Interreg North-West Europe GenComm

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Renewable Smart Hydrogen for a Sustainable Future

Authors

Alejandro Tristán[1], Francesco Contino[2], Diederik Coppitters[2], Isabelle Polaert[4], Lionel Estel[4], Lokmane Abdelouahed[4], Daniel Aklil[5], Vincenzo Ortisi[5], Bodo Groß[1], Paul McCormack[6], Pahvai McKee[7] , Kieran McLaughlin[8], John Bell[7] , Mark Welsh[9], Federico Azzolina-Jury[10], Rory Monaghan[3]

[1]IZES gGmbH, Altenkesseler Straße 17, D-66115 Saarbrücken, Germany
[2]Vrije Universiteit Brussel, Pleinlaan 2, 1050 Brussels, Belgium
[3]National University of Ireland, Galway, University Rd, Galway, Ireland
[4]INSA Rouen Normandie, 685 Avenue de l'Université, 76800 Saint-Étienne-du-Rouvray, France
[5]Pure Energy Centre, 3, Hagdale Industrial Estate, Baltasound, Shetland ZE2 9TW, United Kingdom
[6]Belfast Metropolitan College, 125-153 Millfield, Belfast BT1 1HS, United Kingdom
[7]TK Renewables, Station Rd 52, BT46 5EY Maghera, United Kingdom
[8]Energia, Ashtowngate, Mill House, Navan Rd, Pelletstown, Dublin 15, Ireland
[9]ENSICAEN, 6 Boulevard Maréchal Juin, 14000 Caen, France

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Abstract

As renewable sources continue their penetration into the global energy mix, they face a series of challenges that can jeopardise their growth into the future. These include intermittence, overcapacity, curtailment, constraints, long transmission distances, varying capital (CAPEX), operational (OPEX) expenses, and changing market conditions. The use of hydrogen as an energy carrier can mitigate these challenges by acting as a buffer between energy demand and supply, while enabling flexibility between the potential energetic and non-energetic uses of renewable energy. To achieve this potential, hydrogen must overcome its own challenges, which include low conversion efficiencies, high CAPEX and OPEX, while maintaining the highest safety standards.

GenComm aims to overcome these challenges through the creation of a techno-economic model and investment decision support tool that can technically and financially optimize the production and commercialisation of renewable hydrogen.

1. Introduction

Renewable energy sources continue to increase their share of installed capacity worldwide. Their integration, in conjunction with increased energy efficiency and other low-carbon technologies, constitutes the best opportunity to achieve energy sustainability. They also constitute the best option to avert the risks that conventional non-renewable sources pose to health, geopolitics, the economy and the environment. In accordance with their commitment to the Paris Agreement of 2015, 175 parties have created national renewable energy action plans (NREAPs). Each NREAP aims to develop mixed energy systems that rely on a variety of renewable energy sources and energy carriers. These plans involve increasing renewable energy penetration targets for the electricity, heating and cooling and transport sectors. These three sectors alone account for 20%, 40% and 40% respectively of total end-use energy demand. And to shift from a hydrocarbon based economy to a renewable one, there is a need for clean sustainable energy carriers.

Energy carriers have now been identified as the key enabling solution that allow renewable sources to supply different forms of energy demand across these sectors, and thus strengthen their technical and economic viability [2].

Hydrogen is one of these carriers that has attracted much support from across many countries across the globe. In fact, it has the potential to become one of the main energy carriers of the future as it can be easily produced using renewable energy, stored using commercially available technologies and used throughout the entire energy system. The use of hydrogen as an energy carrier however, has been hindered by specific challenges that need to be addressed.

This paper serves to describe these challenges and describe how project GenComm aims to overcome these challenges through the creation of a techno-economic model and investment decision support tool that can technically and financially optimize the production and commercialisation of renewable hydrogen.

2. Hydrogen as a versatile energy carrier

The selection of an energy carrier depends on three main factors: (1) technical, (2) economical and (3) environmental. An energy carrier must be capable of effectively receiving, storing and delivering different forms of energy. From an economic standpoint, the carrier production, storage and utilization should be cost competitive with existing forms of energy. It should also avoid damaging the environment or human wellbeing.

In the past and despite its clear advantages, hydrogen has not been able to compete with conventional non-renewable sources. And this was mainly due to its economic viability, other than in niche applications. Nonetheless, in the current context, where de-carbonisation of the energy system is mandatory and renewable curtailment levels are high, there is a need for an energy carrier that can as act as a buffer between renewable sources and the different forms of energy demand. This is where hydrogen can play a major role and that is why it has now acquired scientific and industrial acceptance.

Hydrogen, as an energy carrier, is a clean fuel that can be used to generate electricity, motive power and heat/cooling. However, even though hydrogen is the most abundant chemical element on earth, it does not exist in its pure form in nature. Therefore, it must be extracted from existing sources such as water (H2O). This requires the use of energy in the form of electricity to split H2O into hydrogen (H2) and oxygen (O2) using a process called electrolysis. The important note to remember about hydrogen produced via electrolysis is that it requires only electricity and water. As long as the electricity is from renewable sources, then hydrogen will be produced free from emissions. On the other hand, when hydrogen is reconverted through electrochemical conversion (fuel cells) into electrical power, heating and motion power, it only produces pure water as a by-product. As such, the full cycle from hydrogen production to hydrogen consumption as fuel is totally free from emissions. This finding is an enormous step for humanity in the search for a solution to emissions for all of the energy sectors. From the above, it is clear that hydrogen is a highly suitable fuel for carbon-free energy generation, heating, cooling and transport systems. Countries can now plan to use excess renewable energy to produce renewable hydrogen. And this solution can resolve the current curtailment and grid constrain problems encountered all over the world.

