GREEN HYDROGEN

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The sustainable development goal number 7 (SDG #7) which addresses the need to adapt clean and affordable sources further reinforce the need in turning the wheel towards renewables. However, the intermittencies and daytime limited availability of these streams again challenge the continuity and reliability of the national grid while depleting the grid inertia due to the disconnection of non-renewable power plants. While enriching the national power sector with higher capacities of renewable energy sources even beyond the saturation limits, the intermittencies, and extra capacities of these sources such as solar and wind energy will provide opportunities to generate energy vectors while stabilizing the grid such as hydrogen or more specifically *Green Hydrogen*.

Electrolysis of water using renewable electricity, also known as Green Hydrogen, is a net-zero alternative that can meet the energy needs of the modern world while helping to meet climate action goals. Green hydrogen has multiple applications, including serving as an energy storage solution for modern grids and connecting hard-to-decarbonize sectors such as steel, chemicals, long-haul transport, shipping, and aviation with renewable energy. Its untapped potential makes it an exceptional concept. Although the potential is promising; there are some key challenges Sri Lanka in the direction of Green Hydrogen. Economic feasibility, lack of knowledge transfer potential and safety issues are highly visible and demand proper recommendations from scientific and engineering community in Sri Lanka.

This policy document highlights the emergence of green hydrogen as a promising renewable energy sector and offers strong recommendations. Further this document directs readers on directions related to green hydrogen related research which is quite unique when it come to the sector. While electrolysis of water with renewable energy which is technologically mature since the adoption of the process during past few centuries, green hydrogen related research are going in various direction specially on with photocatalytic water splitting and biomethane steam reforming where it leads us to overcome many hurdles we are facing with current choice of technology.

2. Introduction

The core framework of the sustainable development path goes beyond mere green growth and encompasses triple bottom line benefits that address economic, social, and environmental bottom lines in a broader sense. The national energy sector is a vital component of the national development mechanism and requires strengthening through a sustainable framework that addresses the aforementioned triple bottom lines. Sri Lanka's national energy policy (2019) provides a substantial sustainability backbone for this path. The National energy policy framework is developed on ten unique pillars which directly or indirectly address the sustainability triple bottom line aspects. These are,

1. Assuring Energy Security
2. Providing Access to Energy Services
3. Providing Energy Services at the Optimum Cost to the National Economy
4. Improving Energy Efficiency and Conservation
5. Enhancing Self Reliance
6. Caring for the Environment
7. Enhancing the Share of Renewable Energy
8. Strengthening Good Governance in the Energy Sector
9. Securing Land for Future Energy Infrastructure
10. Providing Opportunities for Innovation and Entrepreneurship

Power (electricity) sector of Sri Lanka plays a key role in the national energy sector which also needs to be addressed through above ten pillars in making it par with the sustainable development needs. Energy security which addresses primary and secondary energy supplies of the country will be required to ensure continuity, adequacy, and reliability. The affordability – gaining energy independence and providing sustainable energy security in the future sustainable energy pricing policies.

During the past decades with the short-term vision, the country has planned its primary supplies mainly focusing on finite and non-indigenous non-renewable sources such as coal and oil as the firm power sources. Obviously, they have supported a high level of power grid inertia in maintaining a stable grid. But due to the highly volatile global geopolitical issues, climate change mitigation needs, and multilateral agreements in zeroing the Green House Gas (GHG) emissions by 2050, again the national energy security and affordability has come to a challenging point.

The 2019 national energy policy background invites more and more renewable energy capacities to strengthen the national energy sector. The national renewable energy capacity evaluations reconfirm the super capacities of renewables in the country. The sustainable development goal number 7 (SDG #7) which addresses the need in adapting clean and affordable sources further reinforce the need in turning the wheel towards renewables. However, the intermittencies and daytime limited availability of these streams again challenge the continuity and reliability of the national grid while depleting the grid inertia due to the disconnection of non-renewable power plants.

While enriching the national power sector with higher capacities of renewable energy sources even beyond the saturation limits, the intermittencies, and extra capacities of these sources such as solar and wind energy will provide opportunities to generate energy vectors while stabilizing the grid such as hydrogen or more specifically *Green Hydrogen*. Grid scale battery systems also will support the power grid in the same manner but the high infrastructure cost, high lifecycle cost of such systems and limitations of battery systems to power sector, the relative benefits of green Hydrogen gain a high score in comparative evaluations. Therefore, the combination of renewables and green Hydrogen will offer a high potential in uplifting the national economy through a sustainable path.

