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Speed of Innovation Diffusion in Green Hydrogen Technologies – Variables and their Interdependence

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Declaration

I hereby declare that this document is an original work of my own authorship and that it fulfils all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa and Instituto Superior Técnico.

Declaração

Declaro que o presente documento é um trabalho original da minha autoria e que cumpre todos os requisitos do Código de Conduta e Boas Práticas da Universidade de Lisboa e do Instituto Superior Técnico.

ABSTRACT

The world is facing unprecedented challenges regarding climate change and greenhouse gases emissions; hence the European Union is responding to these issues setting an ambitious yet attainable action plan for a systematic transition towards a carbon-neutral continent by 2050.

Green Hydrogen will be a major player for a sustainable energy transition, representing an energy carrier and a viable solution to decarbonize different sectors over time with numerous uses in transportation, industry, heating, and energy storage. However, this technology is still in its early stages of development with a lack of infrastructure, investment, and low adoption levels. The urgent need for a fast shift to a climate neutral economy and the applicability of hydrogen in a large scale, reveal the importance to achieve fast diffusion of this technology and understand the variables influencing its success.

This dissertation focuses on the innovation diffusion of the Green Hydrogen technologies. This was achieved through a maturity model based on 12 Case Studies to understand how these will diffuse in the current market conditions and how fast will each achieve market saturation, followed by validation interviews and final actionable recommendations. The model presented is based on the diffusion of innovations principles developed by E. Rogers (1983), aligned with recent literature review in the field of value networks, innovation ecosystems, sustainable energy, and hydrogen supply chains.

The model's main conclusions suggest that successful hydrogen projects thrive on robust innovation ecosystems, where a web of partners must cooperate with main focus on the technology's variables of compatibility with existing ways of work, adaptability, ese of trialling and technical readiness.

Keywords: Innovation Diffusion, Green Hydrogen, Speed of Diffusion Modelling, Innovation Ecosystems

RESUMO

O mundo enfrenta desafios sem precedentes no que toca às alterações climáticas e emissões de gases de efeito de estufa, pelo que a União Europeia está a responder a estas questões estabelecendo um plano de ação ambicioso, mas exequível para uma transição sistémica para um continente neutro em termos carbónicos e de outros poluentes até 2050.

O Hidrogénio Verde será muito importante para uma transição energética sustentável, representando um portador de energia e uma solução viável para descarbonizar diferentes setores ao longo do tempo com muitas utilizações, nos transportes, indústria, aquecimento e armazenamento de energia. Contudo, esta tecnologia ainda se encontra nas fases iniciais de desenvolvimento com falta de infraestruturas, investimento, e baixa adoção. A necessidade de uma mudança rápida para atingir as metas climáticas e a aplicabilidade do hidrogénio em grande escala, revela a importância de conseguir uma difusão rápida desta tecnologia e compreender que variáveis influenciam o seu sucesso.

Esta dissertação centra-se na difusão da inovação das tecnologias de Hidrogénio Verde. Isto foi atingido através de um modelo de maturidade baseado em 12 Casos de Estudo para perceber como estes se difundirão nas condições atuais do mercado e a rapidez com que atingirão a saturação de mercado, seguido de entrevistas de validação e recomendações de ação finais. O modelo apresentado baseia-se na difusão dos princípios de inovação desenvolvidos por E. Rogers (1983), alinhado com estudos no campo das cadeias de valor, ecossistemas de inovação, e cadeias de abastecimento de hidrogénio.

As principais conclusões do modelo sugerem que os projetos de hidrogénio bem-sucedidos ocorrem na presença de um ecossistema de inovação robusto, onde a rede de parceiros coopera conjuntamente com um foco particular nas variáveis das tecnologias da compatibilidade com os meios tradicionais de trabalho, adaptabilidade, facilidade de experimentação e disponibilidade tecnológica.

Palavras-chave: Difusão de Inovação, Hidrogénio Verde, Modelação de Velocidade de Difusão, Ecossistemas de Inovação

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BEV	Battery Electric Vehicle
CAPEX	Capital Expenditure
EC	European Commission
EU	European Union
FCEV	Fuel Cell Electric Vehicle
GH	Green Hydrogen
GHG	Greenhouse Gases
HSC	Hydrogen Supply Chain
HRS	Hydrogen Refuelling Station
ICE	Internal Combustion Engine
LOHC	Liquid Organic Hydrogen Carrier
NG	Natural Gas
OPEX	Operational Expenditure
PEM	Proton Exchange Membrane
RES	Renewable Energy Sources
TRL	Technical Readiness Level

1 – Introduction

1.1. – Problem background and motivation

Green Hydrogen - hydrogen produced from water and renewable sources (Kakoulaki et al. 2021) – and used in fuel cells, both for stationary and mobile applications, constitutes a very promising energy carrier in the context of sustainable development in the global energetic mix. Hydrogen technologies have significant potential to improve energy security and mitigate the effects of climate change, hence creating a path to a clean, sustainable energy system. The concept of Green Hydrogen constitutes a disruptive innovation on how energy is produced, stored, and consumed. Currently, the cost of green hydrogen is not competitive compared with fossil fuel based hydrogen (IEA 2019a; IRENA 2020), yet with the development of hydrogen and fuel cell technologies, the increasing fossil fuel prices, and carbon emissions taxation, have resulted in greater competitiveness for hydrogen recently which is expected to improve even more in upcoming years. Several European countries have presented plans to instal hydrogen infrastructures and to accelerate the deployment of the hydrogen economy (European Comission 2020b), although much of the required technology is already available to commercialise, the deployment of a hydrogen infrastructure constitutes a challenging task, because of the inherent CAPEX and OPEX, the need of achieving cost-competitive production and diffusing to mass markets. The hydrogen infrastructure and complementary technologies are seen as an important part of the future energy mix, due to their advantages in terms of reducing GHG emissions in various sectors, from transportation, to industry, and the energy sector itself (IEA 2019a).

Given this context, the need to study methodologies for the deployment and design of hydrogen supply chains is increasing, enhancing both supply and demand through all its environmental, economic, and social benefits. Both research and projects in the field have been growing at an increasing rate in recent years (Chapman et al. 2019; Fuel Cells and Hydrogen EU 2020), yet many concepts still remain undeveloped, namely the diffusion process and variables influencing the adoption of the technological innovations behind Green Hydrogen.

A research-based maturity model for forecasting the speed of innovation diffusion from ideation to market saturation will be developed, with the aim of understanding and enhancing the acceleration of diffusion in the innovations present in the Green Hydrogen technologies. The following thesis will understand the factors enabling the adoption of the mentioned innovations, the variables influencing their acceleration and how they actually diffuse with the influence of all stakeholders present in the ecosystem, with the objective of reducing development costs, financial and market uncertainties and to minimize the time needed to reach the critical mass of adoption.

1.2. – Dissertation objectives

This dissertation work covers the first stages of theoretical approach to the methodological and conceptual background along with the practical application of the mathematical model, whose ultimate goal is to develop a maturity model on innovations in the multiple levels present in the Green Hydrogen supply chain, understand how it diffuses throughout time and present recommendations on the variables influencing diffusion to focus on future ventures. This formulation was developed based on the design of the ideal hydrogen supply chain to be implemented, through a holistic view, in order to reach high rates of diffusion in the whole value chain. The key aspects to understand the methodology proposal to tackle the problem, are the following:

- Review of previous research in diffusion concepts and models, understand how the diffusion of innovations is assessed and how it can be useful to apply in the data retrieval and development of the desired model.
- Description of the technologies behind Green Hydrogen, and its supply chain levels. Understand these innovations as the main focus, align with selected Case Studies, and apply them to the concepts on Diffusion of Innovations, specifically applied to a parametric simulation.
- Development of the maturity model, applied on GH case studies.
- Validate the outcomes of the model assessed through semi-structured interviews with experts in the industrial, energetic and hydrogen fields.
- Recommend the major actions and variables to consider when developing GH projects with the objective of reaching mass adoption faster and more successfully.

1.3. – Dissertation structure

To achieve the previous objectives, this dissertation is divided in the following six chapters:

1. **Introduction:** the present chapter serves to contextualize the central subject of investigation, define the main objectives, and explain the project’s structure.
2. **Problem Definition:** the second chapter presents the main problem to research, the elements that constitute it and the knowledge capacity to apply it to the thesis. In particular, the green hydrogen innovations, the EU role in applying this technology and the different steps present on the hydrogen supply chain are described.
3. **Literature Review:** here the state of art behind the dissertation is presented namely, the main concepts, methodologies, and results of previous investigations. Seeking to present the theoretical foundations on innovation diffusion, value networks, and previous methodologies used to model technological innovations and diffusion models.
4. **Methodology Proposal:** in this chapter an explanation of the origin and method of data retrieval is provided, articulating with the theoretical concepts presented in the reviewed literature. Also, a description of the methodology proposed built on the Bass Diffusion Model, the maturity model used, and the Case Studies in the HSC that were employed as data inputs of the model.
5. **Results: Analysis, Validation and Discussion:** The implementation and computational experiments performed with the proposed model and methodological approach are described. The main outputs of the Innovation Diffusion Model are described, as well as the validation process occurred afterwards, and the final recommendations are presented and discussed.
6. **Conclusion and Future Developments:** the last chapter summarizes the key findings of the thesis, exposes the most relevant features studied and presents the future steps proposed in the development of upcoming research.

2 – Problem Definition

In the following chapter, an explanation is presented of the main problem studied during the dissertation, providing details about the various elements that constitute it and illustrating the capacity revealed to apply knowledge in the formulation of the investigation matter. Specifically, hereafter are described the definitions on Green Hydrogen technologies, how this innovation is growing as one of the big subjects in the field of energy transition in Europe and in the world, and an explanation of the various levels of the Hydrogen Supply Chain (HSC).

2.1. – EU economic decarbonization

Due to the increasing global energy needs, climate change challenges and GHG emissions, the European Union (EU) has aimed to be climate-neutral by the year of 2050, meaning an economy with net-zero greenhouse gas emissions. In this context, in 2019 the European Commission (EC) presented the European Green Deal (European Comission 2020a), this proposal provides environmental actions including, investment in environmentally friendly technologies, rolling out cleaner, cheaper, and healthier forms of private and public transportation, decarbonising the energy sector, ensuring buildings are more efficient and supporting industries to innovate in green businesses.

Four priorities are seen as crucial to deploy EU's energy transition (Tagliapietra et al. 2019): adopt transformative policies to decarbonise the transportation sector, prepare the electricity system for substantial increase in RES, strengthen the EU advantage in low-carbon technologies and foster the decarbonisation of industry, transportation, and buildings.

Henceforth, the role of hydrogen is seen as representing a key role in a clean, secure, and affordable energy future (IEA 2019a). It can represent a major solution to decarbonise different sectors from industry, transportation, and the energy sector itself (European Union 2021) using it as fuel, as energy carrier, or for energy storage. However, nowadays many of its end uses are still expensive and unexplored, as a result the EU is currently investing on the development of multiple hydrogen-based projects from production, distribution, and storage of renewable hydrogen at a large scale (European Union 2021). Currently some of the most relevant projects happening globally in renewable hydrogen are endorsed by the EU, with the establishment of the Horizon 2020 Fuel Cell and Hydrogen Joint Undertaking (Fuel Cells and Hydrogen EU 2020), the EC intends to accelerate the European technologic lead, by funding projects into two main application pillars, energy, and transport, in cross-cutting and overarching activities.

In order to attain a broader use of hydrogen, it needs to achieve a larger scale in the EU's energy mix and become fully decarbonised through the Green Hydrogen initiative. In 2020 the EC presented "A hydrogen strategy for a climate-neutral Europe" (European Comission 2020b), in an early phase from 2020 to 2024 the strategic objective is to install at least 6 GW of water electrolysis capacity in the EU and producing 1 million tonnes of renewable hydrogen, scaling up the production of large scale electrolysers (fit for 100 MW). In the following phase, from 2025 to 2030, the EU plans to install at least 40 GW of electrolysers resulting in up to 10 million tonnes of renewable hydrogen, in this stage it is expected GH to become cost-competitive with other hydrogen production forms and gradually increasing demand in new applications, with steel industries, transportation and gas transition. In this phase, the so-called “Hydrogen Valleys”, understood as regional clusters that produce hydrogen from decentralised renewable energy and supply local demand in industrial and transport applications, will be developed in addition to the application of using hydrogen production to balance energetic grid needs and supplying heat for buildings (EGHAC 2022). In a final phase from 2030 to 2050, it is expected that renewable hydrogen technologies reach maturity and are established at large scale, reaching all hard-to-decarbonise sectors. In this final phase, renewable electricity sources will account as the majority of energy production, if not exceeding the energetic needs, and it is expected that around a quarter of renewable electricity may be used to produce hydrogen (European Comission 2020b). A forecast developed by IRENA, describes the possibility of hydrogen being able to provide 18% of global final energy demand, equivalent to 78EJ by 2050 (IRENA 2018). The new wave of awareness happening in the EU is also arising in countries where, in addition to the environmental benefits, the technology is more profitable due to the high availability of RES and economies of scale, where added value to the economy will be created by the new industry, in countries such as China, Chile, Japan, the United States, and Australia (IRENA 2020).

While providing a good possibility of energetic sustainable growth, Green Hydrogen is nowadays a very expensive technology to develop, therefore it needs incentives, similar to the ones provided in early stages of renewable energy technologies, from governmental and innovative entities to develop the inexistent infrastructure and drive down costs (European Comission 2020b). The EU plans to enable the hydrogen economy by incentivising both supply and demand, through reducing the cost gap between conventional and renewable hydrogen productions, by means of appropriate governmental aid rules and stimulation investments to private and institutional entities, to build a sustained scale up of the hydrogen ecosystems (European Comission 2020b). In the period between 2020 and 2050, investments in production capacities are projected to amount amongst 180 and 470 billion euros (€) in the EU alone (European Comission 2020b). Additionally, the EC launched the European Clean Hydrogen Alliance, as part of the new EU industrial strategy (ECHA n.d.; EGHAC 2022; European Commission 2020), to support these investments and the development of the whole hydrogen ecosystem, from source to the final applicability. Furthermore, the EU in collaboration with the EIT InnoEnergy created the European Green Hydrogen Acceleration Centre (EGHAC) (EGHAC 2022), an initiative that aims to create industrial players which help to de-risk and accelerate their GH initiatives. The initiative acts through early-stage investments and acceleration services which they deliver in collaboration with their open ecosystem.

All the aspects presented above, show the high engagement displayed by the EU to diffuse the technology and accordingly the urgent need to understand the dissemination of the GH technologies globally with particular focus on the European continent. Driving hydrogen development past the tipping point needs critical mass in investment, new lead markets, an enabling regulatory framework, sustained research, technical expertise, and innovation into breakthrough technologies. In favour of bringing new hydrogen solutions to market, a large-scale infrastructure network that currently only the EU can offer and cooperation with other countries to develop a global hydrogen supply chain.

2.2. – Hydrogen role in the energy transition

The decarbonisation of the world economy, a process that cannot be postponed, as aforementioned will give hydrogen more prominence in the energetic framework. It will hold a special part in hard to electrify sectors, such as industry (feedstock to petrochemical and fertilizer sectors), heavy transportation, heating, and energy storage (IEA 2019a).

Currently a major part of the global hydrogen consumption is dominated by two industries: oil refineries 52% and ammonia production 43%, the remaining consumption lies in other industrial applications (IRENA 2019). In Europe, ammonia, and oil production account for 50% and 30% respectively, methanol production represents 5% and metal industries around 3% (Kakoulaki et al. 2021). Most of this consumption derives from fossil fuel based hydrogen, although Iberdrola is currently developing the largest GH project for industrial use in Europe as an off grid hydrogen production to supply an ammonia factory in Spain with an electrolysing capacity of 20 MW (Iberdrola n.d.). Adding to the already developed utilizations, where hydrogen is used as feedstock in refining, chemical and fertiliser industries, the hydrogen potential applications are numerous and still mainly unexplored (Maggio, Nicita, and Squadrito 2019).

According to the IEA, renewable electricity production increased 45% to 280GW in 2020 and it was the only energy source to increase in this year despite the pandemic effects, it also predicted that the share of RES in the global energy mix to increase in the recent future (International Energy Agency 2021). By 2022 solar PV production increased 162 GW representing an addition 50% higher than in 2019, while wind energy production increased a record breaking of 114 GW in 2020 a yearly increase of 90% (International Energy Agency 2021). Bearing in mind the fluctuating nature of RES production compared to the energetic supply and demand, renewable hydrogen has been considered a viable solution as an energy storage method, particularly with large amounts of energy during long durations, through the electricity-hydrogen-electricity cycle (Power-to-Power). The production of hydrogen from RES through electrolysis, storage, and the reconversion into electricity for grid supply, by fuel cells or gas turbines, presents a favourable off-grid application, for instance in isolated areas or as back-up power (IEA 2019a; Maggio et al. 2019; McKinsey and Hydrogen Council 2021). However, it does not yet seem viable due to the low full-cycle efficiency currently between 30% to 40% (Chapman et al. 2019).

Another possible pathway lies on supplying hydrogen through the existing natural gas grid, by blending both together to generate hydrogen enriched natural gas (HENG), which is more energetically dense and can be used in buildings or industrial complexes in combined heat and power systems (IRENA 2020). This represents a viable transitioning solution while dedicated infrastructure, and hydrogen grid are not installed.

