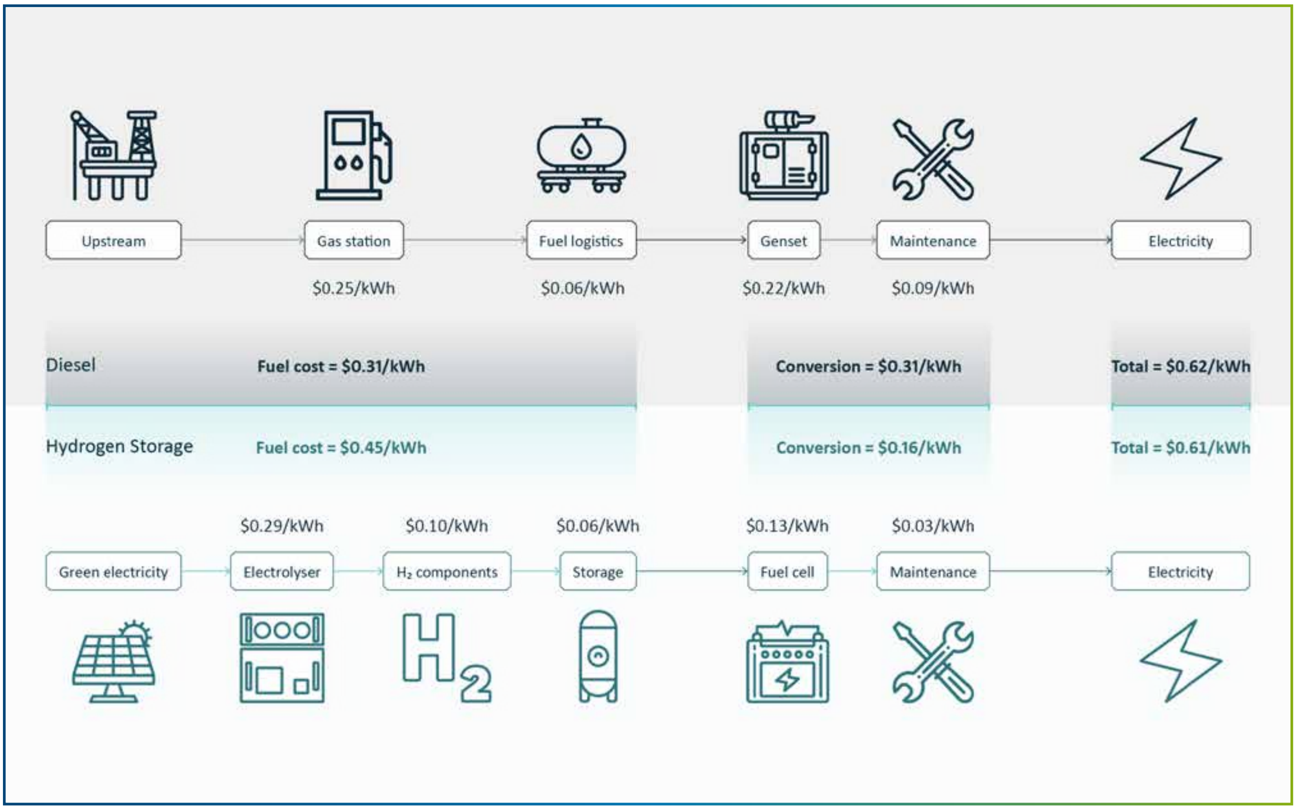

Figure 5: The cost competitiveness of hydrogen-powered mini-grid systems (Enapter, 2020)[5]

3. POTENTIALS AND FEASIBILITY OF GREEN HYDROGEN IN NIGERIAN DECENTRALIZED ENERGY SYSTEMS

3.1 Nigeria's pursuit for a decentralized energy sub-sector

The current energy situation in Nigeria is characterized by an imbalance in energy demand and supply. Over 90 million people in Nigeria are without access to grid electricity. In 2020, power generation dropped to about 35,700 GWh, compared to electricity demand of about 29 TWh.

Energy supply	Installed capacity (MW)
Gas	11,972
Hydro	2,062
Wind	10
Solar	7
Other / Diesel	2,333

Table 1: Generation capacity (on-grid and off-grid) in Nigeria[7]

Due to this insufficient generation coupled with grid constraints, the majority of households, businesses and industries in the nation generate their own electricity with diesel/petrol generators. 80 % of operational energy capacity comes from off-grid diesel/petrol generators. Access to electricity is further made difficult due to the constant increase in the price of diesel fuel as well as the expensive acquisition and maintenance costs of diesel generators[8].