Moreover, hydrogen is present as a raw material in current and future chemical product markets. It is a constituent element in the production of ammonia, methane or methanol. These chemical products, present a value as fuels and, can be easily stored and liquefied. By converting hydrogen gas into liquids, it increases its utility, transportability and usage in many existing energy technologies such as the natural gas grid, engines or power plants. Additionally, the production of methane and methanol uses carbon dioxide, which can be captured from emissions or the atmosphere, as a building block, leading to a carbon circular economy. In the case of methanol, an additional advantage is that it can be liquefied at atmospheric conditions, further reducing the required primary energy.

a. Chemical and physical characteristics of hydrogen

The use of hydrogen as an energy carrier can be traced back to the early 1800s. The possibility for it to become the central energy carrier in modern energy systems came to light in the 1970s as it acquired importance as the fuel behind the Space Race.

Of high importance, hydrogen is the most abundant element on earth. It exists mainly in demineralized form and naturally occurs only as a part of a molecule, mainly in hydrocarbons and water. It exists in gaseous form under normal temperature and pressure conditions (293.15 K and 1 atm). It has a very low boiling point set at -252.76 °C (20.3 K) at ambient pressure. Hydrogen is also, under normal conditions, colourless, odourless and non-toxic, making it environmentally neutral.

Changes of state in hydrogen occur over a small temperature and pressure range. Liquefaction therefore is primarily performed by cooling and not by compression, opening spaces for heat recovery schemes. Liquefaction dramatically increases the density of hydrogen, by a factor amount of 800. In comparison LPG has a factor of 250 and natural gas a factor of 600. This makes hydrogen liquefaction an interesting transportation method for long distances. The transportation temperature is very low (-253°C). It must utilize a highly efficient isolation system to ensure that hydrogen does not evaporate. Transport of hydrogen can also be achieved in gaseous form under moderate or high pressure. However, a promising way of storing hydrogen is currently being developed and known as adsorption on solids and liquids. This promising storage solution can store high H2 quantities even at atmospheric pressures.

Hydrogen has the lowest molecular weight of any compound (2.0016 g/mol). It is combustible in a very broad concentration spectrum, meaning that its ignition range, marked by its lower and upper explosive limit, is correspondingly large. This wide ignition range allows for extremely lean air/gas mixtures, which minimises fuel consumption and leads to more efficient combustion.

Overall, as it can be seen in Figure 1, hydrogen has a high gravimetric, or mass-based, energy density or 120 MJ/kg or 33 kWh/kg, about 3 times higher than current conventional fuels. The mass-based energy density of a fuel is determined by its calorific value or lower heating value. The lower heating value (LHV), is defined as the amount of usable heat that is released in theoretically complete combustion. Figure 1 shows one of the challenges for hydrogen use as an energy carrier. Although its gravimetric energy density is very high its volumetric energy density is low. The challenges for the usage of hydrogen are described in the next section.

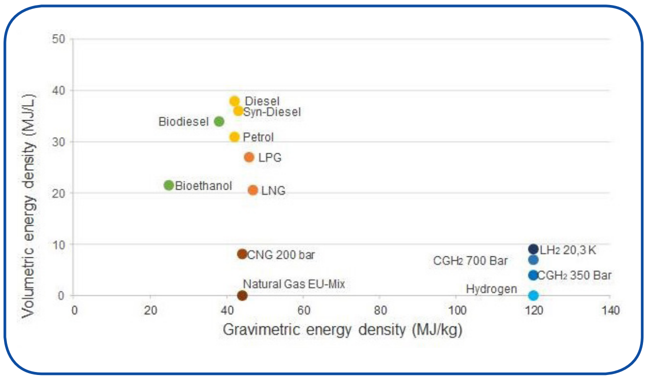

Figure 1.
Volumetric and Gravimetric energy densities of conventional fuels [7][1]

[1] Under normal temperature and pressure

b. Challenges of Hydrogen as an energy carrier

Hydrogen is often associated in the public consciousness with safety concerns. Nonetheless, due to the large-scale use of hydrogen in the petrochemical industry, and rising consideration as an energy carrier, very stringent handling standards have been set in place. As is the case for fossil fuels, hydrogen entails the following risks: (1) flammability, (2) detonability and (3) embrittlement of handling vessels.

Despite having a relatively high auto-ignition temperature of 585 °C, it has a very low ignition energy (0.02 mJ), classifying it as extremely flammable. However, a simple electrostatic discharge of 10 mJ would also be sufficient to ignite almost any other conventional fuel. The detonability range for hydrogen is very wide (18-59 vol%) [9]. Nonetheless, hydrogen has a considerably lower density than air, giving it a high buoyancy in the atmosphere and allowing to diffuse quickly. The embrittlement of handling vessels is caused by the high diffusibility of hydrogen, which therefore requires special materials for storage.

It is necessary to increase the volumetric energy density of hydrogen for practical transportation, storage and use. Storage techniques include compression, liquefaction, cryogenic freezing or material-based storage. The latter involves the creation of metal-hydrides or sorbents that chemically store hydrogen in a metal lattice structure. Furthermore, as hydrogen only appears in nature as part of a molecule; therefore, a thermochemical, biochemical, or electrochemical process is needed for its production.

At large scale, the efficiency of electrolytic H2 production can reach 75%, but when storage, transportation and conversion back to electricity or motive power are considered, overall efficiencies range from 20% to 48%. However, when compared to fossil fuels, hydrogen has a superior overall efficiency cycle. Hydrogen can be clean and sustainable, produced by a renewable energy system; unlike the millions of years to create our limited fossil fuels. Similarly, hydrogen does not have an associated emission at the point of production (if renewable electricity is used) or at the point of consumption (e.g. in a passenger vehicle). This makes it a highly efficient fuel in terms of health, environment and time from production to use. Nevertheless, it is true that the overall cycle efficiency of hydrogen may seem low. However, there is currently no real benchmark that has been put forward by the hydrocarbon industry to describe their efficiency cycle; from drilling, extracting, converting, shipping and distributing hydrocarbon products to end users. To this end, there is currently extensive research focused on improving hydrogen conversion technologies, innovative business models, and the use of hydrogen as an energy carrier.