2.1 Definition and Approach of Green Hydrogen

Hydrogen is an element with many exceptional properties. One of its most striking properties is its gravimetric energy density where one kilogram of Hydrogen contains the approximately same energy as one gallon of gasoline. This makes hydrogen a strong candidate for use as an energy carrier and storage medium. Moreover, hydrogen is an essential raw material for various industrial processes. According to the International Energy Agency (IEA), the annual global production of hydrogen reached 94 million tonnes in 2021. The chemical and petrochemical industries are currently the primary consumers of hydrogen; however, it is expected to become significant in sectors such as steel, shipping, aviation, long-haul transport, and light vehicles. This is predicted to result in a rapid growth in demand for hydrogen, which is forecasted to reach 610 million tonnes per year by 2050. Currently, the primary methods of hydrogen production are Steam Methane Reforming (SMR) and Coal Gasification. Unfortunately, both methods release large quantities of carbon dioxide as a byproduct. In 2020, SMR and Coal Gasification together emitted 900 million tonnes of carbon dioxide into the atmosphere which is an amount equivalent to the collective emissions of a few industrial nations. This level of carbon dioxide emission is challenging for nations committed to the Paris Agreement, which requires them to reach net zero by 2050.

To mitigate the environmental impact of these mainstream processes electrolysis of water using renewable electricity is emerging. This method fully complies with net-zero requirements, as the electrochemical reaction does not emit any carbon dioxide molecule in association with the conversion reaction, unlike SMR and Coal Gasification. The hydrogen produced this way is widely known as Green Hydrogen. Green Hydrogen guarantees in meeting the complex energy needs of the modern world while helping to meet climate action goals. Green Hydrogen has a significant advantage over conventional hydrogen, which currently accounts for 98% of the hydrogen market, in achieving climate targets. However, Green Hydrogen's potential is not limited to being an alternative to conventional hydrogen. It has demonstrated the ability to entirely cater to new avenues, such as energy storage to mitigate imbalances that occur in modern grids due to the intermittent nature of renewable energy sources. Additionally, Green Hydrogen contributes to connecting sectors that are difficult to connect with renewable energy, such as steel, chemicals, long-haul transport, shipping, and aviation. These untapped potentials make this a truly remarkable concept.

2.2 Application of Green Hydrogen

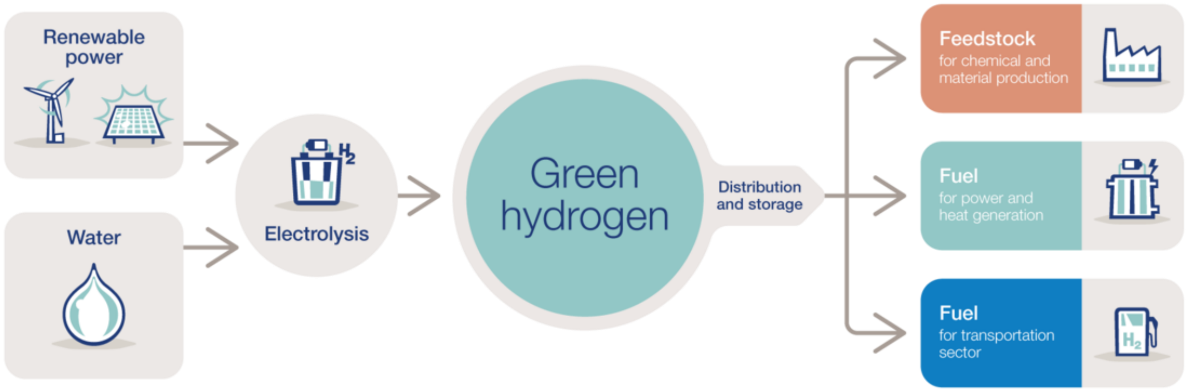

Figure 1: Applications of Green Hydrogen

Green hydrogen has numerous applications in various sectors. It has demonstrated the ability to cater to entirely new avenues, such as serving as an energy saturation option to mitigate imbalances caused by intermittent renewable energy sources in modern grids. Moreover, green hydrogen has the potential to bridge sectors that are challenging to connect with renewable energy, including steel, glass, cement, ammonia, methanol, long-haul transport, shipping, and aviation. These untapped possibilities make green hydrogen an exceptionally remarkable concept.

❖ *Renewable Energy Saturation*

With the increasing renewable energy capacities in the national grid, having a single grid will increase the risk of instability. Rather than a single bulk grid, it will be worth to consider a combination of microgrids that is designed to work in a small community need and smart grid that is designed to handle the electricity supply for large number of communities and IOT technologies are used in two-way communication between utility, consumers and system monitoring sensors along the transmission and distribution lines.

Whether a microgrid or a smart grid, suitable grid balancing options are essential in managing the grid power quality when combining with renewable energy streams especially solar and wind sources due to their intermittencies.

Pump storages are among the best choices when it comes to grid stabilization process, however, it will have limitations due to following issues;

- First and second priorities given to water respectively agriculture / irrigation needs and drinking water needs,
- High rate of evaporation of water due to increasing ambient temperatures and dry wind due to climate change impacts.