Currently, measures to promote power generation in Nigeria are focused on mini-grids based on renewable energy sources such as photovoltaic, bioenergy and hydroelectric power. In recent years, the use of solar PV systems in rural areas has steadily increased. According to the Rural Electrification Agency (REA), the total capacity of the solar home systems (SHS) installed by the agency at selected locations in Nigeria amounts to 22,244 kW[9]. Projects are already underway from the private and public sectors to develop mini-solar grids to meet the Nigerian forecast of 500 MW installed solar PV by 2025[9].

3.2 Potential contributions of green hydrogen in the Nigerian decentralized energy system

Due to the abundance of renewable energy resources, low population density, and accessibility of non-arable terrain suited for the large-scale deployment of renewable energy infrastructure, Africa possesses a unique advantage in becoming a significant producer of green hydrogen. Many African nations, especially those near the tropics, like Nigeria, have exceptional solar resources that have enormous potential for producing green hydrogen.

Figure 6: Technical potential for producing green hydrogen under USD 1.5/kg by 2050, in TWh[11]

Potential contributions of green hydrogen in Nigerian decentralized energy system include:

1. Contributions towards energy transition: Nigeria commits to intensifying efforts towards energy transition and decarbonization to achieve net-zero goals by 2060. Green Hydrogen serves as a viable means to reaching this goal through its potential to decarbonize industrial sectors, contribute to energy access and create a hydrogen economy.

2. Contributions to electricity access: The production of green hydrogen requires the production of renewable energy electricity. Therefore, in situations where green hydrogen is to be produced for a particular industrial off-take or export, allowance for excess capacity of renewable energy systems can be utilized to provide electricity access in a particular region.

3. Stabilization of renewable energy system grids: As the share of variable renewable sources (esp. Solar systems) in the electricity mix in Nigeria grows, consistency of supply and balancing of the grid becomes a greater challenge. Green hydrogen, with its capacity to store excess energy, provides a reliable solution to these fluctuations by balancing the grid as a clean source of dispatchable power.

3.3 Feasibility of Green Hydrogen in the Nigerian Decentralized Energy System

Deciding whether to invest in green hydrogen in decentralized energy systems comes down to the cost, risk and reward matrix. Factors necessary to ensure enhanced feasibility of green hydrogen application in decentralized systems include policy and regulation, infrastructure, logistics, local demand, and export trade. These are further discussed in Table 2 below. These factors also determine the extent to which a green hydrogen market can be established, and off-takers identified.

Factor	Description	Status in Nigeria
Policy and Regulation	Policies and frameworks to create, utilize, incentivize and trade green Hydrogen	• No known specific commitment from the national government to determine standards and codes across the value chain. • Regulation is key to local hydrogen development and demand.
Infrastructure	Electrolyzer Plants, Storage, Safety – PtX & derivatives (Methanol, Ammonia)	• Need to carry out studies to identify possible points and conditions for infrastructure development or upgrade. • The infrastructure base in Nigeria needs to be improved to accommodate decentralized hydrogen production and use.
Logistics	Intra- and international Trucking, Shipping, and Pipeline networks – also connecting Morocco and Algeria	• Infrastructure stock for transport, is still insufficient. • Issues on efficient transport mechanisms are still being figured out, globally.
Local Demand	Local demand for decentralized green hydrogen in Power, manufacturing, and mobility sectors	• Awareness and sensitization campaigns have commenced but need to be greatly enhanced. • Awareness should be cross-level and cross-sectional to improve relatability.
Export Trade	Export of green hydrogen in a derivative form, facilitated involving off-takers and hydrogen purchase agreements, through energy commodity trade.	• Work and plans on this are still ongoing. • Need to commence engagements with off-taker ecosystem both locally and internationally through international cooperation.

Table 2: Factors necessary for decentralized green hydrogen applications and their status in Nigeria

4. PROJECT CASE STUDIES

A fact-finding mission and site visit in Nigeria allowed the under-study and provision of support to indigenous companies developing green hydrogen pilot projects for decentralized energy applications in Nigeria namely, Dunatos Technology Limited and Metikon Engineering Limited. Both companies are developing green hydrogen for decentralized energy applications applying different business models.