A substantial amount of work has already been completed to overcome the above challenges with modern international codes and standards. By developing these, the international hydrogen community is sending a strong statement that the widespread handling and utilisation of hydrogen has been safe for a century and will be safe for the coming century. As already mentioned, the wide deployment of hydrogen as an energy carrier to solve electricity grid stability issues and to complement renewable energy sources is mainly hindered by its economic viability. The necessity of specific infrastructure and the “supposedly low conversion efficiency” affects both the capital investment (CAPEX) and operational costs (OPEX) of hydrogen installations. A concrete strategy therefore needs to be implemented to assure the techno-economic viability of hydrogen infrastructure and its associated mass manufacture potential driving price and cost down. This is where the concept of Smart Hydrogen becomes relevant.

3. The concept of Smart Hydrogen

Smart Hydrogen combines (1) a solution to the electrical grid network challenges faced by the mature renewable electricity technologies, (2) opportunities in hydrogen supply pathway, (3) prospects for new hydrogen applications and (4) creation of different and new trends in energy markets with “Power to X technologies”. The aim of **Smart Hydrogen** is to create a hydrogen value chain that is optimal in technical performance and financial revenues. With this in mind, the concept of “Power to X” (P2X) refers to energy conversion technologies that allow for the decoupling of power production plants from the electrical market to use their product in a number of other sectors (hence the ”X”), such as transport, heating and chemicals. Figure 2 presents the concept of **Smart Hydrogen**. The sections below analyse this concept highlighting the different challenges and opportunities in the energy sector.

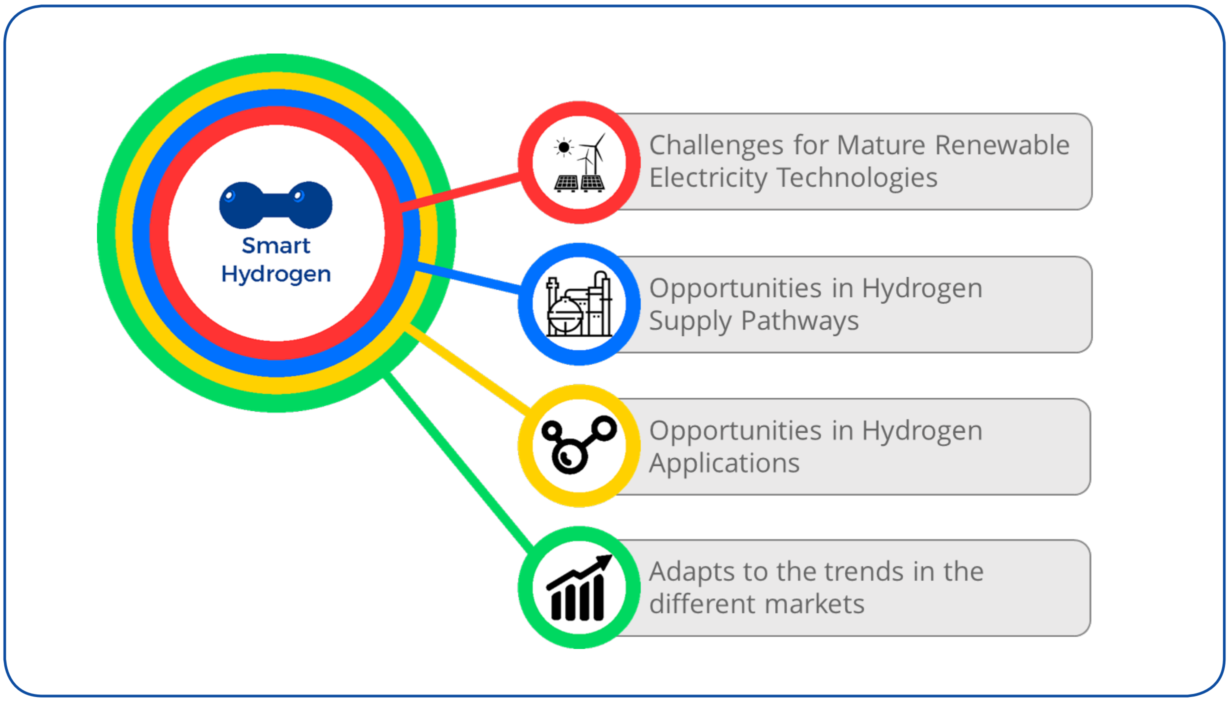

Figure 2.
Concept of Smart Hydrogen

a. Smart Hydrogen as a solution for mature renewable electricity technology

The global energy context can be subdivided in three main sectors: power, heating/cooling and transport. Despite seeing a growth deceleration from the early years of this century, global electrical power demand is expected to continue in a trend of unceasing growth. Projections up to 2040 present an expected average annual growth trend of 0.6% for OECD countries, with a considerably higher expected growth trend of 1.9% for non-OECD nations. Parallel to the constant increase in power demand, renewable energy capacity has experienced, and will continue to experience, an exponential rise. At the end of 2015 renewable electricity represented 23.7% of global electricity production. In Europe alone, continuing an ongoing trend, renewable energy accounted for a large majority (86%) of all new power installations in 2016 [4]. Currently there are eight different renewable sources identified and present in global energy markets, particularly in the power market: (1) biomass energy, (2) geothermal power and heat, (3) hydropower, (4) ocean energy, (5) solar photovoltaics (PV), (6) concentrating solar thermal power (CSP), (7) solar thermal heating and cooling, and (8) wind power. In 2015, the share of renewable energy in global final energy consumption was 24.5 % [3].