Hydrogen can also be distributed to refuelling stations to fuel hydrogen powered vehicles, or fuel cell electric vehicles (FCEV) as a clean energy source, leaving no bi-products other than water. FCEVs are superior in operating range and refuelling time compared to battery electric vehicles (BEV) (IRENA 2018), while their energetic efficiency is significantly lower than that of BEV (electrolysis alone represents an energetic loss of approximately 30% from the useful energetic input). As with common electric vehicles or even traditional ICE cars, a substantial infrastructure is necessary to supply hydrogen-powered vehicles (IRENA 2018). The FCEV range is wide, while also applicable to cars, and trains, ideally fuel cell technologies are most suited in hard-to-electrify, long-haul, and heavy-duty vehicle markets, such as trucks, buses, maritime shipping, and aircrafts (IRENA 2018). These represent means of transport where electrifying through batteries or direct electric current is inefficient or even undoable with currently existing technologies, and a different fuelling method is needed to change from fossil fuel based transports and decarbonise each sector (IEA 2019b). For instance, Airbus is currently developing the first zero-emission commercial aircraft fuelled by hydrogen through modified turbine engines (Airbus n.d.). The Toyota Mirai and Hyundai NEXO are some of the first FCEV to be commercially and mass produced, and other car manufacturers are already investing on the development of similar technologies, such as Renault and Daimler investing in FCEV to be deployed in the next decade (Daimler n.d.; Hyunday n.d.; Renault Press 2019; Toyota 2021). Regarding maritime shipping, around 90% of all freight transportation happens by sea representing about 3% of the global GHG emissions (FCH EU 2020b), as a result the European maritime industry is developing ways of using hydrogen-fuel cell technologies in cargo ships, ferries, and cruise fleets (FCH EU 2020a). Moreover, heavy-duty fuel cell trucks are being developed in Europe as a way of diffusing the technology to truck operators, manufacturers, and policy makers (H2Haul n.d.) and Daimler is developing its first fuel cell truck expected to be deployed in 2027 (Daimler n.d.).

2.3. – Green Hydrogen

Hydrogen (H_2), a universal, light, and highly reactive fuel is the most abundant chemical structure in the Universe. Although it is not directly accessible on earth since it does not hold as an isolated element it can be found largely associated with other elements, for instance in, biomass, coal, and natural gas but also in one of the most common compounds on earth, water (H_2O). Hydrogen has for a long time been used by the chemical industry as feedstock in industrial processes and is likely to become more prominent in other fields (European Union 2021; Maggio et al. 2019).

Green hydrogen (GH) is an energy carrier characterized as hydrogen (H_2) produced from renewable sources, energy, and feedstock, currently it represents only 3.9% of the global hydrogen production (Dincer 2012). The most established technology to produce GH is water electrolysis using renewable electricity in an electrolyser (Azzaro-Pantel 2018).

Nowadays, 95% of the global hydrogen production is obtained from natural gas and coal (IRENA 2020) generating what is recognized as Grey Hydrogen, hydrogen produced with fossil fuels using processes known as steam methane reforming (SMR) or coal gasification (CG), launching into the atmosphere between 70 and 100 million tonnes of CO_2 per year in the EU alone (European Comission 2020b). The production of grey hydrogen incurs in substantial GHG emissions, which do not represent a viable solution considering the long-term goal of economic decarbonization. Another possible way of improving the hydrogen production and diffusion, is what is known as Blue Hydrogen (IRENA 2020) – also acknowledged as low-carbon hydrogen – defined as grey hydrogen with the process of carbon capture and storage (CCS), this technology is presumed by many scholars as a viable way of ensuring a smooth transition in the early stages of infrastructure development from a production based on fossil fuels to producing based on RES and electrolyser technology, it would allow the use of existing production processes while still achieving lower GHG emissions, reducing pressure on renewable energy capacity and Green Hydrogen production, nevertheless it still relies on fossil fuels as feedstock (Almansoori and Betancourt-Torcat 2016; European Comission 2020b).

However, adding to all the disadvantages related to Grey Hydrogen such as using limited natural resources (fossil fuels), the Blue Hydrogen applying CCS does not eliminate the emissions of GHG instead, it only reduces them since the capture efficiencies are between 85-95% in the best case scenarios and these emissions still need to be stored somewhere (IRENA 2020). Moreover, the CCS holds high costs related to transportation and storage of the remaining CO_2 and the inherent surveillance of the stored material. Henceforth, in the short-term Blue Hydrogen can represent a good transition solution while Green Hydrogen technologies develop because except from the production, the remaining Supply Chain levels remain the same, but for the long-term goal of decarbonisation, it does not represent a green and sustainable solution.

Therefore, hydrogen produced from renewable sources and used in fuel cells for both mobile and stationary applications constitute a very promising energy carrier for the energy transition. This technology is the main focus of this thesis, since it represents an innovative and green process to produce hydrogen and is still on its early stages of development with many constraints still present for its diffusion.

Currently, neither Green Hydrogen nor Blue Hydrogen, are cost-competitive compared with Grey Hydrogen (European Comission 2020b). The current price of Grey Hydrogen is around 1.5€/kg in the EU, highly dependent on fossil fuel price fluctuations, compared with Blue Hydrogen, the estimated costs are around 2€/kg. For Green Hydrogen, the cost is between 2.5€/kg and 5.5€/kg, dependent on geography, electricity and material prices, and costs of RES (European Comission 2020b; IEA 2019b). The main parameters determining the cost of producing GH are, the electrolyser capital expenditures (CAPEX), the utilisation factor (operating hours) and renewable electricity prices. The share of electricity in the total cost, depends on the cost of electricity itself, the size of the installation, load of hours and the location of the electrolyser (Dincer 2012). The costs of Green Hydrogen are estimated to reduce at a constant rate in the future, electrolyser costs have already been reduced by 60% in the last decade and are expected to halve by 2030 compared to current costs (McKinsey and Hydrogen Council 2021), these cost reductions are driven by three factors. First, it is expected that the electrolyser CAPEX will reduce significantly by 2030 (McKinsey and Hydrogen Council 2021). Second, the levelized cost of energy (LCOE) is reducing, following continuous reductions of renewable energy costs in recent years and the highest reductions are seen in regions with high RES (wind and solar) availability, such as Spain, Chile, and the Middle East (McKinsey and Hydrogen Council 2021). At last, the utilization levels are increasing, large-scale integrated Green Hydrogen projects are enabling higher utilization rates with major centralized production hubs and while economies of scale are established, the CAPEX and OPEX of large-scale projects are expected to decrease even further. Moreover, including carbon dioxide emission costs in grey and low-carbon hydrogen will allow an earlier breakeven for Green Hydrogen and as RES become cheaper, so will the production costs making Green Hydrogen able to compete in price with fossil-based hydrogen by 2030 (McKinsey and Hydrogen Council 2021). A major future possibility in the GH field and an innovation in the industry itself, lies on producing hydrogen recurring to offshore wind production where RES are highly available and the excess energy produced can be converted to

hydrogen for storage, by using seawater as the source, converting it directly at sea and afterwards transporting via pipeline to the mainland (IEA 2019b; Sun et al. 2021).
Ensuing are explained the two main complementary technological concepts behind GH in the following subchapters: (1) the electrolyser, the production of hydrogen with electricity, without emitting GHG and (2) the fuel cells, the consumption of hydrogen producing electricity, without emitting GHG.

2.3.1. – Electrolyser

The first industrial water electrolyser was developed in 1888 (Chisholm and Cronin 2016), although this technology has only now received attention on the potential of its commercialization, being used to fulfil the world's energetic and climatic needs. The electrolyser is a multistage electrochemical device that converts energy to produce hydrogen in a power-to-gas (P2G) process, based on water electrolysis, a chemical process that involves breaking down water molecules (H_2O) into oxygen (O_2) and hydrogen (H_2) by applying a direct electric current (Azzaro-Pantel 2018). Electrolysers consist of an anode and a cathode separated by an electrolyte (see Figure 1). The two electrodes are immersed in water, connected to a power source where a direct current is applied. The water used in the electrolysis must contain salts and minerals at correct amount to conduct the electricity. The dissociation of hydrogen and oxygen occurs when the electrodes attract ions with an opposite charge to them. During the electrolysis, an oxidation-reduction reaction occurs due to the effect of the electric current applied.

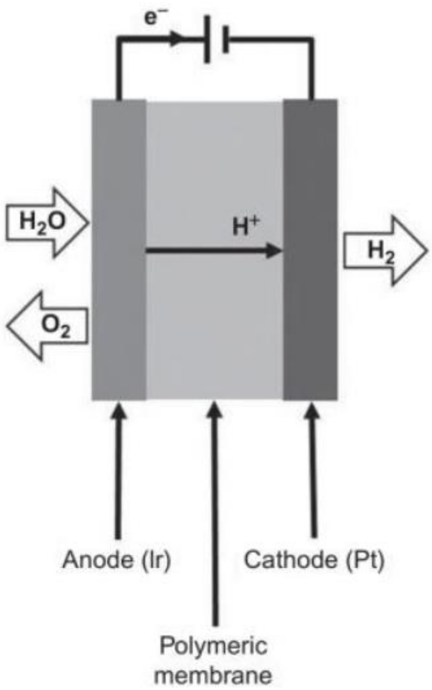

Figure 1 - PEM Electrolysis
(Source: Hydrogen Supply Chains by Azzaro-Pantel)

There are three main types of electrolysers used, proton exchange membrane (PEM), alkaline and solid oxide (SOE) electrolysers, these differ in the type of electrolyte material used. The most flexible, with smaller footprint and most commonly used method in commercial applications, is the PEM electrolysis (Figure 1) (IRENA 2018). This method uses an electrical current to separate the molecules where the electrolyte is a solid specialty polymeric material (PEM), if this electricity is obtained from renewable sources, such as wind and solar energy, it will produce hydrogen without emitting GHG into the atmosphere therefore considered as Green Hydrogen (Azzaro-Pantel 2018).

2.3.2. – Fuel Cells

An inherent technology to achieve zero GHG emission consumption of hydrogen is the Fuel Cell – an electrochemical cell that converts the chemical energy of a fuel, in this case hydrogen, to cleanly and efficiently produce electricity (Azzaro-Pantel 2018; Escobar-Yonoff et al. 2021). When using hydrogen as the fuel, electricity, water, and heat are the only products. Fuel cells are at the end of the hydrogen path, by converting the energy carrier to electricity and can be used in a wide range of applications, such as, stationary, portable, emergency back-up power and in transportation, in FCEV, where the electricity generated feeds an electrical engine and when needed recharges a small battery for backup energy among other applications. Fuel cells operate at higher energetic efficiencies than internal combustion engines (ICE), reaching up to 60% of efficiency (IEA 2019b).

2.3. – Hydrogen Supply Chain / Infrastructure

The following subchapter presents the relevant levels in the HSC. The design of a supply chain may vary depending on the desired goal, hence there is no unique HSC. Many energy sources, production processes, means of distribution, storage modes and end applications exist. As a generic simplification, the various pathways involved in the HSC are presented in Figure 2, with a concise picture of stages in sources, production, distribution, storage, and final utilization. The focus of this dissertation lies in Green Hydrogen production, this means focusing on production through electrolysis via RES. Nevertheless, other sources and production methods were accounted and are present in Figure 2, as currently these still represent a large percentage of global produced hydrogen and their existing supply chain, will serve as a foundation for future developments (Dincer 2012; IEA 2019a).

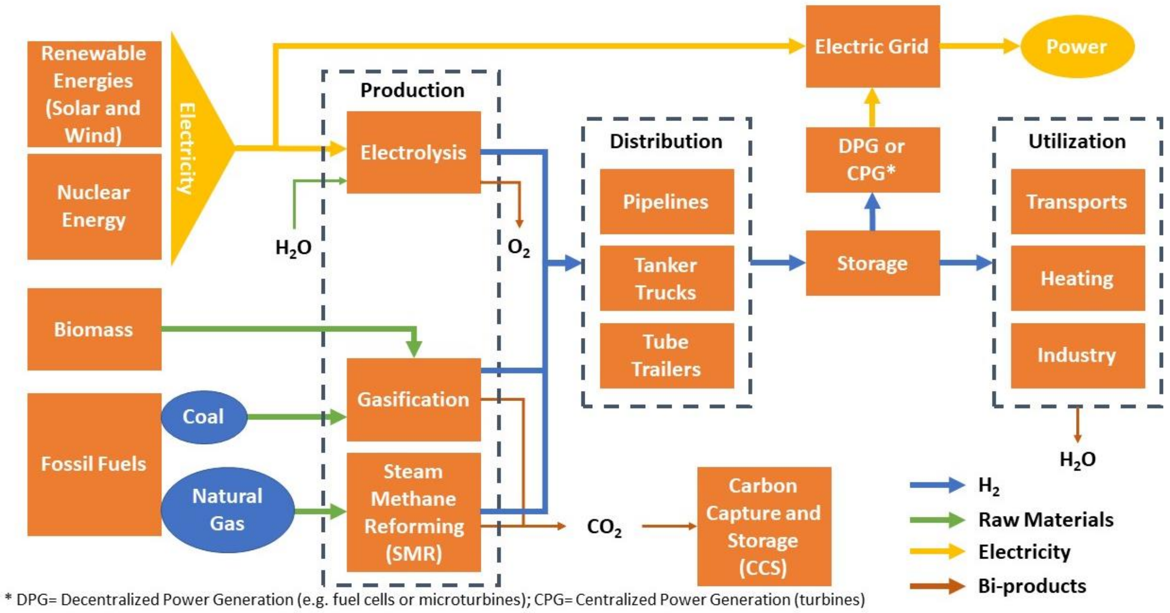

Figure 2 - Pathways involved in the Hydrogen Supply Chain (Adapted from: Hydrogen Supply Chains by Azzaro-Pantel)

2.3.1 – Primary Energy Sources

Hydrogen can be obtained from different natural sources, such as water, fossil hydrocarbons (natural gas and coal), biomass, among other rarer substances. The local market conditions and resource availability at the production facility are key factors to consider when developing a hydrogen production plant. In the case of Green Hydrogen production, it is important to account the presence of the two main resources in electrolysis, abundance of water, and renewable electricity (through existing RES such as, wind, solar, hydro, and geothermal) (Azzaro-Pantel 2018; Dincer 2012).

2.3.2. – Production

There are three main categories of hydrogen production technologies: gasification (or pyrolysis) from coal or biomass, steam methane reforming (SMR) from biomass, natural gas, ethanol, or fuel oil and water electrolysis (Figure 1) with three types, as previously explained. A key factor influencing production is the centralization level of the installation, hydrogen can be produced on-site or close to the final application site (decentralized) or at large facilities and then delivered to the location of use (centralized) (Azzaro-Pantel 2018). In centralized installations the economies of scale lead to higher production and profitability, theoretically incurring in higher production efficiencies and lower costs, but these require higher capital investment and development of substantial infrastructure in transport and storage. Decentralized production consists in smaller facilities that produce hydrogen to supply local and planned demand. These installations obtain lower efficiencies, tough lower losses in hydrogen transport make distributed production able to achieve higher efficiencies than initially presumed. Indeed, many studies consider decentralized production as a viable path on early stages of the hydrogen deployment, due to its easier application without dedicated infrastructure (Azzaro-Pantel 2018; H2FUTURE PROJECT n.d.; IEA 2019b).

2.3.3. – Distribution

There are two main hydrogen distribution ways: pipelines, and trucks (with tanker trucks or tube trailers) there is not only one way of distributing but a combination of these means should be used, depending on the production type and end application (Azzaro-Pantel 2018). Hydrogen pipelines work similarly to natural gas pipelines and are adequate to transport large quantities of gaseous hydrogen, pipelines are seen as key components on the hydrogen infrastructure, since they are superior in energetic demand and consequently result in lower costs (Biurrun, Krieg, and Stolten 2012). In the case of centralized production, pipelines are superior alternatives, ideally complemented with trucks in a second distribution stage. Hydrogen can be by distributed by trucks in liquid (tanker trucks) or gaseous (tube trailers) forms, this is the most flexible way of transporting hydrogen, reaching the end use location for instance refuelling stations (Azzaro-Pantel 2018). In addition, the same methods of liquid and gaseous form of transportation can be distributed by train or boat.

2.3.4. – Storage

An important role that hydrogen will bring is as an energy storage method for excess energy produced from variable RES, so it is important to obtain safe and efficient ways of storing it, due to the hydrogen unique properties (low density and propensity to form covalent bonds with other elements), storing it can represent a challenge (IEA 2019b). Currently hydrogen is mainly stored in gaseous, and liquid forms, through various methods. The appropriate storage method depends on the volume, duration, speed of discharge, production and demand rates, and geographic availability of the method (IEA 2019b). While tanks provide a viable option to store liquid or gaseous hydrogen, these are more suited for small quantities and short-term storage. The underground storage in salt caverns, aquifers and depleted oil and gas fields is revealed as some of the most suitable and economic options of storing large quantities of hydrogen during long periods. This option holds low operational and land costs (Antonia and Saur 2012; Maggio et al. 2019).

2.4. – Problem Definition

The primary challenge present on developing an efficient hydrogen infrastructure is overcoming the issue of who develops first, this is particularly problematic for the vehicle sector where the private consumer is dispersed and high in volume of individuals to reach. On one hand, the vehicle manufactures are reluctant in investing on fuel cell technologies and vehicles, with a lack of refuelling infrastructure since the consumer will not buy a vehicle if there is no close location to refuel it. Conversely, energy and gas companies will not invest on hydrogen production, and distribution through refuelling stations while vehicles are not commercially available, as the return on investment would take too long to achieve (IRENA 2018). Finally, the end user is awaiting the development and maturity of these two complementary technologies when deciding to invest and use an FCEV.

On other sectors of applicability, such as industrial, energetic storage and grid balancing, where the number of players involved in the ecosystem of diffusion and the complexity of the network are lower, there are less constraints for the diffusion to mass consumption. Nevertheless, it is possible to interpret the need to understand what can be done in the EU as a holistic view, to influence a smooth energetic transition in the various end uses in such a short time period to the defined goals.

The different infrastructure levels presented are currently inexistent as a global supply chain, hence they will generate different innovations, in different fields (e.g., production through electrolysis, distribution through pipeline, use via FCEV, etc.) (IRENA 2019), with different stakeholders, that need to be implemented and developed. The degree to which each one of the members influences the upcoming level needs to be understood and the key uncertainty factors of diffusion in the referred innovations need to be assessed (Meyer and Winebrake 2009).

The goals of the EU on achieving a climate neutral continent until 2050 are noticeably clear, along with the investment in expertise, in funding, resources and materials described on the previous subchapters, with a structured strategy to grow the hydrogen economies towards a large scale applicability and mass consumption. However, the obstacles to diffuse this technology are still here to be tackled with, and there is an urgent need to overcome these with the aim of reaching diffusion faster and develop the technologies as soon as possible, since the target of 2050 is not that far away, and such a complex innovation takes years if not decades to be fully operational as can be understood in the targets set by the EU. The hydrogen economy is still in its very early stages of development and there is still a long road ahead regarding infrastructure, cost reductions, both the supply and demand factors, scientific and technological developments.