4.1 Dunatos Technology Limited

Dunatos Technology Limited (Dunatos), traditionally a telecommunication and solar energy company with 6 years of corporate experience in Nigeria, plans to develop a 50KWp Hybrid Solar PV, battery and hydrogen-based energy storage system with fuel-cell for electricity conversion at Araromi Seaside community of Ilaje Local Government Area, Ondo State, Nigeria. The firm's business model entails primarily using excess electricity from their mini-grid system to produce green hydrogen, and then re-generate electricity, using a fuel cell which will potentially be transmitted through the electricity grid using existing grid infrastructure (see overhead lines in Figure 10).

A portion of the green hydrogen produced is planned to be applied to powering a green hydrogen shuttle bus for local transport within the community. The project is planned at this first stage to be a proof of concept, which will potentially spur the interest of the government and other investors. It is also planned to serve as a case study for capacity building for industries and academia.

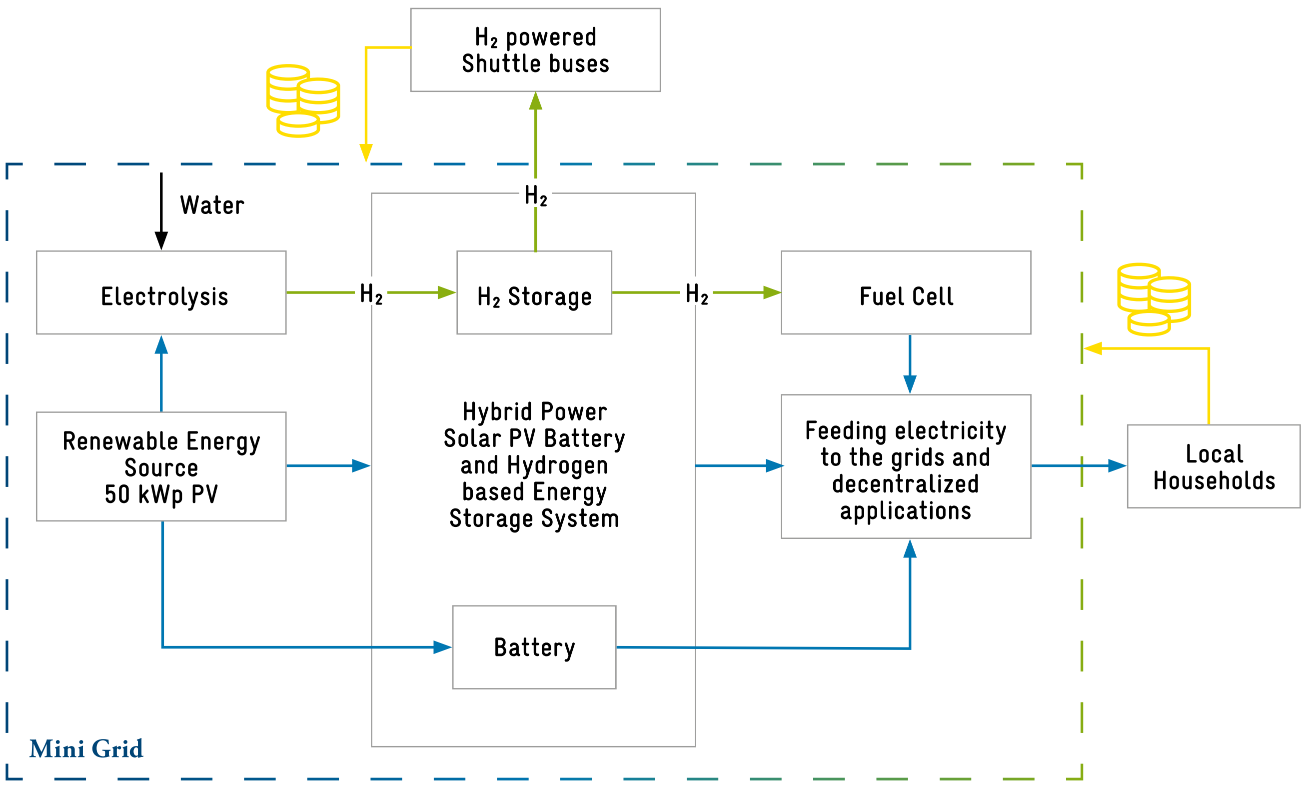

Figure 7: Schematic showing Dunatos' proposed hydrogen business model and flow (Blue: Electricity, Green: Hydrogen, Yellow: Revenue streams)