Mature technologies are those that have reached competitive levelised costs of electricity generation (LCOEs) compared to conventionally generated power. At present, the technologies that are considered mature include: onshore and offshore wind, solar photovoltaics PV, hydropower, geothermal power, and some forms of bioenergy.

Energy use for heat (water and space heating, cooking and industrial processes) accounted for more than 50% of total world final energy consumption in 2016. Energy demand for cooling is significantly lower, but it is increasing rapidly in many countries, particularly emerging economies located around the tropics. Renewable energy can, by either direct use or through conversion to renewable electricity, be used to supply these heating and cooling demands. In 2016, renewable energy's share of final energy use in the heat sector remained stable at around 25%. The main renewable source for heat, more than two-thirds, was traditional biomass, wood fuels, agricultural by-products and dung burned for cooking and heating purposes, used predominantly in the developing world. In 2016, Europe was the region in the world with the highest share, 18.6%, of renewable energy for heat production. The primary source for renewable heat in the continent is solid biomass. Nonetheless, in Germany, Europe's largest consumer of heat, the share of renewables in heating and cooling remained stable in 2016.

Global energy demand in the transport sector has followed a continuous increase of 2% annually on average since 2005. The sector accounts for about 28% of overall energy consumption and for 23% of energy-related GHG emissions. Crude oil products account for around 93% of final energy consumption in transport. Renewable energy in the transport sector has three main entry points: (1) liquid biofuels as a standalone fuel or in a mixture with conventional liquid fuels, (2) gaseous biofuels, and (3) electric transport, which relies on battery storage or hydrogen as an energy carrier [5].

The considerable progress and potential of renewable sources in the different sectors (electrical, heating and transport) has underscored the challenges faced by renewable technologies, of which intermittence is the most frequently mentioned. Intermittence is defined as the lack of continuous availability of an energy source due to some factor outside direct control. Solar and wind energy technologies in their different forms are perhaps the most common examples of intermittent renewable sources due to the constant variation of their availability and generation capacity.

Nonetheless, most renewable technologies -with the notable exception of geothermal power and heat- are susceptible to intermittency, mostly related to relatively unpredictable climatic phenomena. Currently, intermittency, particularly in the power grid is dealt with through the development of overcapacity. While this mitigates against unpredicted production shortfalls, it is detrimental due to its reliance on large-scale non-renewable back-up energy sources that can swiftly ramp up and down and hence compensate any variation in the supply. Overcapacity has been a common practice for a considerable time to deal with unexpected surges in power demand. Overcapacity increases the cost of power system operation and, as mentioned, introduces non-renewable power capacity in parallel to the increase of renewable power capacity.

Although not exclusive to renewable energy sources, the distance between sites of generation and demand is also a challenge faced by renewable technologies. This challenge is explained by the concentration of demand in urban spaces while most renewable sources, with the considerable exception of solar PV, in rural, remote or offshore areas. As nations pursue their renewable energy potential the necessity to increase the capacity and number of power transmission lines has become essential. The investment in transmission lines and other energy transmission infrastructure is in most cases very expensive as distances increase, and meet considerable resistance from local populations. Relying in the transport sector to mobilize energy carriers, in the form of liquid and gaseous fuels, will help in the short to medium term as the existing haulage infrastructure can move the hydrogen as it will be displacing existing petroleum based products.

In power grids, as transmission lines cannot cope with the transportation of peak renewable power generation, grid operators have introduced curtailment. Curtailment is the reduction in the output of a generator from its available generation potential, due to external considerations. Curtailment of generation is a normal practice of power grid operators to give the system a flexible reaction capability to variations in the electrical grids. Nonetheless, renewable sources are suffering operator-induced curtailment due to transmission line congestion. In some cases, operators have gone as far as denying transmission access to renewable power generators, rendering new investments unviable. Another recent form of curtailment that has recently emerged is market-based curtailment. The introduction of multiple sources to supply the electrical demand has created a supply market. This multitude of sources and limited demand at times has created market-based curtailment that occurs when it is not attractive, due to low or even negative prices, to sell power to the grid. This element creates additional pressure to existing and upcoming renewable power projects [6].

As the renewable power markets mature, the legislative schemes that supported their introduction into power grids are also changing. The removal of priority access and dispatch for renewable energy sources in power grids, the absence of binding national targets or indicative benchmarks in new policies, the considerable cutbacks in public subsidies, and the replacement of feed in tariffs for tendering schemes are also affecting the financial viability of existing and new renewable energy projects [7].

For non-mature renewable energy technologies, the current context has also created a challenge for additional renewable penetration. Some renewable technologies have dramatically reduced their costs per unit of power generated. Studies show that for plants entering service in 2022, onshore wind power, geothermal and solar PV will have levelised costs of electricity on par or lower than those of well-established non-renewable technologies. Although this is a positive trend overall, these cost asymmetries between technologies might push investment to focus only in these currently attractive renewable power technologies.

Unilateral investment might create negative drivers such as reduced support for research and development of parallel renewable energy technologies, and jeopardize the economic viability of existing renewable power generation schemes.

In the case of the heat, cooling and transportation sectors, additional challenges are faced by renewable energy. Deployment of renewable technologies in these sectors is inhibited by several factors; (1) limited awareness of the technologies, (2) the distributed and time-dependent nature of energy demand, (3) market fragmentation, (4) comparatively low fossil fuel prices, (5) ongoing fossil fuel subsidies, and (6) a comparative lack of policy support. In developing countries, the lack of installation know-how remains an important barrier, particularly for heat, cooling and transport.