This will be the focus of the dissertation, to understand how the technology develops throughout time specifically how it can be it can be successfully in the EU, and reach the targets set for the hydrogen technologies, by assessing different cases of the HSC through the maturity model and understand, how fast do the diffusion and adoption happen, what variables influence them and what actions should be put together to enable the deployment of a successful hydrogen ecosystem.

3 – Literature Review

In the following chapter, a literature review will be presented by clarifying and discussing relevant scientific literature – the main concepts, definitions, methodologies, and results of previous investigation, which will be applied in the following dissertation's methodology. This information is highly relevant to understand the theoretical context and status of research developments throughout the years, and then articulate this evidence towards the proposal of the thesis methodology.

This scientific review begins with describing the theory of the Diffusion of Innovations written by Everett M. Rogers (Rogers, Singhal, and Quinlan 1983), afterwards are described related concepts in Value Networks and Innovation Webs as well as relevant studies in Innovation Diffusion in Green Hydrogen. It provides the theoretical background for this thesis. Based on these concepts, future work will develop the idea of diffusing Green Hydrogen technologies through the various levels of its Supply Chain.

3.1. – Diffusion of Innovations

The study of the diffusion of innovations was first introduced by Gabriel Tarde (1903), a French sociologist and legal scholar, providing original concepts in his book *The Laws of Imitation* (Tarde 1903) on opinion leadership, the S-curve of diffusion, and the role of socioeconomic status in interpersonal diffusion, even though not defining these concepts with the exact names used in the present day (Djellal and Gallouj 2017). Schumpeter (1939) broadened these studies and classified the phases of technological change in three levels, invention, innovation, and diffusion (Qumar 2015). Based on Tarde's work, Everett M. Rogers, a pioneer in diffusion and adoption research, developed what has been the foundation of research in the field of innovation since the mid-twentieth century. Everett Rogers (1983) with his book *Diffusion of Innovations* (Rogers et al. 1983), has been regarded as a pivotal theory when it comes to understanding how technological innovations become diffused, and potentially adopted by individuals and/or organizations. Rogers defines diffusion as the process by which an innovation is communicated through certain communication channels over time among members of a social system, this process connects the four main elements of the theory: innovations, communication channels, time and, social systems, these elements are identifiable in every diffusion research study. The concept of innovation has been ever-evolving throughout the years, tough the most common definitions are based on the ideas of newness of change and a degree of usefulness or accomplishment in something new (Granstrand and Holgersson 2020).

Rogers describes an innovation as an idea, practice, or object that is perceived as new by an individual or other unit of adoption (e.g., organization). Diffusion is a particular type of communication where the information exchanged concerns new ideas. In this context, the communication channel is the mean by which messages pass from one individual to another. Many different types exist but Rogers identifies two distinct classes of channels as the core ones: mass media and interpersonal channels. Time is a crucial factor when considering successful diffusion of an innovation. The time factor influences diffusion in the innovation's rate of adoption in a social system, in the innovativeness of an individual, this is, how early an innovation is adopted by an entity and, in influencing the innovation-decision process by which an individual passes from knowledge to its adoption or rejection. The final element is the Social System, defined by Rogers as a set of interrelated units that are engaged in joint problem solving to accomplish a common goal. The members of a social system may differ among them as individuals, informal groups, organizations, and/or subsystems.

3.1.2. - Innovation Attributes

The characteristics of an innovation have a major influence on its rate of adoption and serve as aid to understand how it will diffuse throughout time, since users rely on these factors when deciding whether to adopt an innovation. The innovation attributes are defined by Rogers as the following:

1- **Relative Advantage:** is the degree to which an innovation is perceived as better than the idea it supersedes. The degree of relative advantage may be measured in economic terms of inherent costs, yet social-prestige, convenience and satisfaction are also key factors. The greater the perceived relative advantage, the faster the rate of adoption of an innovation.

2- **Compatibility:** is the degree to which an innovation is perceived as being consistent with the existing values, experiences, and needs of potential adopters. An innovation that does not meet the values of a certain social system will not be adopted as fast.

3- **Complexity:** is the degree to which an innovation is perceived as difficult to understand and use. The degree of complexity of an innovation directly influences its rate of adoption, as complex ideas tend to diffuse slower due to the level of expertise and skills needed for the individual to acquire.

4- **Trialability:** is the degree to which an innovation may be experimented on a limited basis. An innovation that is easily triable represents less uncertainty for the individual when deciding for adoption, hence enhancing the diffusion speed of the idea.

5- **Observability:** is the degree to which the results of an innovation are observable to individuals. The easier it is for the adopters to verify the results of an innovation, the more likely they are to adopt it.

Generally, innovations that present higher relative advantage, compatibility, trialability, observability and lower complexity demonstrate higher rate of adoption than other ideas. Rogers regards these five factors as an important way of understanding how innovations diffuse. However, these are not the only ones influencing diffusion, factors such as the type of innovation-decision, communication channels, nature of the social system, and the efforts of change agents' promotion efforts, should also be considered (Rogers et al. 1983).

3.1.3. – Innovation-Development process

Before the diffusion of an innovation takes off, there are several activities that need to happen to reach the diffusion and adoption which itself represents a phase of the process. Rogers defined this set of phases as the Innovation-Development Process which involves a whole set of activities and decisions combined with their impact prior to the diffusion and their consequences as presented in Figure 3. These influence the decision making process of the stakeholders, the role that an innovation holds and how it is perceived in the social system. Subsequent, a brief description of each step is provided:

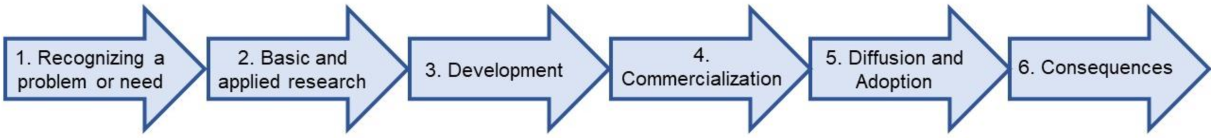

Figure 3 - Innovation-Development Process by E. Rogers (Rogers et al. 1983)

1- **Recognizing a Problem or Need:** this stage represents the beginning of the innovation-development process. It is the main driver for R&D activities to create the innovation and enhances the understanding of the idea behind the innovation. It starts as a general idea to a problem/need faced and afterwards proceeds to the innovation itself. Just like Green Hydrogen is initially seen as a solution for the climate challenges face, in this case the problem/need arises from political pressures and environmental needs for decarbonization.

2- **Basic and applied research:** a crucial step for all technological innovations, these are created relying on scientific research activities, resulting from a balance between scientific method and practical operations, to create a knowledge base which will then be applied to the design and development of the innovation. The basic research includes the theoretical support of the innovation without any practical purposes. On the other hand, applied research consists of providing practical solutions for the concepts developed on the previous step. This process begins through the basic research, followed by the applied research culminating in the beginning of the development stage.

3- **Development:** of an innovation is the process of applying an idea to a materialized concept, in order to fulfil the needs and desires of a potential target adopter. This phase is tightly related with the research phase, just as the R&D concept is known, but for explanatory reasons Rogers decided to define distinct phases. The development stage is complex and thorough and, itself holds various phases in the development of a new high-technology industry, just like Green Hydrogen. These phases are innovation – a period of high uncertainty where trial-and-error problem solving with prototypes occur, imitation – decreasing uncertainty leads to various companies imitating the basic technologic innovation, technological competition – R&D investment improves through production-process and differentiation and finally standardization – when the ideal innovation has been developed, and R&D activities focus on refining the product's quality and life cycle.

4- **Commercialization:** after the innovation is fully developed and ready to be delivered for its adoption, it passes through production, manufacturing, packing, marketing, and distribution of the product or idea that represents the innovation. These are the general stages within commercialization, depending on the type of innovation whether it is an idea, a product, or a technology.

5- **Diffusion and adoption:** when the innovation is presented and begins to diffuse to potential adopters. This may perhaps be the most important step in the innovation-development process, as the different members of the ecosystem need to be in synchrony when it comes to unravelling a technologic innovation. These ecosystems members are entities at different levels of the value chain, they can be the entity producing the innovation, the investor(s), the key users, regulating agencies, and other stakeholders all with different interests on the innovation and its diffusion to the potential adopters. During this stage, organizational relationships turn out to be crucial on improving diffusion and adoption of the innovation (Gomes and Osman 2019).

6- **Consequences:** an inevitable step is the outcome of the adoption, and even non-adoption, of an innovation. The consequences show if the original problem/need that triggered the innovation is solved or not. Occasionally, new problems/needs arise from the introduction of an innovation, causing another innovation-development process to begin. The Green Hydrogen production may come as solution for decarbonizing some energy sectors but in order to have the expected impact, it needs to have an appropriate infrastructure present and R&D in complementary technologies, for instance in Fuel Cells technologies.

In accordance with the research theme that guides this thesis, the focus will lie on the diffusion and adoption of Green Hydrogen technologies by organizations. Moreover, while the concept of Green Hydrogen and its applications have been described, it can be considered that this technology has passed through phases 1, 2, and 3 of Rogers innovation-development process and it is now developing in the phases of commercialization, and diffusion and adoption, both crucial stages for an innovation to diffuse successfully. However, in an innovation as the GH, this in an ever-evolving process, since these technological innovations need to have a cyclical process that is recurring to the previous stages of R&D to improve its current performance, instead of a straight and unidirectional process that has a beginning and end. Meaning that in the late stages, this technologic innovation can recognize needs of improvement or uncover problems yet undetected, which leads to the restart of the innovation-development process.

3.1.4. – Adopter Categories

Rogers uses a simple representation for the adoption of innovations with the percentage of adopters over time within a social system, through the bell-shaped curve and with the cumulative number of adopters throughout time, the result is an s-shaped curve in which diffusion adopts a slow rate in the beginning, accelerates to an inflection point, where the rate begins to decrease until reaching the saturation point (Rogers et al. 1983) (Figure 4). These curves serve as a starting point for the distribution of adopter categories.

Furthermore, based on the findings of previous studies (Tarde 1903), Rogers uses a measure of "innovativeness" to distinguish different categories of adopters. Applying the average time of adoption for a population and each individual's time of adoption, the individual can be associated with one of the following five categories, depending on how early they adopt the new idea. Boundaries between categories are based on standard deviations from the average time of adoption (Rogers et al. 1983). The five adopter categories are based on ideal types, theoretical formulations to serve as possible real-world comparisons. In practice there is no actual differentiation from each category, with a continuous

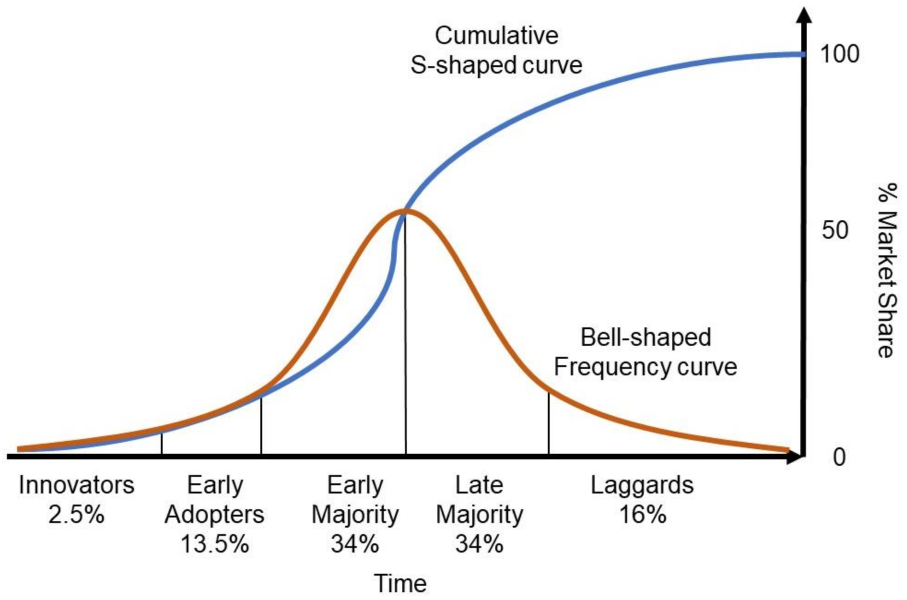

Figure 4 - Bell-shaped, S-shaped curves and adopter categorization, E. Rogers (1983)

spectrum of adopters over time. These categories are used as a framework for research findings, which will be used in this project. Rogers proposed the following categorization of adopters as given in (Rogers et al. 1983):

1- **Innovators:** are the first adopters and described as being venturesome and interested in new ideas. Innovators play a crucial role in the introduction of new ideas into a social system, they are usually prone to the degree of uncertainty, financially stable to cope with possible losses, cosmopolites, more independent from their social systems and highly informed in the area.
2- **Early Adopters:** differ from innovators in more integrated in their social system and, more local than cosmopolite. This type of adopter represents a role model for individuals within their social systems, so their part is to decrease uncertainty regarding the innovation adopted, and afterwards providing a validated evaluation of the idea to near-peers.
3- **Early Majority:** approximately a third of the adopters in a social system are in the early majority, these adopt innovations just before the average person as done so. While they do not lead adoption, they are vital members on the diffusion process providing connection between a major proportion of the social system.
4- **Late Majority:** on the opposite side but with the same dimension as early majority, this type is referred as the sceptical one by Rogers. Adoption is motivated mainly by economic need or increasing peer pressure. Due to their lower resources, the uncertainty present in the adoption must be removed before they feel it is a good adoption. This is a very important level to reach when trying to achieve for high diffusion and market saturation (Schwabe et al. 2020).
5- **Laggards:** are oriented towards the past, have precarious economic situation, are traditional, and usually isolated from the rest of the social system. Because of their lower resources and risk aversion, they need to be sure that the investment will be worthwhile.

Rogers emphasizes the main characteristics that influence each type of adopter, naming three as the most influencing factors: (1) socioeconomic status, (2) personality variables and (3) communication behaviour.

3.2. – Value Networks

The existence of inter-organizational relationships and collaboration, enable the dissemination of information and products, this represents a vital role for the diffusion of innovations, mainly happening through value networks (Barile et al. 2020; Valkokari et al. 2017; Yang and Li 2019). Value network analysis in an important process in the diffusion of innovations since it allows to understand the members present and assets that are exchanged. The theoretical foundations of value networks derive from the exchange theory and living systems theory (Homans 1958) and from Rogers previously described Social Systems. A value network is a set of connections between organizations and/or individuals interacting with each other to benefit all parties involved. It allows members to exchange both tangible and intangible assets, as well as sharing information (Allee 2008). The benefit that a value network provides comes from the way a business or individual applies the resources, influence, and insight of others to whom they are connected (Allee and Scwabe 2011). Allee provides studies on the value network analysis of tangible and intangible transactions, mainly focusing on integrating intangible assets, such as knowledge, favours, and benefits that go beyond the actual service or product (Allee and Scwabe 2011). Generally, a tangible transaction incurs in parallel intangible transactions and initiates a unique chain of relationships, interactions, and exchange of resources in value conversion networks. Allee introduced a framework of Value Network analysis (Allee and Scwabe 2011), this process starts by identifying the key participants and stakeholders, then mapping key tangible and intangible exchanges, afterwards an analysis of patterns for creating value and culminates in cost/benefit analysis to increase value outputs for each stakeholder (Allee and Scwabe 2011).

3.2.1. – Innovation Ecosystems and Webs

In the past 15 years there has been an increasing research interest in the concept of innovation ecosystems mostly with business and strategic focus (Gomes et al. 2018). Innovation ecosystems represent value networks related with innovations systems (Granstrand and Holgersson 2020). This concept was initially proposed by Moore (Moore 1993), here he suggested that a company can be considered part of a business ecosystem, in which organizations coevolve capabilities around a new innovation. However, the concept was specially adopted after the article of Ron Adner (Adner 2006) where he provides the most commonly used definition of innovation ecosystems as “the collaborative arrangements through which firms combine their individual offerings, into coherent, customer-facing solution”. A review on innovations ecosystem has shown that emphasis is put on collaboration/complements and actors, as the main components, also indicating the importance of the artifact (i.e., product or technology) (Granstrand and Holgersson 2020). Nevertheless, Moore (1993) emphasizes equally on the elements of collaboration and competition, as ways for companies to co-evolve new rounds of innovations. The same review of Granstrand and Holgersson 2020, also provides a new definition of innovation ecosystems as “the evolving set of actors, activities, and artifacts, and the institutions and relations, which are important for the innovative performance of an actor or a population”. Ecosystem strategies allow an organization to generate value and benefits in key factors such as platform leadership, keystone strategies, open innovation, and hyperlinked organizations (Adner 2006).

Innovation Webs are specific forms of value networks (Schwabe et al. 2021), these represent the basis for how innovations spread throughout all the stakeholders. Aligned with the theory of the innovation-development process by Rogers (Rogers et al. 1983), an idea is diffused through the different innovation web archetypes: (1) Research, (2) Socialization, (3) Market Validation and (4) Commercialization (Schwabe 2019a, 2019c, 2019d, 2019b; Schwabe et al. 2021). Each archetype forms a pattern of roles and interactions which involve, Buyer, Commercializer, Funder, Innovator, Marketeer, Product Packager, User and Web weaver. On the innovation web perspective, what influences the speed of value creation from ideation to market saturation comes from a combination of concepts reaching from value network analysis (Allee 2008), process analysis (Quinlan et al. 2019), complex adaptive systems (Miller and Page 2007) and social and network analysis (Cross and Parker 2004).