To achieve these plans, Dunatos is currently engaging with the Ondo state government, the Araromi Seaside Community and another private infrastructure company to form a Special Purpose Vehicle (SPV), based on the Public-Private Partnership (PPP) model. The proposed project is currently benefiting from sub-national government and local community interest, engagement and support. The company and the community have already signed a Memorandum of Understanding (MoU) that allows the construction of the project.

The construction of the first phase of the project began in the 4th quarter of 2023 with the construction of a 50KWp Hybrid Solar PV system, in the acquired 6 plots of land closer to the Atlantic Ocean. The company is currently in discussion with several German partners including H_2 Core Systems for Engineering, Procurement and Construction (EPC) as well as a firm to serve as its Original Equipment Manufacturer (OEM) for the fuel cell system. Satisfying these will allow Dunatos to conclude its project cost estimation and feasibility studies.

Figure 8: Meeting with the project host community leaders at Araromi Seaside, Ilaje Local Government Area of Ondo State, Nigeria

Figure 9: Project site visit at the Donatus project site at Ilaje, Ondo State with the State Government Officials

Figure 10: Sign-post illustrating planned overhead distribution line project to be constructed by Ondo State government

Figure 11: Sign-post illustrating Ondo state government presence and infrastructure development activities near the project site

Figure 12: Experts and Investors "Develop Ondo" Conference at Akure, Ondo State – the Dunatus project host State

4.2 Metikon Engineering Limited

Metikon Engineering Limited (Metikon), traditionally an energy engineering, utility (mini-grid), and telecommunications company with 20 years of corporate experience in Nigeria, plans to build out a decentralized green hydrogen project called the Nsofang Hybrid Power Plant phase 2. It is planned to integrate a modular anaerobic digester, a dual-mode Climate Positive Plant (PtX and Gas to Power) and a mobile hydrogen power plant. The project is envisaged to impact 200-250 households in an agrarian host community predominantly dealing in Cocoa, Plantain, Cassava, Maize and oil palm.

The integrated power cum hydrogen project is currently underway and was initially planned to be an integration of the construction of a solar mini-grid system with 278 kWp/ 443.4 kWh battery storage and an 80kVA diesel generator hybrid system. To adopt a decentralized green hydrogen system, Metikon decided to displace its planned diesel back-up generation with hydrogen production and for further electricity generation. The planned project is envisaged to produce biogas from agricultural waste using the anaerobic digester technology and to capture the $C0_2$ from the production of the biogas. Its business model is to sell the renewable/biogenic $C0_2$ to breweries and other industries within the project's proximity to help improve their sustainability rating. Metikon's integrated project seeks to solve the market gap existing in the fluctuating and increasing pricing of diesel fuel and its environmental impact at scale, the logistical challenge of transporting liquid fuels (diesel and gas) into most of the off-grid or underserved communities, and provision of energy access in a competitive manner while promoting circular economy sustainability in Nigeria.

This project is envisaged to improve the productivity and income of the rural community by the provision of electricity, and the purchase and re-use of agricultural waste produce. The Project is also intended to contribute to a cleaner environment by eliminating the use of diesel generating sets and improving the sustainability rating of industrial firms who would like to use its derivatives as industrial stock. Metikon plans to deploy German OEM Reverion's dual-fuel reversible power plant that can generate electricity from biogas and green hydrogen, and also produce green hydrogen with excess renewable electricity via electrolysis. Metikon is also currently sourcing a modular anaerobic digester OEM that fits into its business model.