Grid connected green hydrogen generation will provide a grid stabilization option while generating hydrogen (as green hydrogen) will provide multiple opportunities to utilize the generated hydrogen in modes such as;

- Reconverting to power through gas turbine systems or fuel cell systems and feeding to the grid in power deficiencies,
- Use green hydrogen as a transport fuel (either through IC engine applications or Fuel cell technology based electric vehicle systems,
- Use of hydrogen to enhance the thermal capacity of Biogas or natural gas applications,
- Manufacturing green ammonia and use of liquefied green ammonia as a fuel in marine vessels,
- Manufacturing green fertilizer (green ammonia and urea etc.),
- Green methanol production,
- Use as a carbon capturing agent to produce methane.

The versatility of green hydrogen will open a wide spectrum of sustainable opportunities which needs to be assessed in utilizing the best sustainable path. Renewable (Solar and wind) energy DC microgrids will offer an efficient green hydrogen generation opportunity as there won't be any step down or AC to DC conversion losses. Such operations will be highly feasible in decentralized green Hydrogen requirements.

❖ *Green Hydrogen for heavy industry*

Green hydrogen can be used as a source of energy as well as feedstock from the industry perspective. It is looked at as a source of energy in this chapter. From the Sri Lankan perspective heavy industries such as tyres, ceramics, cement, steel, and glass are heavily energy consuming industries. These heavy industries could be early adopters of green hydrogen for the boilers, kilns or furnaces. Compared to the other applications of green hydrogen, industrial adaptation as a source of energy would be straight forward with relatively less complex system modification. Considering intermittency of green hydrogen production from renewable energy, if the green hydrogen is used in industry as a fuel, it could be fed into boiler furnaces and kilns as a mixed feed with another fossil fuel such as diesel, furnace oil or LPG. If natural gas were available, it is an ideal situation to feed green hydrogen with natural gas as a mixed feed.

Green energy produced using solar PV, wind or biomass in the industry premises shall be converted into green hydrogen by using an electrolyzer and feed the green hydrogen straight to either boiler furnace or kiln where there shall not be complex energy storage infrastructure such as battery storage or hydrogen storage. Economical use of green hydrogen in the industry as a source of energy would depend on the cost to produce a kilocalorie of energy from green hydrogen.

Comparison of Energy content in Hydrogen with commonly used fossil fuels in Sri Lanka. (Approximate calorific values were taken)

Table 1: Comparison of Energy content in Hydrogen

	Green Hydrogen	Diesel	Furnace Oil	Coal
Calorific Values	31,000	10,800	10,500	7,000
Average Price ($)	6.0	0.8	0.7	0.3

If green hydrogen is compared with diesel, calorific value will be approximately three times. However, the current international price indication of green hydrogen is US$ 6.0 per kg. The current gray hydrogen price is approximately 2.0 dollars per kg. It is expected that green hydrogen price will come down to 2 dollars per kg by around 2030 or early 2030s. By the time green hydrogen price reaches this value of 2 dollars per kg, green hydrogen would be able to economically use in industrial applications such as boilers, furnaces, kilns etc.

❖ *Hydrogen Ready Boilers*

Hydrogen-ready boilers are designed to run on hydrogen gas, which is considered a clean and sustainable alternative to natural gas. There are different types of hydrogen-ready boilers available on the market, including boilers that can be converted from natural gas to hydrogen, partially converted boilers that can operate on a mixture of natural gas and hydrogen, and 100% hydrogen-ready boilers that can operate exclusively on hydrogen gas. One of the main advantages of hydrogen-ready boilers is that they can help to decarbonize the heating sector, which is responsible for a significant portion of global greenhouse gas emissions. By using hydrogen instead of natural gas, these boilers can help to reduce carbon emissions and contribute to a more sustainable future.

However, there are also some challenges associated with hydrogen-ready boilers, including their cost and availability, as well as the technical challenges involved in converting existing natural gas infrastructure to accommodate hydrogen. One potential option for converting LNG boilers to hydrogen is to replace the burner and combustion chamber with hydrogen-compatible components. This can be a costly and complex process, as it may require modifications to the existing infrastructure, such as pipelines and storage tanks, to ensure compatibility with hydrogen gas. Another option for hydrogen conversion is to use a partial conversion approach, where a mixture of natural gas and hydrogen is used as a fuel source. This approach can help to minimize the cost and technical challenges associated with full conversion to hydrogen, while still providing some of the environmental benefits of hydrogen fuel.

In terms of efficiency, hydrogen-ready boilers can have similar or even better efficiency ratings compared to natural gas boilers. However, the exact efficiency ratings can vary depending on the specific design and technology used in each boiler. Hydrogen-ready boilers are currently available in the industry, and several leading manufacturers have developed models that are compatible with hydrogen gas.