The use of hydrogen aims to eliminate the problems associated with intermittence, as hydrogen can function as a buffer between supply and demand. The physical properties of hydrogen make it particularly suited to large-scale, long-term energy storage applications. The high energy density also allows for extensive storage capacity, while benefitting from negligible loses during the storage phase. Furthermore, current advancements in conversion technologies will allow hydrogen to supply different forms of energy demand. These conversion technologies also grant the use of hydrogen as an energy carrier the necessary flexibility to react to the variable natures of (1) energy supply and demand and (2) energy markets. In the case of overcapacity, the ease and speed with which hydrogen fuel cells and combustion engines can ramp up and down will render the need for this practice obsolete. Hydrogen can offer several alternatives to the problem of distance between energy supply and demand. Hydrogen transport technologies are mature due to its important role in the petrochemical industry. New routes of transport such as pipelines and ocean transport are under extensive research investigation.

b. Opportunities for Smart Hydrogen Production

Hydrogen exists naturally on Earth as a constituent element in other compounds, so it needs to be extracted through thermochemical, biochemical or electrochemical processes. The primary energy sources include solid, liquid or gaseous fossil fuels, and renewable electricity. Currently, the most important primary energy source for hydrogen production is natural gas, at almost 70%, followed by oil, coal and, far behind, electrolysis of water using electricity. Figure 3 presents the production share of the different sources.

The different energy sources involve different synthesis processes. The most widely used process to produce hydrogen is Steam Methane Reforming (SMR) of natural gas. Reforming is the conversion of hydrocarbons and alcohols into hydrogen by chemical process, giving rise to the by-products water vapour, carbon monoxide and carbon dioxide. In SMR, pure water vapour is used as an oxidant and the introduction of heat is required (endothermic). Other thermochemical conversion processes used to produce hydrogen are Partial Oxidation (PO) and Auto-Thermal Reforming (ATR), and to a smaller extent, gasification. PO is the exothermic conversion of mainly heavy hydrocarbons with the aid of oxygen (O2), instead of steam, as oxidant. ATR is a combination of steam reforming and partial oxidation, operating with a mixture of air and water vapour. Gasification is the reaction of a solid carbon carrier -e.g. coal- with oxygen or an oxygen-containing gasifying agent to form a synthesis gas that is later refined to hydrogen. These techniques are well mastered (controlled) in petrochemical industry but the main drawback is that it usually starts from fossils fuels (not renewable) and produces CO2 and as such contributes to the greenhouse effect.

Hydrogen generated from electricity relies on electrolysis. Electrolysis is the electrochemical process in which water is split by an electric current into its constituent elements, Hydrogen (H_2) and Oxygen (O_2).

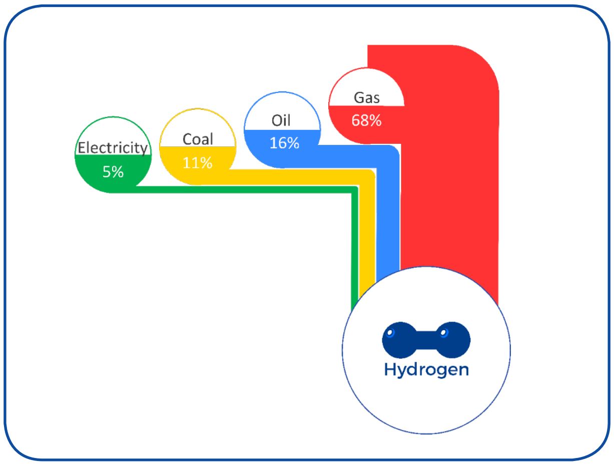

Figure 3.
Primary energy sources for current worldwide hydrogen production [8]

The production of hydrogen from biomass might also be a possibility in the longer term. Hydrogen from bio-feedstock is mainly produced by thermochemical or biochemical methods. Thermochemical methods are those previously described but rely on biofuels, biogas and biomass as energy sources. Biochemical production of hydrogen relies in micro-organisms that either ferment the feedstock or split water into H_2 and O_2 by bio-photolysis. Although highly promising, this technology is still not available at a commercial scale.

The electricity share of hydrogen production presented in Figure 3 includes conventional power production technologies. This creates a considerable problem regarding Greenhouse Gas (GHG) emissions as can be seen in Figure 4. While electrolysis itself produces no GHGs, the use of carbon-intensive electricity does.

Figure 4 gives a clear view of the synergetic relationship between renewable sources and hydrogen production. While hydrogen can provide answers to the main issues being experienced by its generation technologies, renewable electricity electrolysis is the only technique that allows hydrogen to be a truly environmentally neutral energy carrier and a sustainable value chain. Ideally, hydrogen production from renewable power will have no GHG emissions. Nonetheless, due to the current state of equipment production techniques, storage and transport technologies, they will present minimal emissions. Therefore, simple electrification of the hydrogen supply pathway will be counterproductive. The opportunity of Smart Hydrogen is to support production only when excess renewable electrical capacity is available. The use of excess or idle capacity can also help to reduce production costs.