3.3. – Modelling the Diffusion of Innovations

The practical implementation of the diffusion of innovation theories may encounter various mathematical models to understand the penetration of new ideas and forecasting future market demands. These models have been extensively used in various fields such as political, social, economic, and technological (Qumar 2015). Additionally, research on adoption of an innovation has enabled the interest of many scholars in the theme, modelling diffusion of innovations also provides processes of pre-launch data collection alongside with identifying and controlling the key variables enabling consumer adoption. The most widespread methods used are logistics and Gompertz models (Gompertz 1825; Qumar 2015), although when developing technological diffusion and marketing research, the Bass diffusion model (Bass 1969), a combination of both logistic and modified exponential model, is the most commonly used. While a wide variety of other diffusion models exist, including space-time, dynamic diffusion models, multi-innovation, and multi-stage diffusion models, there is not one method that applies to all occasions. Benjamin Gompertz (1825) proposed a model mainly useful for analysing empirical cases assuming an asymmetric growth pattern. In the Gompertz model the maturity is longer compared with the different phases of introduction, take off, and growth (Gompertz 1825). Another perspective of the diffusion of innovations is through the substitution models, when an innovation is seen as an evolutionary process and an old technology is replaced by a new one more suited to tackle the initial problem or fulfilling similar objectives. Mansfield (1961) initially developed this concept applied to the substitution process in industrial sectors, substitution models typically result in the deterministic interpretation of the time dependent aspect of the technological replacement. Several variations exist deriving from the aforementioned models, providing distribution functions that are deterministic in nature. However, recent studies are developing ways of explaining the laws of diffusion through more flexible models, with the aim of unifying the idea that innovations spread through an infectious rate of information-sharing that differs the adopters from the non-adopters (Qumar 2015). The main aspects to be aware when assessing diffusion models are the bio-economic interactions between costs and prices, the biological adoption rates and carrying capacity (Mehmood, Barbieri, and Bonchi 2016).
The areas of application of the diffusion models are plentiful, described in Table 1 with a brief summary some of the main innovation studies, their authors, and applications:

Table 1- Summary of applications of diffusion models (Qumar 2015)

	Study by:	Diffusion Model adopted:	Application:
1	Tarde (1903)	Logistic	Law of imitations
2	Ryan and Gross (1940)	Logistic	Hybrid seeds
3	Griliches (1957)	Logistic	Hybrid corns
4	Bass (1969)	Bass	Consumer durables
5	Fisher & Pry (1971)	Fisher & Pry	Technology substitution
6	Blackman Jr.	Blackman	Technology diffusion
7	Rogers (1985)	Rogers	Innovation diffusion
8	Olshavasky (1980)	Mansfield	Consumer durables
9	Kobrin (1985)	Bass	Oil production
10	Shrivastava et al. (1985)	Bass	Financial investment
11	Mahajan et al. (1988)	Bass	Adoption process of technologies
12	Modis & Debecker (1988)	Mansfield	Growth patterns
13	Mansfield (1961)	Mansfield	Infrastructure
14	Rao & Yamada (1988)	Lillien, Rao & Kalish	Diffusion of drugs
15	Takada & Jain (1988)	Bass	Consumer products
16	Meyer (1994)	Bi-logistic	Population dynamics
17	Gatignon et al. (1989)	Bass	Consumer durables
18	Ghosal & Rai (1986)	Dynamic logistic	Time lag
19	Karmeshu (1988, 1998)	Stochastic	Diffusion of information and consumer durables
20	Jain, Rai & Bhargav (1991)	Bass, Fisher-pry	Consumer durables, technology substitution
21	Rai (1999)	Rai	Technology substitution
22	Rai & Kumar (1998, 2002)	Bass, Fisher-pry and Rai	Innovation diffusion and substitution
23	Marchetti (1980, 1989)	Fisher & Pry	Technology substitution

3.4. – Innovation Diffusion in Hydrogen technologies

The research on innovation diffusion of Hydrogen technologies has been increasing in the past few years, searching the keywords “innovation diffusion” and “hydrogen” (Web of Science) illustrates the increasing number of articles in the area since 2018, with a lack of literature in the area prior to that year. This attention increase is mostly influenced by the prospect of using hydrogen as an energy carrier in transportation through Fuel Cells (Meyer and Winebrake 2009). Although not carrying as much momentum, the research focus has also been increasing in the implementation of relevant infrastructure to meet the increase in hydrogen demand, since both are complementary goods for each one’s diffusion.

Meyer and Winebrake (2009) studied the diffusion of hydrogen in FCEV's and associated decentralized refuelling infrastructure using System Dynamics modelling, analysing the mentioned technology deployment, and coordinated policies needed (Meyer and Winebrake 2009). In this study three attributes were the main diffusion factors: level of FCEV adoption, level of infrastructure development, and favourability of hydrogen market conditions. Concluding that incentives on the diffusion of hydrogen technologies must affect both FCEV and complementary infrastructure to reach high rates of market penetration. Although it does not provide specific solutions, the study recommends a coordinated policy implementation focused both on vehicles and infrastructure to reach systematic market development, through tax credits, offering subsidies for infrastructure development and hydrogen production and delivery. A conclusion reached by various studies enhances the same importance on developing infrastructure to reach a constant growing rate of adoption (Chapman et al. 2019; European Comission 2020b; IEA 2019a). Another study by Chapman et al. assesses the hydrogen penetration in four case studies as the different ways of applying hydrogen for decarbonisation (Chapman et al. 2019). The cases, explore different crucial areas of hydrogen application to make the transition to a hydrogen economy, these are: the global energy model, social welfare and economics, hydrogen as an energy carrier for mobility and the use of hydrogen for gas grid decarbonisation. It shows that if FCEV penetrate the market as expected, and the gas grids suffer a shift from natural gas to using only hydrogen, the global energy system may potentially account hydrogen as 3% of energy consumption, this market share results from various present restrictions to the technology that should be reduced at current rates of development with reduction in costs of hydrogen production, storage, distribution, and use. Chapman et al. concluded that with the current technological maturity, the main obstacle for hydrogen diffusion lies mainly in its high costs (Chapman et al. 2019). Nevertheless, there is still a lot happening in the field of Green Hydrogen and there is still relatively little scientific research in how this innovation diffuses at its different levels of the supply chain, and an increasing concern on hydrogen technologies has been occurring in the past couple of years, yet there is a great deal of focus on diffusing GH, the product, without understanding the role that the ecosystem has on influencing a successful rate of adoption.

4 – Methodology Proposal

Based on the information presented across the literature review, in the current chapter it is intended to articulate the previous data, with the methods proposed for the master thesis. In particular, the origin of data retrieval and main variables present in the study, and an explanation of the diffusion model used in the next steps of the dissertation. Furthermore, this chapter provides a brief description of the case studies researched in Green Hydrogen technologies, which will be applied to the same model, concluding with the general dissertation proposed methodology that will be applied in the next steps.

4.1. – Bass Diffusion Model

The Bass Diffusion Model (Bass 1969) is used as the theoretical foundation for the tool applied in this dissertation, this method allows to mathematically model the Diffusion of Innovations theory (Rogers et al. 1983) and outline the major ideas of the theory as they apply to the timing of adoption. It is extensively used as one of the methods to assess the diffusion of ideas specially in technological innovations for forecasting purposes (Qumar 2015), as already mentioned before in the state of art. It assumes the traditional S-shaped curve of adoption, from a mixture of internal interactions with peers from the social system for instance word of mouth, and external influences, effect of change agents such as advertising and market conditions. The Bass model aggregates the adopter categories defined by Rogers in two main classes, the innovators and the latter four categories as imitators, that unlike the previous are influenced in timing of adoption by pressures from the surrounding social systems and not by the urge to innovate.

Therefore, in mathematical terms of the model formulation, two coefficients are calculated to measure the degree to which external and internal influences impact the rate of adoption, the coefficient of innovation (p) and the coefficient of imitation (q). As time progresses the number of new innovators adopting the idea decreases while the number of imitators starts to increase until it reaches a peak. The model can be simply expressed through the following mathematical form:

$$\boldsymbol{\frac{dN}{dt} = \left(p + \left(\frac{q}{M}\right) \times N\right) \times (M - N)} \qquad (\mathbf{1})$$

The equation represents the growth of adopters N throughout time t, it contains two distinct sections, the first one $(p + \left(\frac{q}{M}\right) \times N)$, represents the diffusion effects and the second one $(M - N)$ represents the saturation effects, where M is the size of the total potential market and N represents the cumulative number of adopters at instant t.

The model provides close approximations of the rates of adoption, when compared with historical observations. Bass initially applied the model to study the growth of sales in certain consumer durables back in the 1960s, such as televisions, lawnmowers or freezers, the real values throughout the years were proven to be in a respectable agreement with the predicted ones, similarly more recent studies supported this evidence (Ashokan, Zenarosa, and He 2018; Bass and Bass 2001).

4.2. – Litmus Test

This dissertation will develop a mathematical tool, the Innovation Diffusion Litmus Test (Schwabe 2020a) developed by Dr. Oliver Schwabe, to understand how fast a technological innovation diffuses from ideation to market saturation, identifying what variables are present and their interdependence in the present ecosystem. The test is aligned with previous literature in Diffusion of Innovations (Rogers et al. 1983), Value Networks (Allee and Scwabe 2011; Homans 1958), as well as the previously described Bass Diffusion Model (Bass 1969). A survey and research tool will be used to provide a high-level assessment of the underlying innovation web model created by Dr. Oliver Schwabe (Schwabe 2020b; Schwabe et al. 2021). The test performs as a simple set of core questions applied to an Excel (R) based maturity model to understand the level of maturity of the innovation web present in the idea's environment.

An innovation needs a network (innovation web) in order to be successful, and the test's objective is to understand how someone designs an idea, product, or service to travel as fast as possible through that same network (Schwabe 2020b).

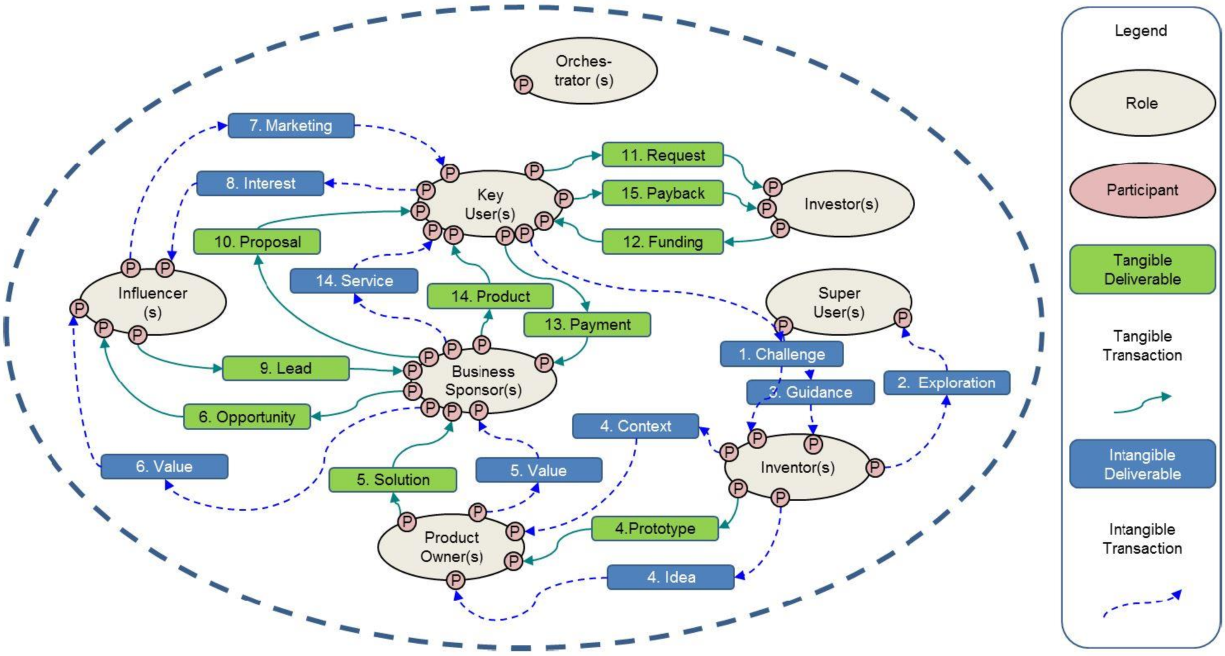

Figure 5 – Value Network of Innovation Diffusion to Late Adopters [Schwabe et al. 2020]

The key elements are (1) roles of (2) individual participants, who exchange (3) tangible and (4) intangible deliverables.

The web narrative used consists in a series of relations and exchanges between the stakeholders as displayed in Figure 5. The Innovation Web begins when the Inventor(s) receives an intangible challenge from the Key User(s). Inventor(s) investigate the matter with Super User(s) and develop the possible solution for the problem as a tangible prototype that is presented to the Product Owner(s). The Product Owner(s) take the prototype and transform it into a potential tangible solution with the clarification of the ways it can generate value to the consumer. Afterwards, the solution and possible value creation is shared with the Business Sponsor, who reshapes the solution into a tangible opportunity and presents it to the Influencer(s). The Influencer(s) commercialize the solution and provide value proposition back to the Key User(s), to create an intangible expression of interest, which the Influencer(s) convert in a tangible asset passed through to the Business Sponsor(s). The Business Sponsor(s) provide a tangible commercial proposal for selling the solution to the Key User(s), after receiving the proposal, they request funding from the Investor(s), and ideally it is provided that is used as payment for the tangible solution to the Business Sponsor(s). After receiving the required payment, the Business Sponsor(s) provide the developed solution and needed intangible services back to the Key User(s). Key User(s) eventually use the product to solve the problem/need initially announced and then provide the feedback and assets, necessary for relevant changes in return of the funding from the Investor(s) (Schwabe 2020b). The roles presented in the web must be attributed to at least one participant for each Core and Accelerator roles. The core roles are responsible for triggering the initial innovation development these are, Key User, Inventor, Product Owner, and Business Sponsor. Accelerator roles provide the momentum needed to reach 84% of adoption in the proposed schedule, these are Investor, Influencer, Super User and Moderator.

The high levels of uncertainty that an innovation suffers, mainly result from complex adaptations of highly regulated design and technical production solutions with highly complex product life cycles, also these processes frequently happen in worn out global value chains and ecosystems. An important factor to consider is the shift from a linear and modular perspective to considering the whole ecosystem as a living and continuous interchange of tangible and intangible assets between the many stakeholders present in the diffusion process. Precisely, the idea presented in the Litmus Test is as a “virus” spreading as quickly as possible through the living ecosystem of the innovation web.

Moreover, it is considered that the “success”, or market saturation, of the diffusion of an innovation is the sustained use of the idea or product by the late majority of adopters, accordingly, aiming for 84% of adoption in the total market share to achieve sustainable use and enough value created for continued stakeholder investment (Rogers et al. 1983; Schwabe et al. 2020).

The Litmus Test is designed as a semi-structured interview assessing the factors that influence the diffusion of the idea, as well as the degree of commitment that all the roles and participants present in the generic diffusion of the innovation web, while at the same time, intaking the level of confidence for each factor assessed. The evaluation of the aspects is performed through a qualitative analysis based on a Likert scale from 0 (Not at all) to 5 (Very High), as the inputs of the models vary within this range. The aspects analysed for the idea/technology are degree of innovativeness, technical readiness level, budget and resources, number of competitors, degree of complexity, compatibility with existing technologies, ease of understanding, ease of use and ease of adoption. Regarding the population aspect the main attributes are if its behaviour in the web respects: urgency, priority, motivation, expertise, collaboration, and if they are voluntarily engaging in the innovation’s development. The score for the idea and participant aspects is weighted as an average of all answers to reach a relative score while considering the degree of confidence.

Two important factors to consider when modelling the diffusion are the total market size and the time forecast of the project. The level of maturity reached, originates from the case study assessment tool, and evaluates the ability of the case study to diffuse to the late majority within the expected timeframe.

The referred maturity levels are: Level 5 (Maturity: 80%-100%) where the idea is successful and should be launched, Level 4 (Maturity 60%-79%) with relatively high diffusion where quotation is required, Level 3 (Maturity: 40%-59%) intermediate diffusion rate and proposal is required, Level 2 (Maturity: 20%-39%) lower diffusion and more information is required, Level 1 (Maturity: 1%-19%) very low diffusion where the recommendation is to explore the strategy and find improvements, and Level 0 (Maturity: 0%) when the innovation does not diffuse and should not be launched.
The amount of new adopters over time ($s_a(t)$) is determined using the two coefficients of innovation (p) and imitation (q), Total market size (m) and the Cumulative number of adopters (S(t)) (Schwabe et al. 2020), through the following equations adapted from the Bass Diffusion base equation:

$$s_a(t) = (p + \left(\frac{q}{m}\right) \times S(t)) \times (m - S(t)) \qquad (\mathbf{2})$$

$$p = m \times s_r(t) \qquad (\mathbf{3})$$

$$q = p \times s_r(t) \qquad (\mathbf{4})$$

Presuming that each phase of adoption only starts when reaching the 84% of the adopter category, this is applied to each adopter segment separately and then aggregated.
The main outcomes of the test can be resumed as:

1. Evaluate the Innovation's maturity level (adequate for Innovators, Early Adopters or Late Adopters)
2. Evaluate the Population's maturity level (Forming, Exploring, Educating/Training and Performing)
3. Assess the overall maturity level of the project (Do not Launch, Improve or Launch)
4. Forecast how long the innovation takes to reach the late majority share of the total population relatively to the initial timeframe and the expected project schedule.
5. Identify the aspects that need improvement to accelerate diffusion and reach sustainable market growth.

4.3. – Case Studies

A major component of the data retrieval lies in defining relevant Case Studies as examples of the distinct levels of the HSC, to understand how the cases diffuse throughout time, which cases tend to diffuse faster and most importantly, what are the factors accelerating or slowing the diffusion and adoption of the projects. The cases represent practical innovations already underway that are at the early stages of development and commercialization, these need to be well-defined, structured and must cover two key dimensions – the technology related with producing storing, distributing or commercializing GH, and the network/ecosystem of partners implementing that same technology (i.e., individuals, companies, governmental organizations, among others), must be well established and easily accessible in order to assess their engagement on the development of the project and the technology itself.
There was a selection of 12 suitable technological innovations of diverse backgrounds as case studies, the number of cases was defined as a significant measurement for a parametric analysis such as the Litmus Test (Dincer 2012; Grammelis, Margaritis, and Kourkoumpas 2018). The process of selection

occurred by understanding the product/idea, align it with the GH Supply Chain, identifying the participants in the ecosystem, and understanding their roles in the innovation web as present and relevantly connected to the project. Afterwards, each one of them was submitted to the questionnaire and applied to the model, providing the main outputs of the maturity level, forecast of diffusion, and identify what actionable interventions should be implemented to improve the speed of diffusion of the studied portfolio.