❖ *Transport Sector*

The Sri Lankan Transportation demand is mainly through land transportation of which over 93% is through road transportation when it considered the passenger transportation. Even though railways are good transportation option for heavy loads, there are insignificant contributions (0.7%) for freight transportation by railways as of now. Even though the railway is the best mode for long distance freight transportation, the present incompetence with respect to the road freight transportation, the railways are not adequately utilized for freight transportation. Therefore, 99.9% of the freight handling is done through road transportation throughout the country across all the geographical zones. The total passenger transportation by mass transportation (Railways) in Sri Lanka is around 6% at normal economic and the bus transportation contribution is of 43 – 47% range on average under normal circumstances whereas this too is declining at an average rate of 2% per year as a result of increased per capita income and mode shift to private motorized modes over the last two decades. Therefore, it is understood that the public transportation share is highly affected by private vehicle ownership that contributes to high economic impacts with other externalities such as traffic congestions, accidents, and higher emissions by inefficient use of fuel consumption that has increase the imports of petroleum products which is nearly 20% of the total imports of Sri Lanka at stable economic conditions. Therefore, it is mandatory to review the present inefficiencies and the required future planning for an efficient transportation supply setup for Sri Lanka to reduce the energy cost and to contribute for direct economic benefits to SL economy.

When it considered the green hydrogen for transportation, it is very important to consider the mode of supply of green hydrogen to the existing transportation system and for the future planned transportation systems for expected outcomes to be sustainable. As per the experts in green hydrogen production, storage and use, it is understood that green hydrogen is most suitable for mass transportation than the individual transportation modes which is also the practice in most of the countries as the priority for fueling green hydrogen to transportation system. Hence, the available public transportation and the future potential shall be to encourage for Railways and Bus Transportation to use the green hydrogen as the alternative fueling source even though they consume only 18% of the total petroleum fuel as of now. However, this will help for having more efficient and friendly public transportation system that was expected to improve over decades, will encourage to attract more and more private vehicle users to shift back to the public transportation with increased facilities such as air-conditioned low floor buses, air conditioned railway compartments with accurate time schedules.

When considered the overall transportation setup in Sri Lanka, Sri Lankan Railway operates approximately 396 trains per day which include 67 Long-Distance and 16 Intercity trains and carries about 3.72 million passengers kilometers daily. SLR owns and maintains 1561 km of rail tracks, 72 locomotives, 78 power sets, with a total of 565 carriages as of today. There are 27,000 omni buses available in Sri Lanka in which approximately 7,000 and 20,000 in numbers belong to SLTB and Private Sector respectively.

Out of nearly 27,000 buses available in Sri Lanka, only less than 10,000 are operated as of now as a result of the present economic crisis and after the covid related impacts (new normal conditions). There are 778 buses at present under Sisuseriya in service to provide facilities for school children and teachers. The buses are consuming around 17% of the total fuel demand in the transport sector under general economic growth in the recent past. Under these circumstances, the total of 82% of the petroleum demand in the transport sector is consumed by all modes other than buses and the railways. Hence, such transport modes too contribute a high impact to the transport sector energy demand and hence shall not be neglected to consider for alternative clean energy options.

When considered, the improvements to the bus transportation will reduce the demand for energy consumption as it is more than 10 times effective use of the per capita energy and the over 10 times effective use of the road space compared with private motorized modes. Therefore, the orientation on mode shift from private modes to public transportation is an essential goal to be achieved during any reformation to the development of transportation in Sri Lanka that has been earmarked over decades by research, experts and the different governments that came to power. This concept has been proved by many developed countries, especially for computer services and hence to be a very important factor when we consider to switch from present petroleum fuel to much more efficient and clean energy sources. The economic contributions of such reformations can be accurately estimated with the available data in the market and through the research and experiments and shall be considered in the pre-feasibility studies and feasibility studies of the use of green hydrogen in long term in Sri Lankan context despite they are already attempted by our neighboring country like India. The direct and indirect benefits shall be critically analyzed to prove the overall benefits to the transport sector by direct fueling to public transportation while creating avenues for the private mode users to switch to the improved clean and comfortable public transportation systems especially for urban users and the long-distance users.

2.3 Challenges for Sri Lanka

- *Economic Feasibility*

The economic feasibility of the introduction if green hydrogen to energy and transport sector shall be carried out through proper analysis with adequate data for analysis to ascertain the economic returns of the investments. The green hydrogen technology and capital investments figures shall be the critical factors for economic feasibility study with all cost factors shall be identified through investigations as this is yet new to Sri Lanka even though the technical knowhow is known to Sri Lanka. The quantifiable benefits and the non-quantifiable benefits such as savings through many externalities namely reduction in congestion cost, environment cost savings etc., through strategic planning of overall transport systems changes are essential to include in the economic analysis accurately by utilization of international norms. Since, the production of the green hydrogen will be within the renewable energy sources, this shall make a high significant economic savings to the GoSL despite the short-term financial gains shall be delayed as a result of lesser energy requirements with improved efficiency. However, such can be overcome through the taxation policies and through the economic development of other sectors as a whole as a results of the use of green energy for many sectors (tourism, transportation, production, and other service sectors such as heavy constructions).