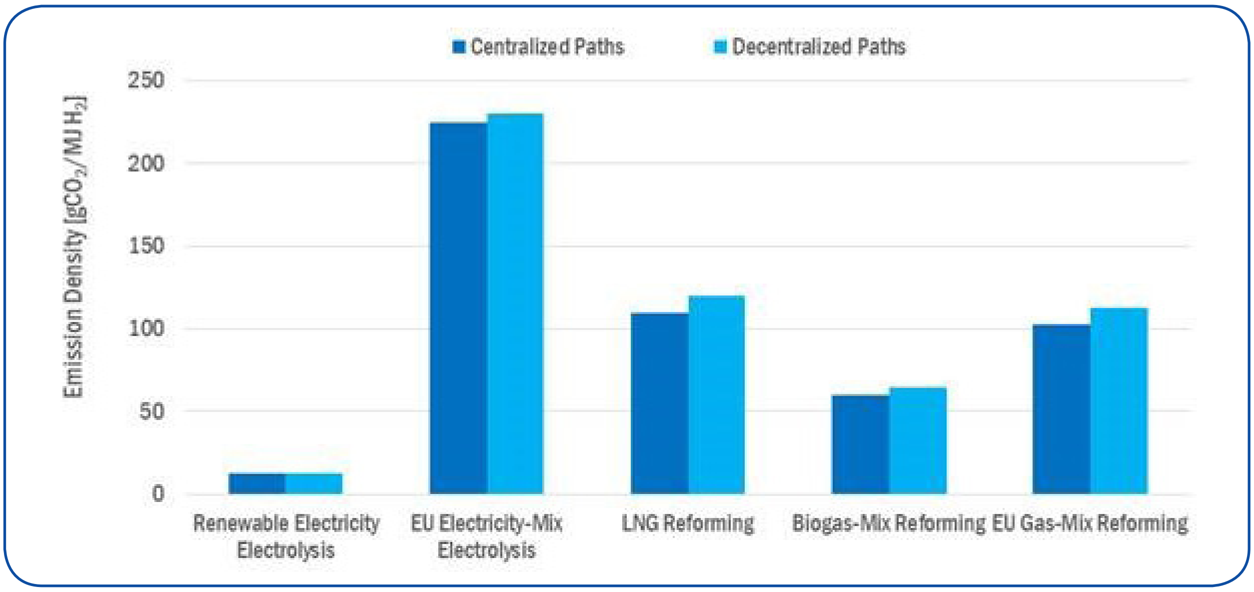

Figure 4.
GHG emissions from hydrogen production technologies [9]

Figure 5 presents current and projected hydrogen production costs. In Figure 5 there is a considerable gap between electrolysis and the benchmark hydrogen production process, reforming. The cost difference is explained by two main factors, (1) the cost of the production facilities and, (2) those of the necessary inputs. This first element is understandable as electrolysis technologies are in continuous state of development while the reforming infrastructure is mature due to its connection with fossil fuels refining. As the share of hydrogen production through electrolysis increases, the effects of economies of scale will considerably reduce the gap between production techniques.

Furthermore, the use of the idle renewable capacity can also reduce the cost of electrolysis if the price of the electrical input is lower than the average market price of electricity, particularly if it takes advantage of negative market prices. It is important to observe that based on current conditions, if renewable hydrogen is to replace the current and expected hydrogen demand, using the excess power from the current and expected share of renewable sources will not be enough, and hence the approach is to also pursue the optimisation of the revenue streams of renewable hydrogen, allowing for the offset of these costs.

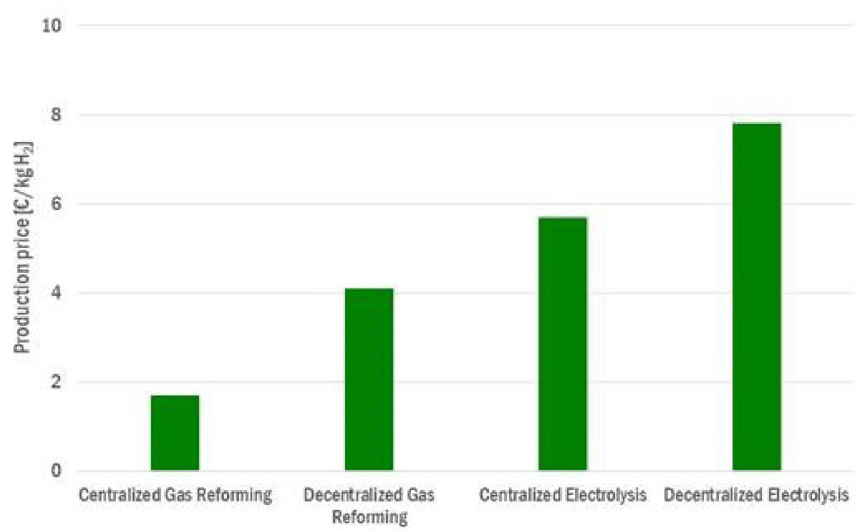

Figure 5.
Costs of hydrogen production technologies [9]

c. Opportunities for Hydrogen Utilization

Hydrogen can be used in multitude of applications through (1) hydrogen fuel cells, (2) combustion in modified engines, and (3) conversion to chemicals. Fuel cells follow a process that can be described as electrolysis in reverse. This converts the stored chemical energy of hydrogen into electricity and heat through an electrochemical reaction with oxygen. On the other hand, hydrogen combustion is the high temperature exothermic redox chemical reaction of hydrogen with oxygen in an engine. Both fuel cell and combustion reactions will only produce water as a by-product. Both technologies can be used for electricity and heat production supplying the demand of the three main sectors: power, heat/cooling and transportation. These sectors can be further divided into stationary and mobility applications.

Stationary energy applications include the use of hydrogen for storage and conversion back to electricity. In terms of storage, hydrogen is very attractive in applications that demand large quantitates and extended periods of time. Technologies include compression, liquefaction, cryogenic and material binding schemes. The use of salt-caverns, exhausted oil wells, gas fields and aquifers are currently of interest for storage schemes. Fuel cells are increasingly being used as a backup power supply alternative to engine or turbine-based generators and rechargeable batteries. Since fuel cells and hydrogen engines generate electricity and heat, their use in combined heat and power (CHP) schemes is promising for energy efficient residential and commercial buildings. Major demonstration projects are already in existence including "Callux" in Germany, "Ene-Field" across Europe and "Ene-Farm" in Japan. Japan leads the micro-CHP hydrogen fuel cell market with 200,000 units by 2016 and 5.3 million are expected by 2030.

Mobility applications involve using hydrogen as an energy source for the transport sector. As for the case of stationary applications, transport technologies make use of fuel cells and combustion engines and cover all the different forms of transport. Nonetheless the different forms of transport have different levels of maturity. The US space agency, NASA, has created a system to contrast the level of maturity of different technologies called Technology Readiness Level (TRL). The TRL scale goes from levels 1 to 9. TRL of at least 8 implies sufficient technological maturity, which means at least proven functionality in the field of use. Table 1 presents the different readiness levels for hydrogen mobility applications based on their applications.