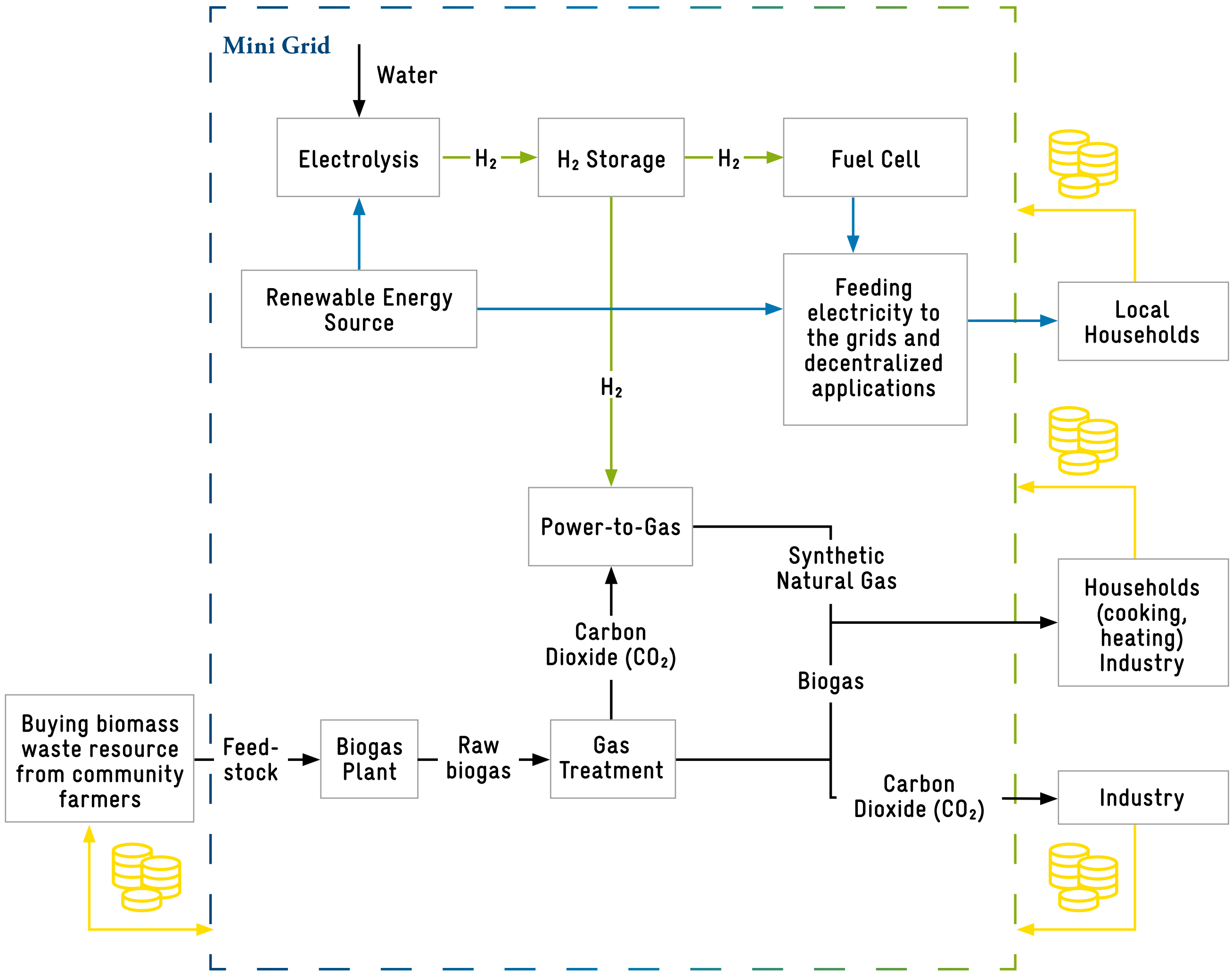

Figure 13: Diagram showing Metikon's proposed hydrogen business model and flow (Blue: Electricity, Green: Hydrogen, Yellow: Revenue streams).

5. CONSIDERATIONS FOR GREEN HYDROGEN PROJECT DEVELOPMENT FOR DECENTRALISED ENERGY APPLICATIONS

5.1 Technical and Economic Feasibility

To foster the development of a hydrogen market and support decarbonization efforts, it is vital for Nigeria to develop a clear and comprehensive technical and economic feasibility study. Assessing the technical and economic feasibility of green hydrogen projects for decentralized energy applications requires a comprehensive evaluation of various factors. Here are some expert recommendations to consider:

Factor	Description
Resource availability	Evaluating the availability of renewable energy resources, such as solar, wind, or hydropower, which are essential for producing green hydrogen for decentralized energy applications, considering factors like resource intensity, intermittency, and the potential for scalability.
Electrolyzer and fuel cell technologies	Assessing the current state of electrolyzer technologies and their efficiency, cost, and scalability and look for reliable and proven electrolyzer manufacturers that can provide the required capacity for the project. Considering both alkaline and proton exchange membrane (PEM) electrolyzers, weighing their pros and cons in a decentralized energy use case.
Infrastructure development	Evaluating the existing infrastructure and identifying the necessary upgrades or additions required for green hydrogen production, storage, and distribution in a decentralized application model. This includes pipelines, storage facilities, transportation means, and refuelling stations. Considering the costs, regulatory requirements, and potential challenges associated with infrastructure development in a decentralized application model.
Demand and market analysis	Conducting a thorough analysis of the potential demand for electricity in decentralized settings in the target market. Evaluating the market size, growth potential, and competition, along with any policy or regulatory support for hydrogen adoption in decentralized systems.
Cost analysis	Assessing the cost of hydrogen production, considering factors such as electrolyzer capital costs, electricity prices, operational and maintenance costs, and feedstock expenses. Comparing these costs with alternative energy sources or competing technologies to determine the competitiveness of green hydrogen fit for application in decentralized systems.
Project financing and funding	Evaluating the financial viability of the project, considering upfront investment costs, potential revenue streams, and payback periods. Identifying available financing options, including government incentives, grants, or partnerships with private investors or institutions specializing in green energy projects for decentralized applications.
Risk assessment	Identifying and mitigating potential technical, regulatory, and market risks associated with the decentralized green hydrogen project. Evaluating factors such as technology maturity, supply chain vulnerabilities, regulatory frameworks, policy uncertainties, and market volatility.

Factor	Description
Lifecycle assessment	Conducting a comprehensive lifecycle assessment to evaluate the environmental impact of the green hydrogen project for decentralized application. Considering the greenhouse gas emissions associated with green hydrogen production for decentralized application, including upstream processes, and comparing it to conventional alternatives to quantify the project's environmental benefits.
Collaboration and partnerships	Exploring collaborations with relevant stakeholders, such as research institutions, technology providers, energy companies, and potential off-takers of produced green hydrogen for decentralized application. Engaging in knowledge sharing, leveraging expertise, and considering partnerships to accelerate green project development for decentralized applications, while overcoming challenges.
Long-term viability and scalability	Assessing the long-term viability and scalability of such green hydrogen projects for decentralized applications. Considering factors such as technology advancements, evolving market dynamics, future policy and regulatory developments, and the potential for expansion or replication of such decentralized green hydrogen projects in other locations.

Table 3: Technical and economic feasibility of green hydrogen projects for decentralized energy applications in Nigeria

It is important to note that each green hydrogen project is unique, and a detailed feasibility study tailored to the specific circumstances is recommended. Consulting with experts in the field, including engineers, financial analysts, and policy specialists, can provide further valuable insights and ensure a comprehensive assessment of the project's technical and economic feasibility.

The project development of green hydrogen projects for decentralized energy applications generally follows important processes which are illustrated below:

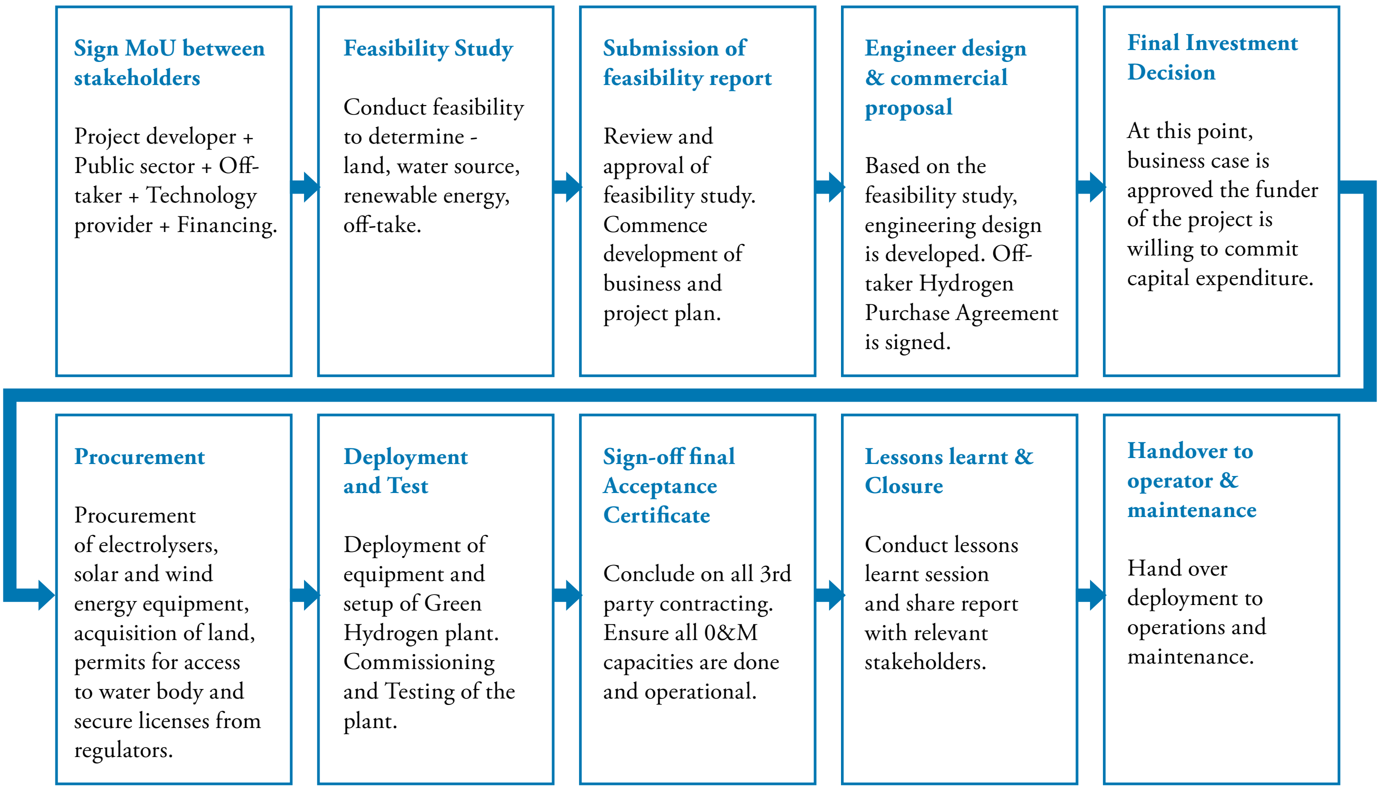

Figure 14: Process chain of development for green hydrogen in Nigeria (developed together with Dunatos Technology Ltd)

5.2 Challenges, Risks and Approaches

Addressing these challenges and mitigating the associated risks is essential for the successful development and deployment of green hydrogen in decentralized energy applications, and for ensuring it plays its role as a sustainable and low-carbon energy source.

i. Cost competitiveness
ii. Technical/Technology efficiency
iii. Land conflicts
iv. Safety and hazards

Continuous awareness creation, engagement with stakeholders and innovation of workable strategies through dialogue to foster the development of decentralized energy applications for green hydrogen projects is important. This is why the International Hydrogen Ramp-Up Programme (H2Uppp) convened renewable energy and electricity sector stakeholders to its Workshop on Green Hydrogen in Decentralized Energy Applications which was held in Abuja, Nigeria on Thursday 27th July 2023 as part of this advisory study to collectively review, discuss and address the issues around the concept.

Enabling environments, a strong political will, development of national policies, strategies and masterplans, awareness and sensitization, collaboration with academia, infrastructure development, demonstration projects and the deployment of innovative climate finance were proposed by experts to achieve the utilization of green hydrogen in decentralised energy applications in Nigeria. See the workshop photograph below:

Figure 15. GIZ H2Uppp expert workshop on Green Hydrogen in decentralized energy applications in Abuja, Nigeria [10]

5.3 Critical Success Factors for Green Hydrogen Projects for Decentralized Energy Applications

It is important to note that the following critical technical factors determine the success of green hydrogen projects for decentralized energy applications in Nigeria.