- *Knowledge transferring*

The availability of competent professionals with the knowledge and skills required for managing the financial, legal, and technological and research & development aspects of Green Hydrogen Technologies is an essential requirement for ensuring the prudent establishment of a Green Hydrogen based economy in Sri Lanka. Hence, it is essential to establish a resource pool locally who are capable of ensuring the continuity of Green Hydrogen as a viable industry. This requires the identification of capable professionals for further training and development in the respective areas of competence related to the Green Hydrogen economy. The necessary institutional support should be provided by the Government through relevant agencies such as the Ministry of Power, Ministry of Energy, PUCSL, Ministry of Higher Education, Ministry of Foreign Affairs, Department of National Planning etc. The Government shall ensure that Capacity Building is carried out through either a single or multiple international agencies possessing the necessary expertise and competence. Donor agencies such as the ADB, JICA, USAID and any other such agency shall be approached for the required assistance and funding. Capacity Building can be carried out through long term Postgraduate Studies, Training programs, International Seminars and Workshops, Local Seminars and Workshops etc. for the selected professionals of the resource pool.

While donor agencies may provide funding or concessionary loans for Capacity Building in the Green Hydrogen sector, it must be recognized that the Government of Sri Lanka (GOSL) may have to provide funding as well. Hence, such funding obligations shall have to be considered well in advance and budgeted accordingly.

It is also emphasized that Sri Lanka may stand to gain by joining both regional and global networks who are already carrying out work related to Green Hydrogen.

- *Regulations, Operation safety*

It is both an ethical and practical requirement to identify and safely manage hazards, resulting consequences and the risk imposed on society when introducing a new technology in terms of both complexity and scale. It is an ethical requirement as the risk imposed on society is involuntary and practical as the level of safety of a technological system is tightly coupled with business continuity. Hence, it is imperative that the safety aspects and implications from the adoption of Green Hydrogen technologies and the resulting value chain (i.e. production, transportation and end use) be managed at a level of safety acceptable to Sri Lankan Society and be in compliance with global norms.

Industry in general has ample experience in the safe use and handling of Hydrogen by competent and well trained industrial professionals. However, wider use of Hydrogen requires the public at large to interact with Hydrogen and related infrastructure on a frequent basis which shall necessitate the adoption of stringent safety regulations and technologies.

The usage of Hydrogen on a mass scale in Society will require the assurance of safety with respect to hydrogen installations (i.e. Production, storage, transportation and dispensing infrastructure) and its application (i.e. Industry, transportation sector, home use etc.). The hazards associated with Hydrogen can be broadly characterized as physiological (e.g. Frostbite and asphyxiation), physical (e.g. Component failures and embrittlement) and chemical (e.g. fire and/or explosion). The primary hazard is the potential for the formation of a flammable or explosive mixture with air if there is a release of Hydrogen gas. Hence, Hydrogen is managed as a Hazardous Material globally with the application of both Occupational Health & Safety (OH&S) as well as Process Safety Management initiatives. It is imperative that a well-defined Process Safety Management System (PSMS) with rigorous Risk Assessment Systems, Inherently Safer Design, Asset Integrity Management Systems and Emergency Response Systems including Crisis Management be established for the safe use of Hydrogen. The understanding of potential hazards and risks must be complemented with the determination of risk zones and safety distances with respect to installations where Hydrogen is produced, stored, transported and dispensed; to be suitably reflected in Land Use Planning (LUP) in Sri Lanka. Hence, the primary focus should be on both loss prevention and public safety.

The management of Hydrogen as a Hazardous Material should be supported by the legal system of Sri Lanka. The legal requirements are usually mandatory Regulations, codes and directives imposed by legislative bodies such as the Government and Parliament. Sri Lanka at present does not have specific legislation addressing the safe use of Hydrogen. It is imperative that a regulating agency be established or such duties be assigned to an already existing related agency (e.g. Ministry of Energy, PUCSL etc) capable of conducting the regulating process. It is emphasized that appropriate regulations are established to manage licensing, permitting and monitoring of the safe use of Green Hydrogen in Sri Lanka. Such regulations are already in place globally through the Seveso III directive in the European Union (EU) (Seveso III is a very broad directive applying to all Categories of Hazardous Material and not only to Hydrogen). However, voluntary documents such as standards (e.g.ISO), guidelines (e.g.ATEX, NFPA) and codes of practice related to the Hydrogen industry too can provide a well-defined framework for the management of Safe use of Green Hydrogen.