The EC is currently funding a large number of projects in several applications of hydrogen technologies in electrolysis, fuel cells, hydrogen transportation or storage among many others (European Comission 2020b; Fuel Cells and Hydrogen EU 2020). These projects are currently in various stages from ideation, development, and some already concluded and fully operational and commercialized. The Case Studies applied are based on some examples of these European projects, as previously explained, since the EU is one of the main global territories actively developing the hydrogen economy, deeply engaged in accelerating the diffusion of such a complex technology and recognizing this technology as a crucial need in the future for economic and environmentally sustainable growth. The majority of the cases, with the exception of the NortH2, are in some way related with the European Union's efforts to develop the Green Hydrogen technology in the continent, in the orchestration/moderation and funding of projects. The Case Studies used are the following 12, a brief explanation of each one is provided in the following:

1- **H2 FUTURE**

The H2 FUTURE (H2FUTURE PROJECT n.d.) is a European ground-breaking project with the aim of producing clean hydrogen from RES to use in its own industrial facilities of steel production in Austria. With an installed capacity of 6MW and the production 1200m^3 of hydrogen per hour to be injected into the Voestalpine gas network. The long term goal is to replace the consumption of fossil fuels, in particular NG, with green hydrogen in steel manufacturing.

The project is funded by the EU through the Fuel Cell and Hydrogen 2 Joint Undertaking (FCH-JU), and consists of a consortium coordinated by the utility company VERBUND, other members are the steel manufacturer Voestalpine, the PEM electrolyser provider Siemens Energy, the Austrian transmission system operator Austrian Power Grid (APG), the Netherland's research centre TNO and Austrian research centre K1-MET will investigate the replicability of the experimental results on larger scale projects in the EU27 for the steel industry.

2- **NortH2**

NortH2 (NortH2 2020) aims to achieve large-scale production of green hydrogen through offshore wind power in the North Sea at large of the Netherlands. This project is still in preliminary stages of development, but the main goal is to produce 4GW of GH by 2030, initially in Eemshaven and in later stages to start hydrogen production offshore, scaling the output up to 10GW with approximately one million metric tons produced annually by 2040. The consortium behind this project consists of the gas network operator Gasunie, the port operator of Groningen Seaports, the energy utility multinational Shell Nederland, the broad energy company Equinor and electricity generator expert RWE, with the financial support from the Groningen provincial authority. Additionally, the project also contemplates the condition of storing and distributing the utility, by developing a smart storage and transmission network across the Netherlands and north-western Europe to transport the hydrogen to high-volume consumers, firstly these will be industrial consumers but ideally it is intended to reach the domestic consumers, as possible final uses are developed such as heating or transportation. This project is the only one of the 12 Case Studies that is not directly funded by the FCH-JU and sponsored by the EU.

3- BIG HIT

BIG HIT (BIGHIT 2020) is an EU funded project focused on the production of GH in isolated territories, by implementing a fully integrated model of hydrogen production, storage, transportation, consumption for heat, power, and mobility in the Orkney Islands of Scotland. The project holds a total electrolysing capacity of 1,5 MW, these PEM electrolysers are expected to produce approximately 50 tonnes of hydrogen per year, that will be used to heat local buildings, and also be transported by sea ferry to the closest town of Kirkwall where a 75 kW fuel cell will convert the GH into electricity, supplying several local buildings, additionally supplying the new hydrogen refuelling station in Kirkwall which fuels 5 Symbio FCEVs for the local government. This project's main objectives lie on demonstrating the use of hydrogen as a flexible local energy storage and vector, carrying hydrogen by tube trailer, and applying it in real end-use applications in remote areas. The benefits from BIG HIT will support the much wider replication and further deployments of fuel and hydrogen related technologies in isolated or constrained territories.

4- H2 Ref

The H2Ref (H2Ref n.d.) project is a R&D project focused on advanced new compression and buffering solution for hydrogen refuelling stations, through a cost effective, efficient, and reliable compression way of storing hydrogen. This project addresses this compression and buffering function for the refuelling of 70 MPa passenger vehicles and encompasses all the necessary activities for advancing a new process, which represents a critical step on the HSC. The project encompasses all the necessary activities for advancing hydraulic accumulator based hydrogen compression, from experimentally proven concept to technology demonstrated in relevant environment. This project is also composed by a consortium of six European partners and is funded by the Fuel Cells and Hydrogen 2 Joint Undertaking receiving support from the EU.

5- HySTOC

HySTOC (HySTOC 2020) is an EU funded project that demonstrates the cost effective transport and storage of hydrogen to a commercially operated hydrogen refuelling station in Finland, using LOHC technology in an innovative field test. The HySTOC consortium is composed by 5 European partners, which cover the whole value chain from basic research and testing (FAU & VTT), through core technology development (Hydrogenious and HyGear) to the end-use entity that will operate the whole LOHC supply infrastructure (Woikoski). The storage facility can hold 23 kilograms of hydrogen in approximately 480 litres of carrier medium. The project is set to demonstrate the whole HSC from a small-scale centralized hydrogen loading, transportation to the end-use in the mobility sector through a FCEV HRS.

6- HPEM2GAS

The HPEM2GAS (HPEM2GAS n.d.) case is focused on developing a small-scale and low cost PEM electrolyser optimised for grid management through both stack and balance of plant innovations, resulting in an advanced 180-300 kW PEM electrolyser with improved lifetime and a reduction of the system complexity without compromising safety or operability. These factors lead to significantly reduced CAPEX and OPEX costs. The consortium behind HPEM2GAS is built by 7 European partners, three of them are industry focused (Solvay, ITM Power and IRD Fuel Cells), 2 research focused (CNR-ITAE and Hoschule Emden Leer) and 2 focused on services and power supply (Stadtwerke Emden and Uniresearch). The main objective of the project is to develop, validate and demonstrate robust, flexible, rapid response, self-pressurising and innovative solutions in the PEM electrolysis technologies aiming to prove the potential to reach the KPIs, CAPEX, OPEX and efficiency targets at a realistic production at small scale.

7- H2ME

The Hydrogen Mobility Europe (H2ME) is one of the most ambitious initiatives to deploy the hydrogen mobility in Europe (H2ME 2021), the project deployed the first European network of HRS to create 49 stations as well as investing on the increase of FCEVs by introducing more than 1400 vehicles in circulation. The project is expected to finish in 2022 and since 2015 it has implemented 49 refuelling stations in Northern Europe (Germany, France, the Netherlands, Sweden, Norway, Iceland, Denmark, and the UK) and introduced in circulation more than 1400 FCEVs in circulation (500 original equipment manufacturer FCEVs and 900 FCEV vans). Additionally, some of stations deployed under H2ME, are designed to provide grid balancing services and other smart electricity price optimisation strategies with some of the HRS equipped with onsite hydrogen production, eliminating the need to supply the gas to the station henceforth needing less energy and reducing costs. As previously discussed, the introduction of a HRS network is essential to the market development of the vehicles, the H2ME project will confirm the technical and commercial readiness of vehicles, fuelling stations and hydrogen production technologies. It will also demonstrate the breadth and depth of the commitment to hydrogen-fuelled road transport as a pan-European solution to the need to have a viable and competitive alternative to fossil fuels.

8- H2 Haul

The H2 Haul (H2Haul 2021) is an EU funded project similar to the H2ME but focused on developing the hydrogen mobility sector of heavy duty vehicles, developing, and deploying 16 fuel cell trucks on four locations (Belgium, France, Germany, and Switzerland), and introducing 6 new HRS that will supply the fuel to these FCEVs. The consortium behind the project consists of 15 partners from seven European countries, including equipment manufacturers and analysis, dissemination, and coordination partners. Similarly, to the H2ME project but focused on long haul mobility, the main objectives of H2Haul are to validate the ability of Fuel Cell trucks to provide zero-emission mobility on heavy-duty applications, laying the foundations for commercialisation of this sector in Europe, in particular providing proof of concept for truck manufacturers and operators, retail sector representatives, policy makers and the hydrogen industry as a viable and efficient end-use for the energy carrier.

9- Neptune

Neptune (Neptune 2021) is a project focused on developing breakthrough solutions at materials, stack, and system levels of GH production through PEM electrolysers. In order to achieve large-scale application electrolysis, a significant reduction of capital costs is required together with a large increase of production rate and output pressure, while assuring high efficiency and safety, to tackle these challenges there are step-changes in the current system that will to be improved through R&D in the Neptune project, in the aforementioned levels. The consortium behind Neptune is composed by six European partners, four of these focused on industrial expertise and two in the research field. The final outcomes of the project aim to improve the KPIs of the previous system as well as significantly reducing the electrolyser CAPEX and OPEX costs, providing a techno-economic analysis and an exploitation plan to bring the innovation to market.

10- Hy Stories

The HyStories (Hystories 2021) project addresses the main technical feasibility questions for underground storage of pure hydrogen in aquifers or depleted fields, and will provide market, societal and environmental insights on the deployment of underground storage of hydrogen. The consortium is composed by 7 partners and 17 third parties in 17 European countries, from different fields of action and roles in the work packages. The overall objectives of the project are to deliver public subsurface technical developments for LOHC storage in the innovative ways of storing large quantities of hydrogen, providing the assessments of geologic and techno-economic feasibility and of implementing this technology in preferred locations throughout Europe, in order to enable structured decision making on pilot demonstration and industrial deployment for the relevant stakeholders in government and industry.

11- REFHYNE

The REFHYNE (REFHYNE 2022) project aims to install and operate world's largest PEM electrolyser for industrial use with a peak capacity of 10MW, producing approximately 1300 tonnes of hydrogen per year in the Shell Rhineland Refinery in Wesseling, Germany. The project will install a fully integrated process from GH onsite production to consumption in the oil refining process. There are 5 partners present in the consortium, the main players are the Shell Rheinland Refinery and ITM Power adding research and energy transmission experts. The main objectives of REFHYNE are to process and upgrade oil products at the refinery site, evaluate the PEM technology at the largest scale achieved to date, and explore applications in other sectors including power generation, other industrial uses, heating for buildings and transportation.

12- ELY 4 OFF

The ELY4OFF (ELY4OFF 2021) project aims to implement a fully integrated off-grid production of GH through the use of a robust, flexible, highly efficient, and cost-competitive PEM electrolysis system recurring to direct coupling photovoltaic generation installed in the premises in northern Spain. The final industrial prototype holds a maximum capacity of 50 kW and demonstrates the basis of development, validation, and demonstration. The consortium includes a PEM electrolyser manufacturer, research organizations, and specialized companies in power electronics and control and communications systems. The purpose of the project is the development and demonstration of an autonomous small scale off-grid electrolysis system linked to track the solar photovoltaic source with cold start ad rapid response considering electric grid changes, with the possible replicability and serving as a new business model in larger scale or similar conditions.

4.4. – Dissertation Methodology

This dissertation is organized by the theoretical foundations and inherent methodological steps to complete, as well as the practical applicability of the Litmus Test model to the different cases researched. The main goal is for an innovation to achieve rapid diffusion to late adopters, its success depends on reaching 84% adoption of the potential target market, specified to Green Hydrogen technologies. Ultimately, the research effort will provide actionable interventions and recommendations to design a technologic innovation, in the many levels of Green Hydrogen technologies, to diffuse as quickly as possible. Therefore, the proposed methodology for the steps in the dissertation is presented in Figure 6:

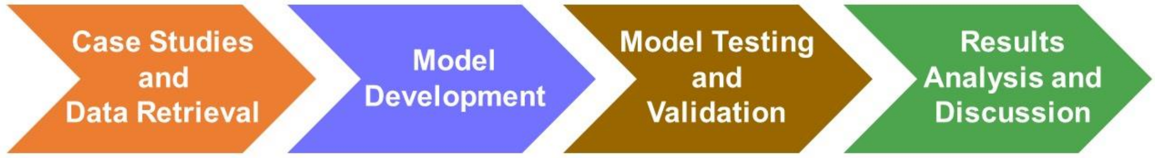

Figure 6 - Overview of the Dissertation work

The developments of the master thesis can be simply described in the following steps:

1. **Case Studies and Data retrieval** – research and identification of twelve relevant Case Studies in different levels of the HSC, specifically technological innovations happening in the EU, including the retrieval of relevant data to apply in the model and its validation, namely in the Innovation's Characteristics and Ecosystem (Population).
2. **Model development** – customize the maturity model with the questionnaires in the project and run the Litmus Test for each Case Study.
3. **Model Testing and Validation** – validation interviews of the results with experts in the area to assess the robustness of the model and outputs. Additionally, test variations of the inputs to understand which variables have more influence in the speed of diffusion and what changes should be made.
4. **Results Analysis and Discussion** – reveal key findings of the diffusion in the different levels of the HSC, understand where the main obstructions are, and provide recommendations for future implementation in related innovations. Additionally, provide the main findings and future developments.

Additionally, the dissertation methodology is summarized through the Input/Output model present on Figure 7. The scheme serves as an oversimplified synthesis of all the work developed during the thesis starting on the inputs which represent the content given so far on the Problem Definition, Literature Review and Methodology proposal, which explains the Case Study research and selection. Generally representing the theoretical background, where the concepts reviewed in the state of art, align with the technology defined in the problem definition to achieve the objective, which then connects with the Drivers for Innovation on the concept of justifying the need for a technological innovation such as the Green Hydrogen. Afterwards, arises the practical application applied to the Innovation Diffusion model to achieve the described outputs as presented in the subsequent Chapter 5 – Results.

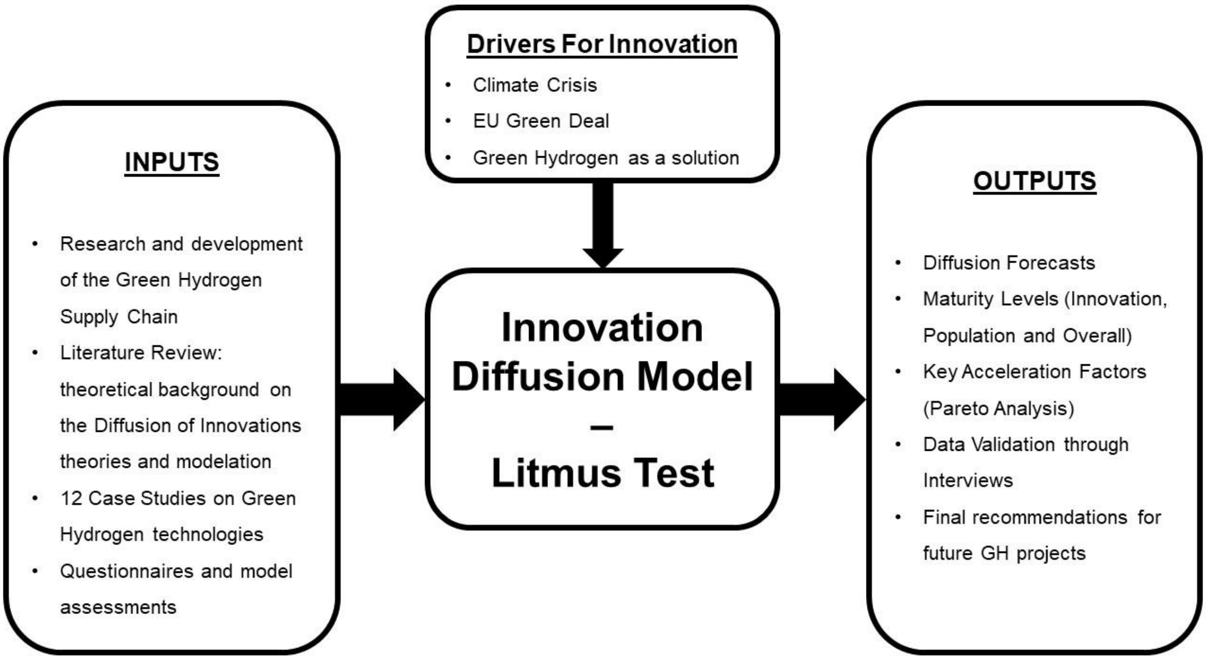

Figure 7 – Input/Output Model for the Dissertation Methodology

5 – Results

5.1. – Results Analysis

The following subchapter presents the analytical and qualitative results obtained from the model, on the Case Studies perspective presenting the maturity of each case and on the innovation factors perspective the detailed outputs. The results obtained are displayed on Table 2, with the innovation maturity, population maturity, overall maturity, level of adherence to the schedule forecast compared to the initially expected and the confidence level of the inputs in the model for each case. The overall Case Study results displayed on Table 2 also show the first Case Study which is the Reference Model as developed by E. Rogers, where the diffusion throughout the value network is ideal, henceforth resulting in 100% on the totality of the outputs. This reference model converts into the aforementioned bell curve as described by Rogers, present on Figure 8 which represents the basis of comparison of the ideal diffusion rates for an innovation to achieve mass adoption and the desired 84% of adopters faster, additionally on Figure 9 the cumulative values for each case are displayed in function of the adherence to the aspired schedule.