Factor	Description
General Assessment Scores	1. Settling on a suitable type of business, ownership; 2. Clarifying outlines of the business plan (Why will this business be a success?); 3. Identifying (potential) key partnerships, strategic partners and OEM suppliers; 4. Viable financial projections, and source of funding; 5. Estimating (industry) outlook and target market. Including volatility, estimated growth, and price fluctuation.
Green Hydrogen Optimal Assessment Scores	1. Power generation via locally available clean electricity including clarity about permits and land titles. 2. Production, storage and distribution of hydrogen. i. description of hydrogen production in the bespoke project context: technology, risks, processes; ii. logistics of storage and/or distribution. 3. Offtake by specific sectors and identified (potential) clients. i substantiated off-take needs; ii. willingness for off-take (e.g. Letters of Intent); iii. estimates of conversion costs for (potential) clients.
Sustainability in the entire value chain.	1. Sustainability concerns with regard to PtX must be considered at different assessment levels; 2. Analysis of the environmental, economic, social and governance dimensions of PtX applications; 3. Sustainability report/plan. Including efforts to fight climate change and sustainability efforts; 4. Social impact: How will the project impact society and near surroundings? Including direct and indirect job creation; 5. The various environmental dimensions are essential to determine the level of sustainability; 6. The transformation of energy systems must become a "Just transition"; 7. Leap-frogging potentials should be tapped; 8. Renewability and additionality for the production of additional renewable power; 9. Cooperation on aspects of sustainability and certification in the context of Power-to-X (PtX sustainability & certification).

Table 4. Critical success factors for green hydrogen projects for decentralised applications in Nigeria

6. SUMMARY OF FINDINGS AND CONCLUSION

6.1 Summary of Findings

Technical application of hydrogen in decentralized energy systems in the Nigerian context
1. Mini-grid projects with a high share (up to 100 %) of renewables involving green hydrogen as a means of electricity storage can be financially feasible solutions, due to relatively higher economic and environmental costs of diesel (fuel, transportation & CAPEX replacement costs) 2. Green hydrogen can be a competitive alternative to diesel as electricity storage. 3. The inclusion of green hydrogen production for sales (from excess renewable generation) may increase the profitability of the system. 4. Capacity of battery and green hydrogen assets have significant costs to achieve a 100 % renewable energy share scenario
Benefits of green hydrogen integration in decentralized energy systems in the Nigerian context
1. Energy Storage 2. Grid Stabilization 3. Flexibility and Portability 4. Decarbonization 5. Energy Resilience 6. Energy Access/Rural Electrification 7. Integration with Existing Infrastructure 8. Optimization of Battery Storage
The importance of policy and incentives
1. Introduce policy measures to establish credibility with potential investors and to support crowd investment of local communities in mini-grids 2. Create incentives for further investments in mini-grids that utilize green hydrogen as an energy source
Necessary steps from the government and public sector
1. Massive GW Renewable Energy Deployments (Solar, Wind) for decentralized application of green hydrogen development in Nigeria 2. Capacity Building with academia and industry on the use and benefits of decentralized energy applications of green hydrogen in Nigeria 3. Accelerate regulation of green hydrogen for decentralized energy applications and align with global standards 4. Stimulate local demand for green hydrogen for decentralized energy applications through incentivization like tax breaks, carbon credits, and import/export exemptions 5. Bilateral agreements and international cooperation for green hydrogen development for decentralized energy uses 6. Building Public-Private Partnerships (PPPs) and consortia for green hydrogen projects for decentralized energy applications

Table 5: Summary of findings

6.2 Conclusion

With energy access challenges still very predominant in Nigeria, green hydrogen holds the potential to solve the twin problems of decarbonizing local heavy industry, while providing energy access through the deployment of decentralized energy systems powered by green hydrogen. After the successful implementation of this advisory study, compelling results that support this concept were discovered.

As the cost of diesel fuel for decentralized power generation continues to rise, green hydrogen provides a comparative and competitive advantage to make decentralized energy systems 100 % renewable at a lower cost, thus completely displacing diesel generation. This model is being piloted in Nigeria for rural electrification, off-grid telecommunication transmission sites electrification and in urban load clusters like school campuses, hospitals and residential estates. Decentralized green hydrogen energy systems are versatile and go beyond their primary application to provide extra social and economic value for stakeholders e.g. providing treated water for community use, capturing oxygen for use in local hospitals and providing clean mobility around local communities. Such projects' end-use applications of green hydrogen that demonstrate extra cross-cutting value and impacts should be promoted. Following the project feasibility, process chain, risk and success factors matrices provided in this advisory report is a great starting point for the implementation of green hydrogen projects for decentralized energy applications.

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