Sri Lanka can form alliances or partnerships with International Parties and Research Organizations with the required competence and experience in managing the Safety aspects of

Hydrogen (e.g.HySafe). It is absolutely necessary that the required knowledge, skills and exposure in Loss Prevention and Public Safety related to Green Hydrogen be imparted to Sri Lankan professionals and the necessary capacity building carried out either prior to or at least in tandem with the adoption of Green Hydrogen Technologies in Sri Lanka.

3. Methodology

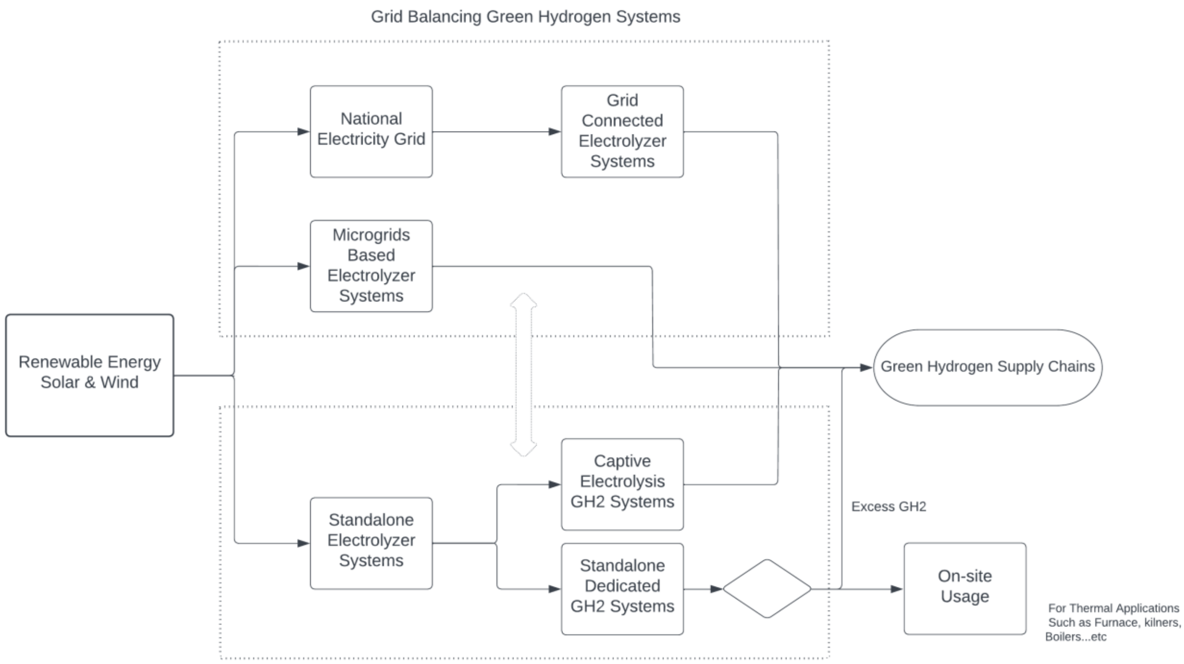

Figure 2: Green Hydrogen systems

Globally popular hydrogen systems are mainly focused on macro scale generation, storage and distribution (either through pipeline systems or bulk transport modes such as tankers in liquid or pressurized forms) supply chains. Considering the national circumstances relevant to green hydrogen infrastructure needs centralized production and distribution may not initially feasible as it will require storage facilities long distance pipeline distribution system it will be not economically feasible to consider. In such context, the following nationally appropriate methodology is proposed. However, with global technology development if any further feasibility option raised will be considered in a flexible manner. Accordingly, for the country small or medium scale production and short distance transport would be conceded subjected to their operational need scales.

According to the definition of “Green hydrogen” it should be an outcome of renewable energy-based generation process. Initially the most proven electrolysis operations will be the parent operations of the green hydrogen generation. The Renewable energy generated in a form of electricity will be the main input for green hydrogen generation process.

Two options are offered for green hydrogen generation process;

- Dedicated self-utilized green hydrogen generation systems
- Grid connected green hydrogen generation systems
- Dedicated bulk green hydrogen generation systems

3.1 Dedicated green hydrogen generation systems

These are mainly designed to generate hydrogen at their own sites and for captive use of the gas for their own operational requirements such as powering furnaces, kilns, boilers, district heating / cooling systems etc. However, in these systems flexibility required to be maintained subjected to the economic feasibility of the use of renewable power source directly to fulfil the thermal energy requirement (using directly either resistance or induction heating technologies). Selection of mode of operation will be a flexible SMART technology based rather than a fixed. Heating operations are required to dual fuel (direct electrical or hydrogen combustion) which will required to designed according to process requirement and stability of the thermal energy need which will be highly process specific. If required these systems will be connected with national grid for the mutual benefits preferably with the focus on organizations thermal energy requirement.