Regarding the overall results of the Case Studies present on Table 2, it is possible to observe high values for the Idea Maturity with the totality of the cases located on the highest level of Maturity, level 5, showing a high level of maturity on the technological innovation component, with the lowest percentage at 86%. The case studies assessed represent a holistic view of the GH value chain thus, considering the technology it is possible to interpret an elevated level of maturity in hydrogen projects regarding the idea, whereas concerning the population perspective there are lower values of maturity in the generality

Table 2 – Wider Case Study Results

Case	Context (Detailed assessment results available in the assessment tool)	Idea Maturity	Population Maturity	Overall Maturity	Schedule Forecast	Assessment Confidence
1	**Reference Model:** Perfect innovation diffusion curve based on the research method	5 (100%)	5 (100%)	5 (100%)	100%	100%
2	**H2 FUTURE:** Generation of Green Hydrogen with the purpose of supplying a steel production plant in Austria	5 (86%)	4 (72%)	67%	260%	58%
3	**NortH2:** Large-scale Green Hydrogen production resourcing to offshore wind power in the Netherlands	5 (90%)	5 (90%)	77%	180%	72%
4	**BIG Hit:** Production of Green Hydrogen in isolated territories in the Scottish islands	5 (88%)	4 (78%)	64%	260%	61%
5	**H2 REF:** Develop cost effective and reliable FCEV refueling systems	5 (85%)	4 (84%)	64%	260%	56%
6	**Hy STOC:** Supply and transportation using liquid organic hydrogen carriers (LOHC), to a commercially operated HRS	5 (86%)	4 (80%)	60%	260%	53%
7	**HPem2Gas:** Develop, validate, and demonstrate robust, flexible, and rapid response PEM electrolysis	5 (84%)	4 (72%)	56%	280%	53%
8	**H2ME:** Deploy the firstEuropean netwok of HRS and implement a significant fleet of FCEVs	5 (87%)	4 (76%)	76%	180%	86%
9	**H2HAUL:** Develop hydrogen mobility in heavy duty and long haul transport by implementing fuel cell electric trucks	5 (88%)	4 (83%)	72%	180%	71%
10	**Neptune:** develop solutions at materials, stack, and system levels of PEM eletrolysers	5 (88%)	4 (80%)	66%	200%	63%
11	**HySTories:** adress main technical feasibility for underground storage of pure hydr hydrogen in aquifers or depleted fields.	5 (89%)	4 (76%)	65%	260%	62%
12	**REFHYNE:** install and operate world's largest PEMWE for industrial use (10MW) produced onsite and apply directly in the oil refining process	5 (88%)	5 (90%)	76%	180%	72%
13	**ELY4OFF:** implement a fully integrated off-grid production pf GH through efficient and cost-efective PEMWE	5 (86%)	4 (72%)	61%	260%	61%

of the projects. Concerning the population maturity, the majority of the portfolio appeared on Level 4 with only 2, NorthH2 and REFHYNE indicating Level 5 maturity. The average for the 12 case studies was 87% on the idea maturity and 79% on the population maturity, this comparison can prove the previously discussed idea that the hydrogen technologies necessary to develop the industry, are slightly ahead compared with the maturity of the innovation ecosystem needed to diffuse these projects. The lower value of the overall Population Maturities, shows the need to focus on the ecosystem present on hydrogen projects and at the same time that the ideas behind the cases are already mature enough to be commercialized and adopted in large scale, currently lacking only the financial, market and technologic incentives, necessary to engage on a stronger network of stakeholders in order to reach higher rates of diffusion.

The Schedule Forecast stands for the time needed to reach 84% share of total adopters compared to the initially aspired schedule, this factor illustrates essentially how fast the innovation will reach mass adoption compared to the ideal reference model. This variable needs to be considered when comparing the different cases, their speed of diffusion and the success of the innovation. There are four cases (NortH2, H2ME, H2HAUL and REFHYNE) demonstrating lower Schedule Forecast at 180% which accordingly also display the highest Overall Maturity. On the other hand, the highest Forecast Schedule was 280% at the HPEM2GAS case where the diffusion occurred the slowest and lead to the lowest Overall Maturity of the portfolio. The remaining cases showed a low adherence to schedule at 260%, with the exception of Neptune that had a schedule forecast at 200%. These values appear to be relatively high considering the initial forecast, however it is a completely statement since the comparison is to the Reference Model where the diffusion is ideal without any constraints to its idea and ecosystem. The Confidence level introduced in the assessment of the Litmus Test heavily influences the Overall Maturity, this factor is affected by the availability of information, uncertainties on the knowledge about

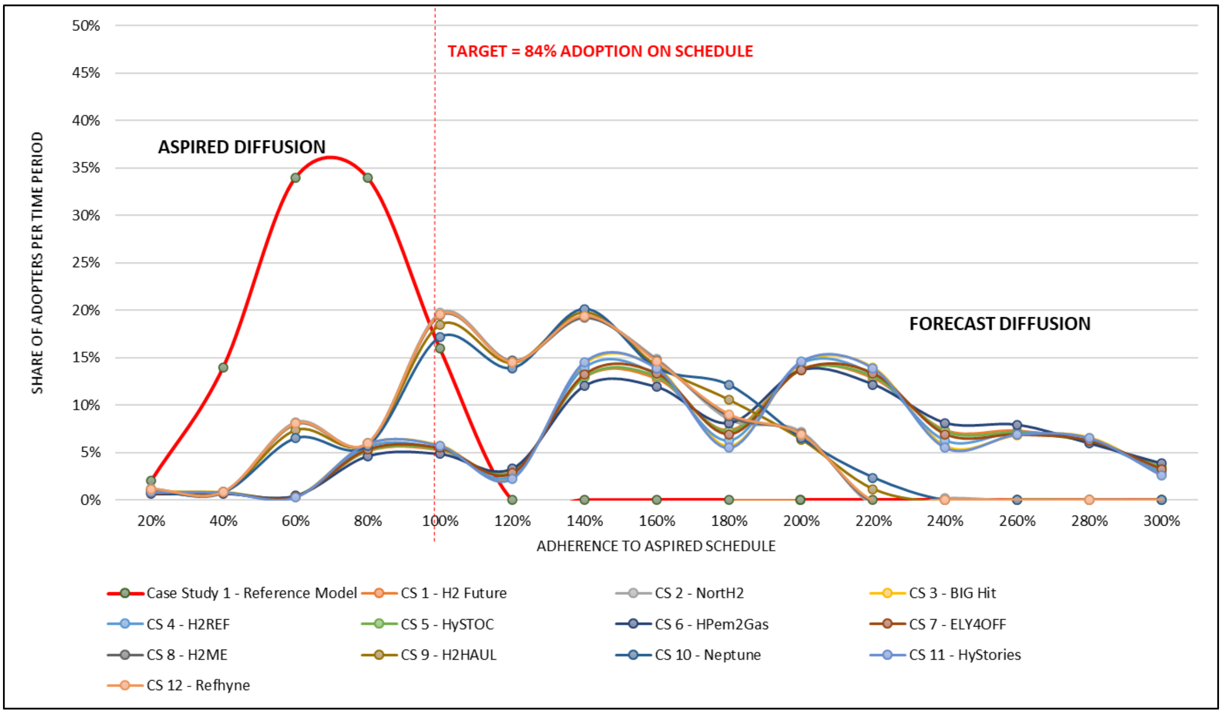

Figure 8 – Share of Adopters per Time Schedule for the Reference Model and the12 Case Studies

the subject assessed and on the innovation factors studied. The confidence assessment negatively influences the overall maturity of the projects, in the majority of the cases.

A covariate analysis of each case then assesses the Overall Maturity weighing the idea, the population, and the assessment confidence, as previously pointed, the highest overall maturity stands on the NorthH2 (77%) on Level 4, with a robust diffusion of the innovation and the lowest maturity lies on the HPEM2GAS (56%) at Level 3, where the population and idea maturities are relatively lower and highly influenced by the degree of confidence on the assessment. The weighted average of the Overall Maturity on all Case Studies is 66% at Level 4, which shows a relatively high rate of diffusion for the hydrogen projects studied but where quotation is required, and where improvements are still needed mainly.

The share of adopters throughout time is represented on Figure 8 as function of the percentage of the original aspired schedule, the Case Study 1 is the previously described Reference Model as the basis for the ideal diffusion, the value of 100% of aspired schedule is set when the bell curve reaches the 84% share of adopters.

Complementary, the cumulative share of adopters throughout time on Figure 9 where the Reference Model also sets the basis for the aspired diffusion, this graph presents an easier way of interpretation of the results where the closer the curve of each case is to the reference, the faster the speed of diffusion. The graph on Figure 7shows the distinct forecasts of diffusion for the 12 Case Studies, here there are two distinct patterns easily observed, where 5 cases (NortH2, Refhyne, H2ME, H2HAUL, and Neptune) acquire a larger share of adopters earlier on ensuing an earlier arrival to the mass adoption of the network and higher maturity for these cases, the second pattern shows a lower diffusion curve for the 7 remaining cases (BIG HIT, ELY4OFF, HyStories, HPEM2GAS, H2 Future, H2REF and HySToc)

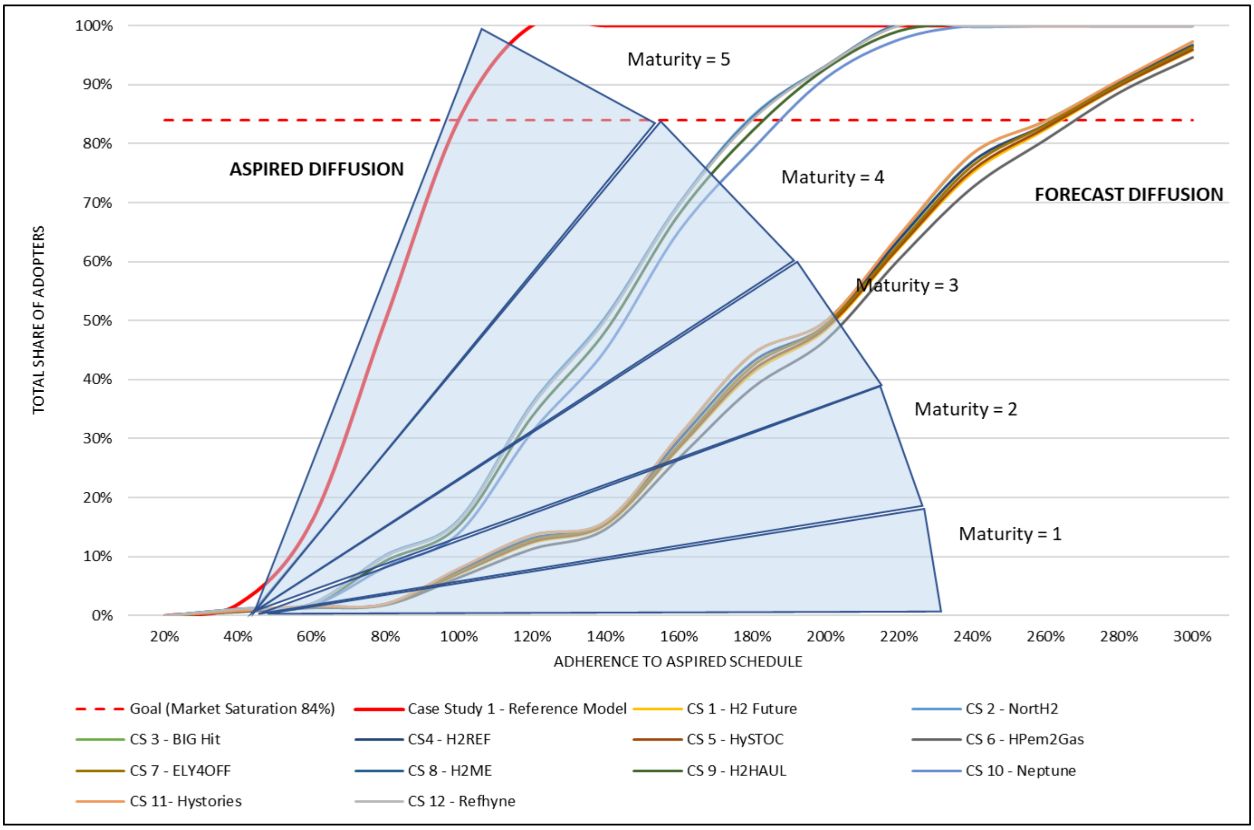

Figure 9 – Cumulative Share of Adopters for the Reference Model and the 12 Case Studies

where the maturity levels end up with lower diffusion rates. The patterns present on the diffusion forecast support the different maturity levels previously observed and can be explained by the Case Studies dimension and applicability, as well as the development of the ecosystem present on the project. For instance, the NortH2 project which shows the highest overall maturity and most successful diffusion curve is set to be one of the biggest GH production projects globally, also displaying a robust innovation web where the stakeholders are strongly engaged on developing the technology of the PEMWE through off-shore wind energy and developing the HSC by making it economically viable for a large scale application, not only by developing the offshore technology, but also by setting goals of developing an advanced hydrogen economy in the Netherlands and in the north-western European area, hence heavily engaged in the ecosystem of stakeholders present in the technological and economic environment.

On the other hand, the lower curve displays a slower diffusion rate with low adherence until 140% of the time schedule, and at that point the diffusion increases significantly, tough resulting in a slower rate compared to the upper curve, causing a slower speed of diffusion and consequently lower values of Overall Maturity.

The graph on Figure 9, as the cumulative equivalent, here the two patterns aforementioned are more specifically reflected on the table, where it is possible to interpret that none of the patterns are going to go to market on time, when compared with the aspired curve of diffusion on red (Case Study 1 – Reference Model), it is a standard statement since this curve defines the ideal diffusion rate without any constraints to its process of diffusion and consequently measuring 100% on the assessment of the model, nevertheless this difference between the ideal curve and the remaining CS curves, shows the available space of improvement to reach higher and faster diffusion since none of the CS outcomes reached market saturation anywhere near the 100% aspired schedule.

The blue area in Figure 9 defines the 5 maturity levels where the cumulative share is located at each time period, the lower curves begin their diffusion at the lower maturity Levels (1 and 2), afterwards proceed to gain momentum rising up to Level 3 and eventually ending on an Overall Maturity of Level 4, reaching the market saturation at approximately 260% of the aspired schedule. Even though the upper curves start on the lower Level 3, these gain momentum sooner with higher rates of diffusion and stabilize on level 4 approximately at 100% of adherence to the schedule and reach faster the 84% share of adopters, the line goal, at approximately 180% of the expected schedule.

The different factors that affect the diffusion, are assessed through the model's questionnaire and are present on a Pareto analysis, where the factors that contribute the most for the success of the innovation are projected on the benefit delivered to the diffusion, hence emphasizing the top and bottom causes that need to be addressed to solve the lower maturity of certain Case Studies.

This comparison happens through the maturity level of each factor meaning that the variables with higher maturity levels influence positively the diffusion, while resulting in faster adoption these factors need to be enhanced in the future proposals for GH projects. On the other hand, the variables with lower maturity levels are the ones delaying the diffusion of the Case Study and these need to be accounted with particular attention when attempting to accelerate the diffusion of the project, since these are the factors delaying the speed of diffusion. The final observations must reflect on the overall balance of these opposites, there needs to be an improvement on the lower maturity ones while maintaining high maturity of the successful variables.

The innovation factors studied derive from the innovation's characteristics and impact, as well as from the population present on the innovation web, a brief description of the factors examined can be found on Table 3.

Table 3 – Innovation factors and brief description

Factor		Description
Innovation	Budget and Resources	Budget and resources available within the funding and raw materials available for the development of the innovation
	Compatibility with Existing Ways of Work	Regarding the innovation itself and how it engages with the technological environment and the conventional ways used in the field
	Degree of Certification (Legal/Policy)	Legal certification and level of suitability to the policies present in the region/state being developed
	Degree of Complexity	The level of complexity in the development of the innovation as well as how complex it is seeen by the different stakeholders
	Degree of Innovativeness	Level of innovativeness in the conventional ecosystem where the innovation is being developed
	Ease of Adaptation	How easily the innovation adapts to changes in the ecosystem that affect its development
	Ease of Trialing	How easily the innovation can be experimented by consumers in its possible end uses
	Ease of Understanding	How easily the different stakeholders understand the innovation and its benefits
	Ease of Use	How easily the innovation can be used in real life situation
	Number of Competitors	The threat of being overtaken by competitors or replaced by other technologies
	Observability of Impact	How the results shown by the innovation can be observed, and how these influence the original problem set to be solved
	Technical Readiness Level	Degree to which the innovation is ready to be deployed, to mass markets and large scale adoption
	Urgency of Need	How urgent the development of the innovation is, considering the current ecosystem and technologies
Population	Business Sponsor	Shapes the solution and value proposition from the Product Owner, into a tangible opportunity and transact it with the Influencer
	Influencer	Market the solution from the Business Sponsor to the Key User in order to generate na intangible expression of interest
	Inventor	Entity who receives an intangible challenge from the Key User and develops an idea to solve the identified need/problem
	Investor	Entity providing funding to the project
	Key User	Individual in an organization using the technology providing a challenge/need that is intended for use by late adoption market
	Moderator	Entity orchestrating and moderating the development of the project with the different stakeholders
	Product Owner	Transforms the input from the inventor into a potential tangible solution, accompanied by a value proposition
	Super User	A Key User receiving the challenge and providing guidance for the development of the innovation by the Inventor

The final average maturity of each factor studied is presented on detail on Table 4. Each value represents the maturity reached by each factor (Table 3) modelled during the assessment of the GH Case Studies. On Table 4 the values are displayed from lowest to highest level of maturity, where the bottom 20% or the four lowest maturities achieved are the Degree of Certification, Degree of Complexity, the Compatibility with Existing Ways of Work, and the presence of the Super User in the ecosystem.

The Degree of Certification shows the lowest level of maturity (50%), meaning that Legal and Political factors of regulation influencing the technology itself are one of the main barriers of the studied GH projects, indeed these still encounter a certain level of certification needed in terms of industrial gases production and distribution, the hydrogen must be certified and a specific gas in terms of legal classification, since it is not a synthetic or fossil based fuel, it finds some legal barriers in the process in countries where the legal patterns are still not established, in addition to the quality and safety assurance of operating this energy carrier.