Table 1.
Technology Readiness Levels (TRLs) for Hydrogen Mobility Technologies [9]

Type of Transport	TRL
Space Travel	9
Material Handling	8-9
Passenger Cars	8
Buses	7-8
Light Rail	7
Shunting Locomotives	6-7
Motorcycles	6-7
Lorries	6-7
Aviation	5-6
Shipping	5-6

Despite the wide range of TRLs shown, it is important to point out that some mobility applications are ready to be transitioned to hydrogen. These technologies will support the creation of the necessary infrastructure that can help other applications reach commercial maturity. In industry today, there are significant numbers of fork-lift trucks running with hydrogen fuel cells. This highlights that this market of small vehicles for transportation or services can also can be developed.

Furthermore, hydrogen can also be used to produce chemicals, materials and fuels. At present, hydrogen constitutes one of the key raw materials for the petrochemical industry. Currently 60 million tonnes are produced per year, constituting a $110 billion market worldwide that is expected to grow to $150 billion in 2024. The largest single share of this hydrogen market is used to produce ammonia, which in turn is used as a fertilizer, fermenter, cleaner and refrigerant.

A final use of hydrogen still under research is its use as a reactant to create or upgrade fuels. Processes of interest include methanation to produce methane (CH_4) with CO2 capture schemes, and the production of methanol (CH_3OH), a promising liquid fuel with characteristics very similar to conventional fossil fuels. Ammonia (NH_3) is also currently under investigation as a fuel.

In summary, the introduction of hydrogen into current energy systems enables a variety of smart solutions that mitigate many aspects of the sustainability challenge. Furthermore, hydrogen opens several new revenue streams for renewable power within and beyond the energy sector, creating attractive economic pathways that prevent curtailment, help compensate price asymmetries, and strengthen the renewable energy market to make it resilient to political and economic variations.

4. The GenComm project and the Smart Hydrogen Concept

GenComm, which is supported by the European Union through the InterReg NWE programme, is a €9.34 million project that aims to validate hydrogen as an energy carrier. It will create a decision support tool (DST) that allow communities to maximize use of their renewable sources and supply their main energy demands using hydrogen storage. The key element at the centre of this objective is the creation and development of a Smart Hydrogen matrix. For this, the project must reconcile the current challenges faced by both renewable sources and hydrogen technologies in the current energy context, and create opportunities that allow the creation of energetically sustainable communities. As the previous sections show, most of the challenges that renewable sources face can be mitigated by maximising the usage of its idle capacity, while flexibility of potential applications for renewable energy can be enabled. Hydrogen challenges can be overcome by minimising operational costs while maximising process efficiencies and potential revenue streams. This is the concept of Smart Hydrogen; hydrogen whose production is powered by the idle renewable capacity of a given location and that is stored and used in a diversity of applications thus maximising its profitability. At the heart of GenComm is the techno-economic model that will match the idle capacity of renewable sources in a specific location with the location's energy demands at different points in time. This will project the potential production of hydrogen and calculate its optimal use routes to maximise return on investment while minimising inherent inefficiencies.

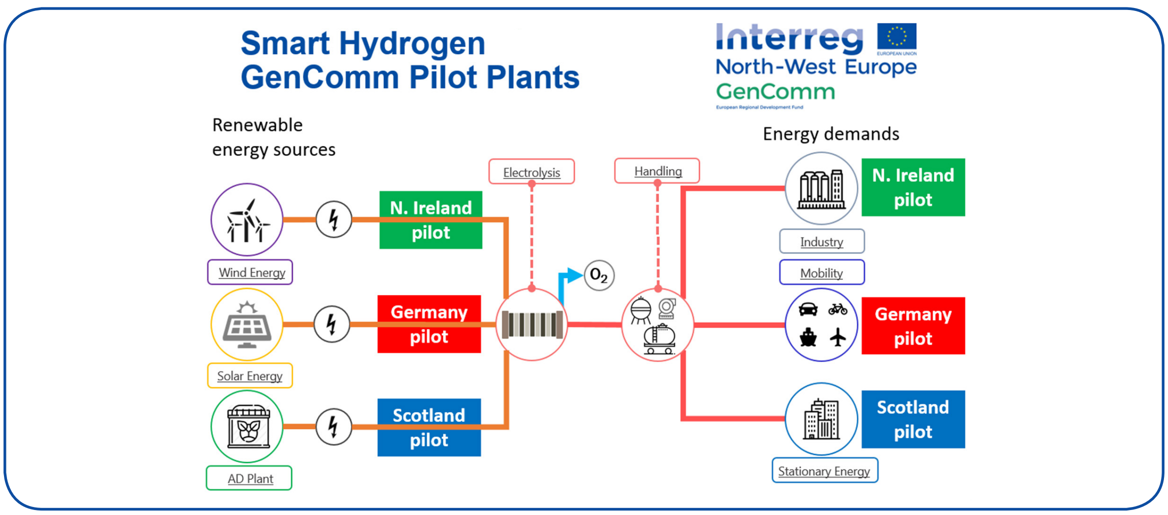

Figure 6.
The Smart Hydrogen concept and GenComm Pilot Plants in North West Europe

As illustrated in Figure 6, GenComm will start with the implementation of three pilot plants in different areas of North West Europe and at different capacities. The pilot plants will connect the three main sources of renewable energy in North West Europe (bioenergy, solar PV and wind), with the three main forms of energy demand (power, heat and transport). The pilot plants will provide the necessary technical inputs to build technical and financial integrated overall models, with the previously described capabilities. To assure the widespread utilisation of these models, they will be adapted into a DST that can provide location-specific results and can provide direction for additional actions that may be necessary to guarantee the success of the eventual hydrogen based energy system. The overall structure and flow information for the project is presented in Figure 7.