3.2 Grid connected Green Hydrogen generation systems

Grid quality / standard management will be the main purpose of the hydrogen generation electrolyzer systems connected in this option. During the intermittencies (especially peaks) of renewable streams, SMART controlled electrolyzer systems will start absorbing such peaks to cushion and stabilize the system. Hydrogen produced in this option will be a byproduct of the grid electricity which is generated during grid overflow levels due to low electricity usage conditions or renewable intermittencies. Microgrid connected systems and SMART grid connected electrolyzers will be the parent plants for hydrogen generation.

i. Microgrid connected Green Hydrogen systems

In the case of microgrid systems (especially recommended for operations such as industry parks) based generated hydrogen is utilized within the microgrid operation for any thermal energy requirements (either heating or cooling with district heating / cooling setups or even individual operations within the same microgrid). Within the same microgrid stored hydrogen is proposed to repower the grid either through fuel cell systems or gas turbine systems. In both this cases Cogeneration applications will improve the economics of these systems due to improved added efficiencies.

Within the microgrid operation any other green energy sources such as biogas generated is proposed to amalgamate with green hydrogen and would be used as a thermally enhances source of energy.

As another option, the outcome Green Hydrogen is connected with the national level green hydrogen supply chains which will create additional business opportunities to the country. DC microgrids options offered further enhanced overall efficiency and feasibility of the system.

ii. SMART grid connected green hydrogen systems

In this scenario renewable sources are grid connected and SMRT operations will activate the grid connected electrolyzer plants in switching them to generate hydrogen. Considering the overall system stability decentralized electrolyzer hydrogen generation facilities are proposed. Generated hydrogen will be utilized for appropriate purposes and needs in transport sector and Industry are more highlighted. The green hydrogen produced either centrally or decentralized (more preferable) will be connected with national green hydrogen supply chains and strong but dynamic supply chain development will be a definite need in the country.

3.3 Dedicated bulk Green Hydrogen generation systems

Dedicated green hydrogen generation systems will be totally grid independent and large-scale renewable facilities such as dedicated solar PV systems (ground mounted or floating systems etc.) or Wind farms (both onshore and off-shore) will be adapted to this option. Land resource limitation will be one of the major barriers to this option. This source will be one of the major components in the national green Hydrogen supply chain network.

Overall green Hydrogen supply chains and value chains will required very effective regulatory mechanism, proposed to be a main requirement in the country.

4. Implications and Recommendation

As a tropical island on the equator, Sri Lanka is blessed with many renewable energy sources, which is the prime mover of the Green Hydrogen Economy. Further, as an island nation, onshore and offshore wind potentials are enormous. With the increasing global demand and identified the potential of uses in local applications, Green Hydrogen seems strongly fitting to the following segments in Sri Lankan economy. The following segment wise implications and recommendations would be helpful for a sustainable incorporation of green hydrogen within.

4.1 Hydrogen Safety

Green hydrogen is a clean and sustainable source of energy that can have significant safety implications if it is included in Sri Lanka's fuel mix. Some of the main safety implications include:

- Storage and Handling: Hydrogen is highly flammable and requires specialized storage and handling procedures. Safety protocols must be established and followed to ensure the safe storage and handling of hydrogen.
- Transport: Hydrogen is typically transported as a compressed gas or a liquid, which requires specialized transport vehicles and infrastructure. Transporting hydrogen safely requires strict adherence to safety protocols and training for drivers and handlers.
- Combustion: Hydrogen combustion produces only water vapor, but it burns with a nearly invisible flame, making it difficult to detect. This can be a safety concern in case of accidental leaks or combustion.
- Compatibility: Hydrogen can have compatibility issues with certain materials used in fuel system components, storage and transportation infrastructure requiring careful selection of materials to prevent corrosion and leaks.
- Production: The production of green hydrogen requires energy and can involve hazardous chemicals and processes. This necessitates strict safety protocols and risk management procedures.

To mitigate these safety implications, it is essential to establish and adhere to strict safety protocols and regulations for storage, handling, transport, and production of green hydrogen.

This includes providing training and education for workers and the public on the safe handling of hydrogen, and developing appropriate regulations and standards to ensure the safe use of hydrogen in Sri Lanka's fuel mix.

4.2 Transportation

It is very important to note that the present demand for fueling for transportation is more than over 40% what is required as a result of the inefficient transport system what we have today. Congestion cost is on top of this as an externalities as a result of improper utilization of road network and could have been resolved with the intervention by the government with needed policy decisions to enhance the public transportation as what developed countries has stepped in the last two decades while neighboring countries are gradually practicing and accepted as the only way out as to resolve the land use limitation in urban context. Sri Lanka is presently considered as a country with private motorized passenger dependent countries when it considered the other regional countries as a result of car friendly policies maintained after introduction of the open economy.