Table 4 – Detailed results of maturity for the 12 Case Studies and respective factors

Factor	NorthH2	H2Me	Refhyne	H2Haul	H2Future	Neptune	HyStories	BIG Hit	H2Ref	Ely4Off	HySTOC	HPem2Gas	AVERAGE
Innovation - Degree of Certification (Legal/Policy)	64%	60%	64%	48%	60%	60%	48%	36%	48%	32%	36%	48%	**50%**
Innovation - Degree of Complexity	64%	60%	48%	64%	64%	60%	48%	48%	48%	48%	48%	48%	**54%**
Innovation - Compatibility with Existing Ways of Work	80%	40%	80%	60%	60%	48%	64%	64%	80%	24%	60%	32%	**58%**
Population - Super User (Identified)	75%	59%	67%	54%	61%	72%	54%	50%	44%	48%	69%	44%	**58%**
Population - Key User (Identified)	72%	53%	69%	69%	64%	52%	46%	48%	56%	50%	69%	61%	**59%**
Innovation - Ease of Use	64%	80%	64%	80%	60%	60%	32%	48%	64%	48%	64%	48%	**59%**
Population - Influencer (Identified)	72%	69%	52%	69%	67%	48%	50%	67%	67%	61%	46%	48%	**60%**
Innovation - Budget and Resources	64%	48%	80%	60%	64%	64%	60%	64%	80%	48%	48%	48%	**61%**
Innovation - Ease of Adaptation	64%	60%	60%	80%	80%	80%	48%	60%	48%	48%	64%	36%	**61%**
Innovation - Technical Readiness Level	80%	80%	80%	48%	48%	48%	48%	64%	48%	80%	48%	60%	**61%**
Innovation - Ease of Trialing	80%	100%	80%	60%	80%	48%	80%	80%	64%	48%	48%	36%	**67%**
Population - Business Sponsor (Identified)	90%	97%	67%	67%	56%	67%	75%	75%	72%	50%	64%	52%	**69%**
Population - Inventor (Identified)	72%	93%	75%	69%	56%	54%	75%	72%	59%	90%	52%	64%	**69%**
Innovation - Ease of Understanding	64%	80%	64%	64%	100%	80%	80%	64%	100%	48%	36%	64%	**70%**
Population - Product Owner (Identified)	72%	67%	90%	69%	69%	69%	75%	90%	48%	69%	72%	69%	**72%**
Innovation - Urgency of Need	80%	100%	80%	100%	80%	80%	60%	48%	80%	80%	64%	60%	**76%**
Innovation - Observability of Impact	100%	80%	100%	80%	64%	80%	80%	60%	64%	100%	60%	48%	**76%**
Population - Moderator (Identified)	72%	97%	93%	90%	60%	77%	93%	75%	75%	75%	75%	75%	**80%**
Population - Investor (Identified)	90%	80%	90%	90%	72%	87%	72%	75%	77%	97%	75%	56%	**80%**
Innovation - Number of Competitors	100%	100%	100%	100%	60%	80%	100%	80%	60%	60%	60%	100%	**83%**
Innovation - Degree of Innovativeness	100%	100%	100%	80%	80%	80%	80%	80%	60%	80%	100%	80%	**85%**
Case Study Average Maturity	**77%**	**76%**	**76%**	**72%**	**67%**	**66%**	**65%**	**64%**	**64%**	**61%**	**60%**	**56%**	

The referred facts present a barrier mainly in the introduction process of the technologies nevertheless these slow down diffusion in the early stages of development, a key stage for attaining sustainable growth. Table 5 shows the overall average maturities summed up, where the Degree of Complexity is the second least mature factor assessed (54%), as aforementioned an innovative technology as the GH Supply Chain does bring a major amount of constraints regarding the complexity of the infrastructure and complementary products needed, namely on the components used in the electrolysers, the need for the whole network of RES, water availability and inherent technologies of production and distribution. The Compatibility with Existing Ways of Work shows up as the third least mature factor scoring 58% of maturity, this variable regards the technological innovation and how it relates with the surrounding environment and traditional methods, in the Literature Review chapter this factor was already pointed as a main challenge for the development of the hydrogen economy. In the GH cases this factor presents a crucial part on the adoption of the technology, as previously pointed, in particular when it comes to the lack of infrastructure from the production source to final consumption. The connection of RES to the production of hydrogen and, more downstream in the value chain, regarding how the hydrogen will be consumed in its many ways of end use, requiring different ways of handling, storing, and distributing the product. This factor displays one of the lowest maturities and must be specially emphasized in the development of such projects, since it determines how the project engages with the current technologies in use.

Table 5 – Case Studies ranked by overall factor average maturity

Factor	Average Maturity
Innovation - Degree of Certification (Legal/Policy)	50%
Innovation - Degree of Complexity	54%
Innovation - Compatibility with Existing Ways of Work	58%
Population - Super User (Identified)	58%
Population - Key User (Identified)	59%
Innovation - Ease of Use	59%
Population - Influencer (Identified)	60%
Innovation - Budget and Resources	61%
Innovation - Ease of Adaptation	61%
Innovation - Technical Readiness Level	61%
Innovation - Ease of Trialing	67%
Population - Business Sponsor (Identified)	69%
Population - Inventor (Identified)	69%
Innovation - Ease of Understanding	70%
Population - Product Owner (Identified)	72%
Innovation - Urgency of Need	76%
Innovation - Observability of Impact	76%
Population - Moderator (Identified)	80%
Population - Investor (Identified)	80%
Innovation - Number of Competitors	83%
Innovation - Degree of Innovativeness	85%
Case Study Average Maturity	**67%**

The fourth least mature factor was the presence of the Super User in the innovation's ecosystem (58%), this factor reveals the lowest maturity regarding the Population's component and displays the need to develop the Super User responding to the challenge(s) expected to be solved by the different GH projects. The presence and action of the Super and Key Users shows the lowest maturity when it comes to the ecosystem members, accordingly with real life cases, these do appear to present the biggest challenge on hydrogen projects regarding the final uses and consumers engagement with the technology.

On the other side of the pareto analysis on Table 5, are the factors displaying the highest levels of maturity, indicating the most successful assessment and diffusion of the overall CS average, these factors positively influence the overall maturity. The top 20% or four highest factors are the Degree of Innovativeness, the Number of Competitors and, on the population perspective, the Moderator and Investor.

The highest maturity level lies on the Degree of Innovativeness (85%) of the assessed case Studies, as a disruptive innovation in the renewable energy sector, the GH technologies do present a high degree of innovativeness as one of the main drivers for its diffusion, solving questions from emissions to the energetic production variability and storage matters for the current environmental concerns.

The Number of Competitors comes out as the second highest maturity factor (83%), where the conditions of the surrounding industrial, business, and economic environments influence the capabilities for diffusion. Specifically, through other companies/entities providing the same product/technology or through substitution products which although being different provide the same desired outcome to solve the initially defined problem. The GH technologies are still at early stages of developments and the presence of a network of competitors is almost inexistent in Europe currently. In fact, the majority of the CS were focused on R&D projects where the commercialization steps are still beginning. The major threat lies not directly on competitors but on the substitute products that may present themselves as superior or improved solutions compared to hydrogen (e.g., the use of BEV in mobility), and the cost of opportunity of investing on GH projects for large scale application, considering the current prices of production and distribution (International Energy Agency 2021).

The two following factors with highest maturity are the Moderator and Investor (80%) these are present in the innovation's ecosystem component. The two are correlated in the sense that on eleven out of twelve of the CS studied, these entities are the European Union through the FCH-JU (the governmental entity funding and orchestrating the projects) and since this stakeholder is deeply engaged in developing the hydrogen economy in Europe, it is expected that these two ecosystem factors show a similar and relatively high maturity level. The presence of these roles in the ecosystem as highly committed to the implementation and diffusion of the technology, brings questions of how dependent the technology is on these entities, and what would happen to the GH current projects if this concern and investment in the field of RES in GH by the EU would be inexistent. Currently the environmental targets and energetic dependency on fossil fuels from external countries such as Russia, the USA, Saudi Arabia, and other middle eastern countries, added to the increasing prices of fossil fuels due to the war in Ukraine, are heavily incentivizing the development of these renewable fields. Hence, added to the environmental benefits there are the economic ones from reducing dependency and creating expertise in a field expected to increase not only in Europe but globally, showing an opportunity in many fronts (IRENA 2022). Henceforth, on a European and even global perspective, the GH technology's development is highly dependent on governmental entities to achieve funding and moderation on an extremely costly and multifaceted technology, which itself is a barrier on the development of a sustainable diffusion in the short term.

To better understand how the different factors influence the diffusion of the portfolio, an in depth analysis was put together. The analysis is drawn on Table 6 with a comparison of two CS, one with highest overall maturity and the one with lowest, aligned with developing speed in the diffusion process and assessing what factors accelerate or slow this diffusion, considering the previous and given the context and results of the Litmus Test. The case with highest overall maturity was NorthH2 at 77%, and the one with lowest maturity was the HPem2Gas at 56%, demonstrating the ones that presented fastest and slowest diffusion correspondingly. With the aim of understanding which factors influence the success and speed of diffusion of the project, the table presents the average factor maturity for each case, the standard deviation analysis, and the delta between all the factors.

Table 6 – Comparison of factor maturity between NorthH2 and HPem2Gas

Factor	NortH2	HPem2Gas	AVERAGE	Std. Dev.	Delta
Innovation - Degree of Certification (Legal/Policy)	64%	48%	**56%**	11%	16%
Innovation - Degree of Complexity	64%	48%	**56%**	11%	16%
Innovation - Compatibility with Existing Ways of Work	80%	32%	**56%**	34%	48%
Population - Super User (Identified)	75%	44%	**59%**	22%	31%
Population - Key User (Identified)	72%	61%	**67%**	8%	11%
Innovation - Ease of Use	64%	48%	**56%**	11%	16%
Population - Influencer (Identified)	72%	48%	**60%**	17%	24%
Innovation - Budget and Resources	64%	48%	**56%**	11%	16%
Innovation - Ease of Adaptation	64%	36%	**50%**	20%	28%
Innovation - Technical Readiness Level	80%	60%	**70%**	14%	20%
Innovation - Ease of Trialing	80%	36%	**58%**	31%	44%
Population - Business Sponsor (Identified)	90%	52%	**71%**	27%	38%
Population - Inventor (Identified)	72%	64%	**68%**	6%	8%
Innovation - Ease of Understanding	64%	64%	**64%**	0%	0%
Population - Product Owner (Identified)	72%	69%	**71%**	2%	3%
Innovation - Urgency of Need	80%	60%	**70%**	14%	20%
Innovation - Oberservability of Impact	100%	48%	**74%**	37%	52%
Population - Moderator (Identified)	72%	75%	**73%**	2%	-3%
Population - Investor (Identified)	90%	56%	**73%**	24%	34%
Innovation - Number of Competitors	100%	100%	**100%**	0%	0%
Innovation - Degree of Innovativeness	100%	80%	**90%**	14%	20%
Case Study Average Maturity	**77%**	**56%**	**67%**		21%

The average of both cases discloses the lowest 20% factors of maturity, highlighted in red, and the top 20%, highlighted in green. The 3 previously commented factors slowing down diffusion (Degree of Certification, Degree of Complexity and Compatibility with Existing Ways of Work) also appear as the lower maturity factors on the comparison of NorthH2 and HPem2Gas, although in this instance the lowest average maturity lied on Ease of Adaptation (50%), the variable slowing the most the diffusion of the HPem2Gas project.

The delta between each factor shows the difference between all the factors from both cases, and the highest deltas (displayed in yellow on Table 5) demonstrate the variables that influence the more negatively the diffusion of the lowest maturity CS, HPem2Gas, while simultaneously positively influencing the maturity of the NorthH2 case results. These factors are the Observability of impact, the

Ease of Trialling, and the Compatibility with existing Ways of Work. These are the main variables to focus on, when improving the overall maturity of the portfolio studied, considering that enhancing these three factors will eventually bring higher maturity levels to the lowest maturity cases, therefore enhancing the speed with which an innovation is adopted and diffused, in particular in the Green Hydrogen technologies studied.

Henceforth, these three factors are emphasised as the main influencers on the successful diffusion of the portfolio of Case Studies modelled on the GH technologies. These are indicated as the actionable measures to recommend on the next step of dissertation, and as possible conclusions of recommendations to be drawn in GH cases. The questionnaire provided for the results validation to the interviewees, is the document in APPENDIX A, here are the recommendations where business, governmental and technological entities must focus their efforts on to reach high rates of diffusion, high maturity levels and ultimately the desired adoption from the end consumers of the technology to achieve successful projects.

5.2. – Results Validation

5.2.1. – Methodology

The results previously presented, which were achieved from modelling the Litmus Test with the Case Studies on the GH field were then submitted to validation by field experts. The validation methodology is set as a semi-structured interview with experts in different fields of application and within each one, a particular focus on Hydrogen technologies. The purpose of the validation is to confirm the results and discuss the barriers and drivers for the results achieved, while assessing the robustness of the model specifically applied to the GH cases.

In this sense, five experts were interviewed in three different online sessions. The first session occurred with a doctor expert in the field of hydrogen governance and regulation, national strategies and policy making, the second session occurred with an engineer specialized in project management of different implementations of hydrogen structures with a motivation on pipeline fuels distribution, the last session had three participants all from the same company in the field of aeronautics.

The interviewees were previously provided with a questionnaire describing the general results as presented on APPENDIX A, in order for them to understand the methodology, to initially interpret the outcomes and then form a supported argument of how the factors are aligned with real projects or their experience on practical applications of hydrogen. The interviews took place as an open discussion so both parts could intervein at will to whatever thoughts that may arise, without a strict script to enquire the intervenient rather to receive an open understanding and interpretation of the model and the key results.

The interviewees who participated in the validation, represent different areas of expertise and understanding of the field, from aeronautics, governance, and project management in the hydrogen infrastructures, to prove the flexibility of the model to different areas of application.

5.2.2. – Interviews

Interview 1: Dr. Paulo Partidário (DGEG)

Paulo Partidário, PhD, is the president of the scientific council of the DGEG, the Portuguese General Directorate of Energy and Geology. He holds a position as a senior researcher in the Division of Studies, Research and Renewables, focused on developing nationwide projects as investigator in cross-cutting projects, through the financial incentives that the government can provide, considering available conditions. In the particular case of hydrogen implementation, through the development of policies and instruments for eco-innovations, such as the co-coordination of the H2 - National Roadmap the Portuguese strategic plan for Hydrogen.

Dr. Partidário started by noting that the GH concept is a disruptive type of innovation, between the incremental and radical disruption. The nature of this innovation leverages on the elements of the ecosystem to adapt easier to the value chain that is being established and depending on the maturity level of the technology it will start creating a puzzle that makes sense on the bigger picture.

Regarding the model results, he started by stating that these are very ambitious, in a sense that it could create problems when trying to extend the actions and recommendations to other cases, in other parts of Europe and the world as in the same technology with other conditions or different ecosystem. There are different value chains being addressed in the current work, within the hydrogen theme, the current analysis does provide a wide perspective but does not translate to a particular type of value chain within a specific industry, since there is not only one value chain, besides it depends on the goal. Although this work may be promising in the long term for wider industry use cases, there must be also an emphasis on the innovation process being decoupled for instance in the Supply, Demand, Infrastructure, Maintenance, and other cross cutting issues, and then proceed to the interlink between all these levels of the chain.

There was an understanding of the holistic approach undertaken on the application of the model, although there is a favourable opportunity of looking at each value chain separately and developing it even further for each case, each sector, or each location. On that note, the variability in the different cases is an important factor when considering the overall factors to conclude the main drivers and barriers. Additionally, each value chain has different players, dynamics, and ecosystem conditions, where the perspective of the government, the technical readiness level, and correlation between the projects are based on these factors.

Concerning the factors presented initially in the questionnaire, Dr. Paulo Partidário agreed with the relevance of the Compatibility with Existing Ways of Work, as the challenge that a disruptive innovation creates as it emerges, especially in the case of the GH since the laggards tend to look at this type of innovation as a threat to the established ways and do not engage automatically with the new business models, when there should exist an enhanced focus on the new ventures arising. Accordingly, he also agreed with the importance of the Ease of Trialling and the Observability of Impact, as an important factor influencing the success of the projects. While describing that the component of focusing on certain parts of the value chain and developing the model on that specific area should be emphasized on the study, he also pointed a crucial factor that should have more relevance on the outcomes to achieve higher maturity in the ecosystem, the Technical Readiness Level, not only of the technology itself but also the maturity and readiness of the ecosystem to consume the innovative technology, in terms of knowledge, capabilities and complementary technologies.

A general recommendation was provided to focus on testing with a more similar portfolio of cases to reach more specific processes of the value chain, for instance the value chain and production processes will differ significantly from on-shore to off-shore GH production and will also differ when it comes to diffusing both.

Regarding the specific case of Portugal's adherence to the hydrogen economy, he stated that the initial step of diffusion in GH could lie in the gas grid integration with enriched natural gas, and the production of biofuels. This end use may be an initial step for early adoption before proceeding to more widely used applications such as mobility.

Dr. Paulo Partidário emphasized that in order to reach a sustainable diffusion there should be an enhanced focus on the CS selection, looking at the main value chain of the GH and decouple it depending on the context of use. He recommended that the methodology of future research specialize the group of factors studied rather than just addressing the population and innovation as a whole, instead focusing on components of the technology, for instance mobility or gras grid injection, and then reaching stronger arguments for each customization of the model.

Interview 2: Eng. Mário Ribeiro (ISQ)

The second interview occurred with Eng. Mário Ribeiro, who is a Project, Asset and Reliability Manager at ISQ (Instituto de Soldadura e Qualidade) with special expertise in fuels, renewable energies, hydrogen, pipelines, and pharmaceutical applications. He has been part of the hydrogen related research and project participation (national and international), he is currently involved in projects related with Hydrogen blending with NG and its effects on mainstream applications. With experience in multidisciplinary technical and practical knowledge of several industries on the areas of reliability, operations, team leading, industrial and organizational technical problem solving using advanced technology and innovative approaches. Regarding the energetic sector, he holds a considerable amount of experience in the fields of Oil & Gas, Renewable Energy (wind, solar, biofuels, hydrogen research), Reliability, Maintenance and Lean Management, R&D on Industrial applications, and Pipeline integrity management.

He started his career in the field of oil, gas, and energy distribution on the Exxon NG terminal at Trafaria, Lisbon regarding the maintenance of the pipelines. More recently he participated in the project Naturally (2004-2009) studying the possibility of injecting hydrogen in the NG network in Europe. At ISQ he participated in the studies of infrastructure integrity, materials, and a decision-making tool. Eng. Mário was related with the pipeline integrity, specifically with the maintenance of the pipelines (gas, fuel, water, etc.), after the H2 national strategic roadmap he wanted to get further involved in the area with projects such as, H2 Atlantic (Sines) and the Green Pipeline (Galp).

On the different H2 applications, he believes that the first and most important application will be on the industry, taking part in replacing the fossil fuels as the main source of hydrogen raw materials and shifting to a much greener production level.

Regarding the mobility sector, he believes that hydrogen will also play a role in heavy hauling, in road, rail and sea transportation. Knowing closely the heavy transportation sector and many players in it, he commented that if there was already a fully operational HRS many long-haul transportation companies would have made the shift to FCEV fleets as soon as they had the chance, mainly due to the independence achieved from fluctuating fossil fuel prices, availability, and the associated emissions costs, where hydrogen provides a stability of costs distanced from fossil fuel distributers lobbies.

After presenting the process behind the thesis, the model, methodology, and the core results, Eng. Mário started by commenting that he was not aware of the model methodology but contemplates it as a very interesting approach which aligns perfectly in the concepts of Asset Management (a field currently developed by him), because it involves a lot of specific areas of the product life cycle, such as infrastructure, stakeholders, and project development and saw the complete model of diffusion of innovation, as a nice surprise that he never dealt with.