The DST will support the development of hydrogen storage in communities across North West Europe and beyond. This will demonstrate the successful and safe operation of the technologies, thus improving the economic viability of hydrogen as an energy carrier.

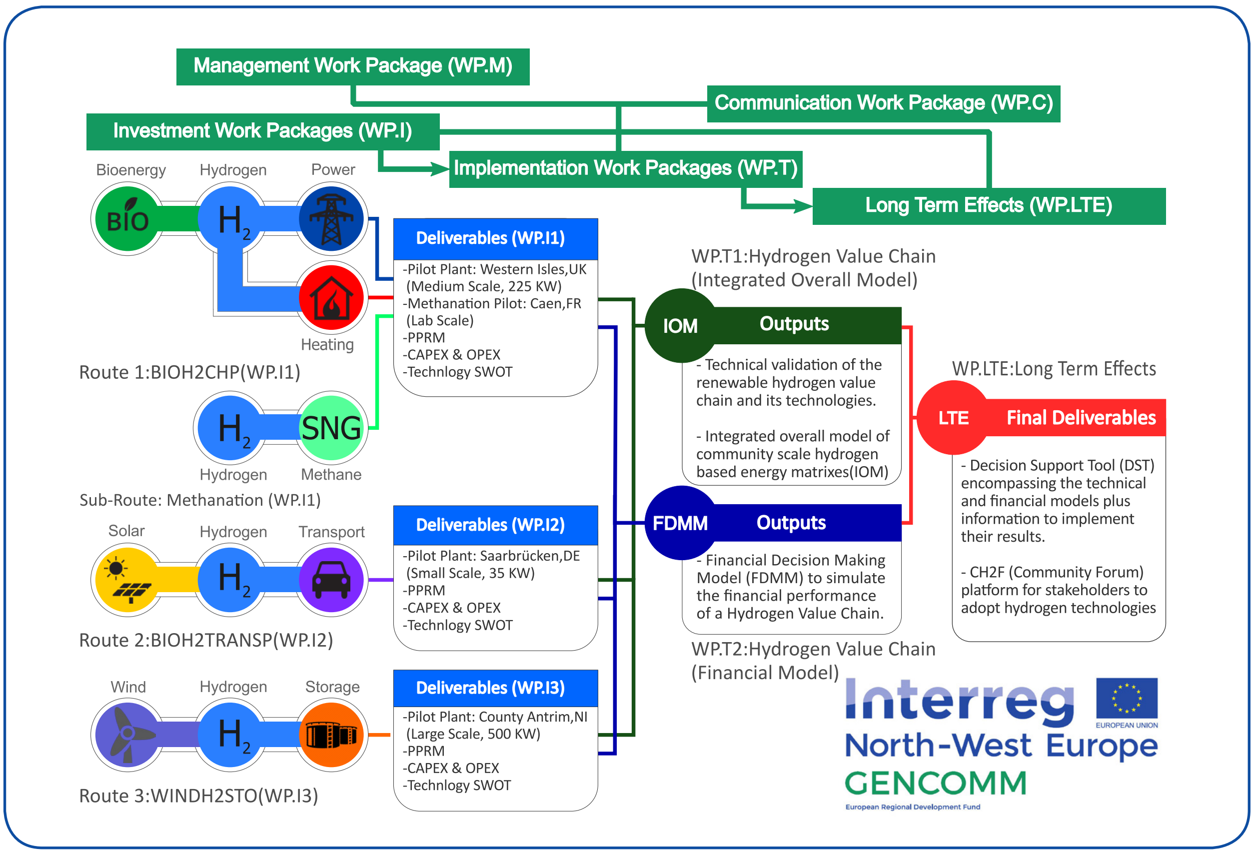

Figure 7.
Project GenComm work package structure

5. Concluding Remarks

This Hydrogen Position Paper aims to give readers an understanding of the challenges faced by increased penetration of intermittent renewable energy in North West Europe, and the potential role that **Smart Hydrogen** can play in addressing them. The key take-away messages from this report are:

1. Electricity accounts for 20% of final energy use. A fully renewable electricity supply cannot on its own decarbonise energy use at the pace and scale needed to avoid potential catastrophic climate change.
2. Increasing penetrations of intermittent renewable energy have reduced CO_2 emissions and increased energy security of supply. This has been achieved using overcapacity, which results in periods when excessive supplies of renewable energy must be stopped, or curtailed. This restricts the economic sustainability of renewable energy.
3. Hydrogen is a highly versatile energy carrier that can be used to meet demand in the heating/cooling, transport and power sectors. The fact that it can be produced efficiently, cleanly and safely using only electricity and water makes hydrogen ideally suited to address the challenges of intermittency, overcapacity, curtailment, and the need to store energy seasonally.
4. Hydrogen can be used efficiently and with no CO_2 emissions in fuel cell powered vehicles. As an automotive energy carrier, hydrogen is not expected to compete with the ongoing electrification of light-duty passenger cars and vans. Fuel cell electric vehicles (FCEVs) will instead compliment electric vehicles (EVs) by decarbonising larger cars, trucks and buses that require energy densities and ranges that EVs cannot provide.
5. **Smart Hydrogen** is a concept that combines (1) a solution to the electrical grid network challenges faced by renewable electricity, (2) opportunities in hydrogen supply pathways, (3) prospects for new hydrogen applications, and (4) innovation in energy and chemicals markets with "Power to X technologies".
6. GenComm is a €9.34 million project backed by the EU through the InterReg NWE programme consisting of 10 partners from 5 countries. It will demonstrate Smart Hydrogen at pilot commercial scale at three sites in Northern Ireland, Scotland and Germany. GenComm will validate the technical and economic performance of **Smart Hydrogen** and develop a Decision Support Tool (DST) to enable the widespread, cost-effective adoption of hydrogen storage solutions.

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