It is recommended to consider the policy changes to enhance the public transportation and attract more private car users to the public modes and make the overall system more efficient before the introduction of the alternative fueling for transportation. The reason is that this shall be another strategy to make the mindset of the high income groups to switch to better public transportation specially for commuting in urban areas by utilizing modern and improved transportation systems such as BRT, LRT, electrified suburban railway systems. Therefore, Introduction of green hydrogen shall be focused on mass transit modes than the private transportation modes as to keep the efficiency of the resource utilization of the overall system. If the private modes are further encouraged for urban users at the beginning to be driven by green hydrogen, there will be continuation of the congestions further and will results more discouragements for them to switching form inefficient private modes to effective use of public transportation modes. Therefore, it is highly recommended to concentrate the green hydrogen use for public heavy vehicles to use (if possible, through policy level decision to delay the private vehicle use or through high taxation if applicable).

The freight transportation is mainly driven by the private sector as of now and almost all internal logistic management are engaged by the private sector. They are always profit oriented in their business and the green hydrogen shall be considered depending on the cost effectiveness compared with the fossil fuel and therefore, as explained by the energy experts, this will be sustainable after year 2030 with the reduced production cost with improved technology and the infrastructure available for them to make the decisions. Therefore, our targets for such use shall be forecasted through a feasibility study before fixing the policy level decisions.

The transport sector economic contributions will be mainly through how efficiently the overall transport infrastructure is utilized by the users. The main challenge is to identify the optimum usage level of the transport infrastructure with the existing and modified systems in the near future and how much contribution is made in different modes of efficient transport systems that can be introduced and operated as a whole. This shall be heavily depend on the set government policies and how friendly they are to enhance the public transportation utilization limiting the private modes for only certain trips through stringent policies for owning, and utilization of them specially in the limited urban land use. Therefore, any new changes to be taken place for energy transferred shall consider first, the most effective system balance in the different modes through supply characteristics to enhance the more utilization of high occupancy vehicles. The switching to crude oil to green energy shall be a golden opportunity to change the perception of the present private motorized users to switch to more efficient public transportation that will save a lot to the national economy through saving lots of foreign expenditure on fuel purchase and spare parts etc.

5. Green Hydrogen Research

Green hydrogen research is rapidly advancing as scientists, engineers and technicians work to develop more efficient and cost-effective ways to produce hydrogen from renewable energy sources. In addition to traditional electrolysis methods which is widely established as the promising solution for commercialization, there are several promising avenues of research in green hydrogen production, including photo catalytic water splitting, bio methane steam methane reforming, sea water electrolysis, and graphene-based catalysts and electrodes.

5.1 Photo catalytic water splitting

Photo catalytic water splitting is a promising approach to green hydrogen production that uses sunlight to drive the electrolysis reaction. This method involves using a photo catalyst, such as titanium dioxide or tungsten oxide, to absorb sunlight and create electron-hole pairs that can drive the electrolysis of water into hydrogen and oxygen. While still in the early stages of development, photo catalytic water splitting has the potential to provide a low-cost and sustainable method of green hydrogen production.

5.2 Bio methane (Biogas) Steam Methane Reforming

Bio methane steam methane reforming is another promising approach to green hydrogen production that involves using methane derived from biomass or bio waste as a feedstock for steam methane reforming. This method produces hydrogen while also reducing greenhouse gas emissions by capturing and utilizing methane that would otherwise be released into the atmosphere. Bio methane steam methane reforming is a promising approach to green hydrogen production that is already being used in several commercial applications.

5.3 Sea Water Electrolysis

Sea water electrolysis is a promising approach to green hydrogen production that involves using seawater as a feedstock for electrolysis. This method has the potential to provide a sustainable and cost-effective source of hydrogen in regions where freshwater resources are limited. While still in the early stages of development, sea water electrolysis has the potential to provide a significant source of green hydrogen in coastal regions.

5.4 Catalysis and Electrodes using indigenous sources

Graphene-based catalysts and electrodes are also being studied as a potential way to improve the efficiency and cost-effectiveness of green hydrogen production. Graphene is a two-dimensional material that has unique electrical and mechanical properties that make it an attractive material for use in catalysts and electrodes. Researchers are exploring the use of graphene-based catalysts and electrodes to improve the efficiency and stability of electrolysis and other green hydrogen production methods. Presently Sri Lanka is gaining a unique position in graphene industry after years of public private partnerships which lead to successful commercialization of Ceylon Graphite base mass production of Graphene Oxide and Reduce Graphene Oxide.

In the future, it is likely that research in green hydrogen production will continue to focus on improving the efficiency and cost-effectiveness of existing methods, as well as exploring new and innovative approaches to green hydrogen production. A central facility which is connected to all other state-of-the-art research facilities in Sri Lanka with workgroups consist of members from diversified background will certainly catalysis the journey towards successful implementation of this technology in Sri Lanka. Further, it is important for the academia and industry to connect with leading international research centers to gain directions since the world has gone far during our absence. As the demand for clean and sustainable energy continues to grow, the development of efficient and cost-effective methods of green hydrogen production will be critical to meeting the energy needs of the future.