He agreed with the three main factors presented, as important for the diffusion of the technology. He commented that he couldn’t help but agreeing with the main conclusions drawn as core factors influencing the diffusion of hydrogen projects nonetheless, he added that didn't find the presence of the cost, in particular the OPEX and CAPEX, of the projects in the energetic industry and in innovative projects in particular, is a variable commonly assessed for the specified GH area adding that the cost can be relevant on a certain level of diffusion to higher maturity, though he didn't know in detail the projects assessed in the Case Studies, but with a brief search understood them as relevant, including in the field of materials, R&D, and important in the GH area. Additionally, he recognized the factor of Budget & Resources as pertinent in the development of the referred cases.

Eng. Mário mentioned some factors to consider as relevant, from his interpretation of the model, considering his experience on hydrogen project development:

1. The cost, it would be very important to calculate or consider the cost benefit analysis of the project studied or interpreted, even as an approximate estimate this value can be very important on the success of the project, and in the field of Asset Management, this factor displays a major role on the assessment of each project, particularly to the stakeholders funding the project and in industrial terms it is really important for companies to consider this factor beforehand. The cost of the initial prototype should also be considered as relevant, a major factor when developing a Life Cycle Analysis and when commercializing a certain product to reach large scale of adoption. The prototype concept and the inherent costs are very important when developing these types of technologies specially in R&D projects as is the case of the majority of the cases studied.
2. Flexibility of the solutions: how the innovation will survive in the long term considering the existent changes in the energetic sector, in the industrial environment and further developments and innovations in the field. The flexibility and adaptability to change throughout time, different geographies, and technological environments, reveal the importance that the created platforms need to hold in order to adapt to constant change instead of being fixed to the initial problem to solve, it is an important factor to contemplate especially considering the present social and global environment with high uncertainty, due to the pandemic, war, and other risk factors currently existing in our society. He understood the factor Ease of Adaptation as the easiness of introduction to the market, not the ease of adaptation to the changing environment conditions and regarding the technology’s flexibility.
3. The social impact that the project brings to local and global communities, as the reach and number of entities that the technology will be useful to, and which are the positive and negative effects on the surrounding, social, economic, industrial, and energetic structure surrounding each project.

He concluded by stating that the factors noted, might be subject to evaluation and may be present in a next version of the Litmus Test as a more in depth analysis of the GH technology. The additional factors commented by Eng. Mário highlighted the importance of the variables studied such as the Budget and Resources, Ease of Adaptation and to provide particular focus on the ecosystem impact of the technology, hence aligning the overall Population with the factor of the Observability of Impact in the Innovation’s component.

Interview 3: Embraer Aerospace Experts (three interviewees)

The following interview occurred with a group of experts from the aerospace field specialized in aviation, strategy, innovation, and biofuels all representing the Brazilian aircraft manufacturer Embraer. The experts who contributed were, Eng. Marcelo Gonçalves, product development engineer with expertise in petroleum, biofuels, aeronautics and more recently working in alternative fuels, Dr. Ricardo Reis, who is currently working in Strategy and Intelligence, Autonomy and Electrification, while leading several European collaboration projects under H2020, and Dr. Dinah Leite, Research and Technological Engineer, in Future Analysis of projects related with pre-competitive R&D, involving low-maturity technologies, with innovation expertise.

Eng. Marcelo Gonçalves, focused his analysis on the aviation industry as fuel (possible hydrogen used in ICE on aircrafts or through fuel cells on electric aircrafts) or to supply airports as an energy carrier to be used in fuel cells or other end uses. Regarding the initial statement proposed, he agreed with the three main factors presented as important to consider when deploying GH projects to late adopters, with particular focus on the aviation industry.

Adding that the Compatibility with Existing Ways of Work is an important factor to consider, when understanding how we can bring the needs of the specific case of an airport together with the projects and consortiums developed in the technologies required, for instance in supplying or storing the material. He believes that the compatibility with existing ways of work and how to bring this technology with a very high TRL are some of the biggest challenges to tackle.

On the other hand, he commented that the Ease of Trialling is probably another major challenges in this matter, since it is critical to have the technology available for consumption for end users in order to bring this technology to an airfield, as an illustrative example, represents an aggregated risk of operations is present at all times in the process, such as material handling leading to the need of expertise in the area with new and improved standards of quality and safety. Frequently it is difficult to align and try this technology as successfully as possible and for aviation it needs to be analysed for feasibility, considering the needs of transporting, operating, and delivering hydrogen to aircrafts.

Moreover, he clarified that the Degree of Complexity, is important for the different stakeholders and how they perceive the hydrogen in aviation, in which ways it will be applied, and the complexity behind using it, can all present a big barrier for the diffusion in the aviation field and as an industry in general.

In his perspective, the methodology presented is a very interesting way of analysing the technology, and the comments displayed show that while considering the major factor of costs on the whole lifecycle of the project for different industrial applications, the procedure can be applied to different industries, and the critical point would be the boundaries, namely the geography and inherent technology available (TRL) at each point of use.

There was a brief discussion regarding the different fuel supply chains present on airports, especially in Brazil and in Germany perceiving the lack of pipelines and efficient ways of transporting the jet fuel or other fuels where it happens mainly by truck in the current case of Brazil, conversely to Germany where all the major airports are supplied via pipeline. Meaning that in the eventual implementation of hydrogen as an energy carrier to the industry, the distribution and supply chain would be fairly different in the two countries, and fairly more difficult to introduce the GH technologies in Brazil where the infrastructure is still behind even for well-established products as are the fossil fuels in the transportation sector. This demonstrates the importance that geography holds, as it influences significantly the diffusion of the technology and the relevance of having the technology available at both ends of the chain in a global network of fuels, there is a boundary as global challenge to account for. Moreover, with a heavy regulatory environment just as the aerospace industry, there are a lot of challenges to undertake in order to achieve mass adoption in the area, and in this case the factor that must be emphasised are the Compatibility with Existing Ways of Work, TRL and Degree of Complexity which arise again as relevant factors to consider when implementing GH technologies.

Dr. Ricardo Reis, initially noted that even though his expertise is on the aviation sector, his remarks are set to the whole ecosystem and not exclusive to his field of activity. He began by emphasizing the need to make the technology cheap not only for aerospace but for the whole value chain, other end uses, and industries, thus the price of hydrogen, will be influenced mainly by other industries and move along until it gets cost effective. Afterwards, he stated that the policy incentives must exist to motivate this diffusion, similarly to what happened in the beginning of the fossil fuel era more than a hundred years ago, he believes that we are experiencing the same developments in an inexistent commercial technology and infrastructure. Hence there is the need to focus on the operational means to affect change that are currently inexistent, with high costs in new equipment, new human resources, new skills, and expertise, and complying with current regulations, on this theme he comments that the questions of Degree of certification (Policy and Legal) and Urgency of Need play a critical role. Regarding the 3 factors presented he commented them as almost universal when it comes to reaching late adopters and achieving maturity through those. In a holistic view, he describes the three points as very open and general when talking about diffusion in different sectors of the market, here is where the issue of details in the different end uses influence the most important variables to consider, since this shift significantly from different industries and end uses.

In a way the GH diffusion reminds him the case of the airplane A380 in the sense that it needed a specific airport infrastructure to operate and only those airports could operate that aircraft. There are little networks that can easily adapt to the A380, just like this particular case the objective is to know how we can adapt and explore the existing infrastructure to receive the innovative technology.

He was curious why he did not find in the population the entity: Policy Regulators, the factor is present on the innovation as Degree of Certification however, he remarked that it would be important to consider the regulators and policy makers as future subject of research. Furthermore, in order to reach mass adoption these entities in the ecosystem still play a critical role.

Similarly, to Marcelo Dr. Ricardo Reis emphasised the importance of defining boundaries in the studies and in the application of the tool, for instance the aviation area there are many boundaries and a lot of variability to consider when defining the factors influencing the success of each project. In this industry the regulator role is so critical that it comes up from a factor only influencing the innovation itself to being present in the network of stakeholders, as a boundary question changing and defining the whole aviation ecosystem.

5.3. – Results Discussion

The development of the innovation diffusion methodologies employed on the Litmus Test and applied to the different CS on the distinct stages, culminated in a variety of analytical and qualitative results, such as the maturity level of each project, the speed of diffusion of the portfolio of cases evaluated, the development of each factor assessed, and the factors maturity through the pareto analysis. This subchapter serves as an alignment of the model outputs with the validation occurred and is meant to achieve an understanding of what lessons can be attained from the aforementioned, while searching for valuable insights on how to act fast and what measures need to be considered when developing innovative projects within the GH value chain.

Primarily, the outcomes achieved from the model showed that none of the Case Studies assessed is going to successfully diffuse on time, in the current market conditions compared to the aspired schedule and ideal reference model of diffusion, meaning that there are key improvements available and necessary that can be implemented on the cases in specific and in future GH projects. Likewise, the lower values of maturity on the overall Population Maturities compared to the component of the Innovation, emphasize the importance of the Innovation's Ecosystem and the development of the stakeholder's presence and engagement in the project, in order to achieve higher diffusion rates. Innovation does not happen simply from giving people incentives and developing the technology, it comes from creating ecosystems where the ideas can connect and develop, in this sense the GH technologies will only diffuse when the value network associated to the project is proactive and motivated to invest time and resources in the technology.

The analytical results of maturity culminated in two interpretations, the factors which positively influence diffusion hence providing higher speed of diffusion and the factors delaying diffusion with lower maturities thus slowing down the diffusion of the cases. The positive factors to consider as drivers for success in the GH technologies assessed, the 4 indicators with highest maturity were the Degree of Innovativeness, the Number of Competitors, the Moderator, and the Investor. On the other hand, the lowest values of maturity were the Degree of Certification, the Degree of Complexity, the Compatibility with Existing Ways of Work, and the Super User. All these factors are emphasized as key elements to enhance diffusion, and in the case of the lowest maturities there must be a particular focus on these fields of action, since improving the maturity of each one of these variables speeds exponentially the diffusion of the cases and consequently the maturity of the assessed portfolio. The previous conclusions align with the previous context explained in Europe, as the need to have a developing and active industrial and energetic ecosystem is in the origin of concerns of the EC, it is equally important to invest in the technologies and R&D projects to drive down costs and implement the necessary infrastructure but also to engage in an alive ecosystem of partners.

After a comparison of the least and most successful case studies (NorthH2 and HPEM2Gas), it was possible to determine a set of specific factors driving down the speed of diffusion in the portfolio of projects, these factors were the Observability of Impact, the Ease of Trialling, and the Compatibility with Existing ways of Work. These were determined as the most relevant ones when achieving to reach faster the market saturation (the 84% target of adopters), by implementing measures focused on the aforementioned set of factors. As the main conclusions drawn from the portfolio of cases studies, these were used as main recommendations for actionable interventions in future projects.

In the course of the different interviews, it was possible to notice a certain consensus between the interviewees on their position concerning the three factors presented as critical to achieve faster diffusion, during the sessions there was a general agreement on their relevance further complemented with personal perspectives of what factors could be emphasized as recommendations or as critical fields for successful hydrogen projects. In the interviews the low degree of knowledge by the experts of the model was a challenge, since it was an open discussion, it often fell to a more personal experience or the ideas of their work rather than the focus on the diffusion factors and their perceived understanding of what could be done to improve the innovation and drive it forward. The drifting from the main topic was already expected as an open discussion, but in a future validation I recommend explaining previously the model, the cases, and the results obtained in depth, for the interviewees to know the importance of the ecosystem and the different factors.

Subsequently, a variety of factors were highlighted during the discussions as relevant to consider on the recommendations for innovative hydrogen projects developed in the future. As initially mentioned, the infrastructure availability, specifically the lack of it or on the current situation, is one of the major factors delaying the diffusion of the hydrogen technologies. this was mentioned frequently by the interviewees as present in the factors of Technical Readiness Level, the Compatibility with Existing Ways of Work, Ease of Use, and Ease of Adaptation.

Accordingly with the lack of infrastructure the question of geography was discussed since distinct locations present different accessibilities or even different levels of development to the GH technologies. This variable was highlighted particularly when considering the global value chain of the aviation industry, although it also applies to other applications and industries. Indeed, this factor was not highly considered in the model as the Case Studies represent developments inside the EU where the GH value chain is being developed jointly as a whole and as seen previously, Europe is one of the global regions more invested in developing this technology, which does not directly translate to the desire of other developing countries.

Another factor emphasized was the political and regulatory perception, in the sense that an enabling legal and political framework engages with the GH technological and industrial development as a driver for successful projects. This factor was particularly pointed as important not only in the innovation's characteristics, where the Degree of Certification is assessed in fact with a low factor maturity, rather than with its presence on the innovation's ecosystem as an entity, performing a key role on the diffusion of the GH in countries where the technology is still undeveloped. It was pointed that this stakeholder must be considered when developing the model in the assessed industry and in future improvements.

The significance of the cost was also mentioned as critical for the development of the technology, in particular the costs of the prototypes, the projects CAPEX and OPEX, the costs of raw materials and complementary technologies. These variables heavily influence the decision making and strategic view of stakeholders on the development and implementation of GH technologies, as excessive costs drive down the incentives from these entities of investing in riskier projects and innovations, therefore investing in safer projects and more traditional technologies. Roughly stated by one of the interviewees: "there is a major need to achieve a cheap technology accessible to the whole ecosystem." Henceforth, the previous statements suggest the need to focus on the population's factor of the Investor, the Business Sponsor, and on the innovation's Budget and Resources factor. While also positively influencing the factor of Number of Competitors, since with higher entry costs the competition is reduced due to higher entry barrier for development of hydrogen businesses.

The validation interviews concluded that the forecast diffusion patterns represent a robust view of the project's history with further specific recommendations, additionally the factors influencing more negatively the diffusion were validated as relevant conclusions of the influences on the GH diffusion to achieve market saturation.

The given results represent supported recommendations for stakeholders implementing the technology, with a specific application for policy makers on where to act while reaching for faster implementation, and governmental entities as the current players showing the most interest in the GH due to climate issues and the achievement of a sustainable economy. Additionally, these variables are recommended for businesses establishing and developing the GH technologies on their operations, namely energetic companies, industrial players or even vehicle manufacturers.

6 – Conclusion & Future Developments

After understanding the problem at hand and what scientific literature resides behind the concepts of a maturity model developed in this dissertation, a general overview on the hydrogen role was described given the European energetic paradigm. Green hydrogen, and the complementary supply chain were presented, understanding the need of these technologies in achieving a green and sustainable economic growth, and proving the urgency of diffusing the hydrogen economy not only in the EU but globally. Subsequently, the context to study was defined, where it is important to mention that hydrogen should not be considered the unique solution to the world's energetic challenges and in particular, it will not be the only solution for the difficulties present in the transport sector, these challenges will possibly be solved by a diversity of solutions working together as one to tackle the upcoming environmental targets. However, green hydrogen will definitely play a vital role on decarbonising hard-to-electrify and carbon intensive sectors, providing major importance for hydrogen technological innovations to successfully diffuse in the next few decades and the need to achieve fast rates of adoption arises as crucial to reach the climate goals.

Followed by a literature review on the diffusion of innovations concepts, value networks and models used to assess diffusion, it is possible to deduce the importance that innovation webs hold on understanding how innovations are adopted throughout the different stakeholders, besides the balance that must be present on a technological innovation's attributes and the population's interest and insight of the innovations. Moreover, the concepts reviewed in the state of art, align with the technology defined in the problem definition to achieve the objective of the thesis, the application of the Litmus Test, in order to assess the maturity levels of the referred innovations and what variables influence their adoption, particular emphasis was applied on achieving the fastest diffusion possible from ideation to market saturation.

6.1. – Main findings and Implications

The population component proved to be an enabling element of diffusion in the GH technologies, by empowering the innovation webs present, while maintaining focus on the technological attributes, the cases tend to reach higher speed of diffusion, and achieve faster sustainable rates of adoption, reach the late adopters, and lastly accomplish market saturation.

The main findings from this dissertation, lie on the importance of 3 main factors highlighted and validated as the key ones driving down diffusion in the portfolio of cases assessed, the Observability of Impact of results attained from implementing GH projects, the Ease of Trialling as the possibility to which an individual or entity is able to experiment the outcome of the technology, and the Compatibility with Existing Ways of Work as the connection with traditional methods of applying the similar or complementary technology, and its connection to different end uses. These are the variables to consider as recommendations that require more investment from the stakeholders implementing future projects. Furthermore, there are also other factors slowing down diffusion that must be accounted for, the Degree of Certification of the technology being developed, the Degree of Complexity of implementing the technology in a certain environment or location, and the presence of the Super User in the population component that must be accounted and enhanced. On the other hand, it is also important to note the factors accelerating the diffusion such as the Degree of Innovativeness, the Number of Competitors, the presence of the Moderator and Investor, and these variables must be enhanced and receive relevance by the stakeholders as major drivers to achieve faster diffusion in new ventures.

6.2. – Limitations and recommendation for future research

When applied to the cases of interest the research method in combination with the assessments of the selected change factors leads to an initially accepted robust validation of the diffusion theory selected. Although monitoring of the cases studies is an ongoing process, that requires further research focused specifically on the diffusion of the assessed projects to continuously refine the approach to the GH technologies. The limitations of this study reside precisely on the holistic view considered during the dissertation, more specifically on the difficulties to present concrete recommendations in particular levels of the Supply Chain or specific value chains, meaning that it can present an inflated view of the industry which is itself composed by several detailed value chains that need to be addressed and studied separately for each case, technology, or location. Bearing in mind the previous, the recommendations for potential future research lie in the development of the Innovation Diffusion model to specific parts of the HSC with the focus on delivering specialized recommendations to a certain value chain and then proceeding to interlink the different assessments to achieve the structured view from the bottom to the top of the value chain. Additionally, the need to examine further factors such as value network intent and value network / ecosystem performance.

Moreover, the geographical variable needs to be considered in addition to the TRL in different locations around the world with different availability and compatibility to the hydrogen technologies. The importance of the Regulator and Policy makers on different industries of hydrogen application (e.g., aviation, long haul, energy storage) are also emphasized as important to consider in future research as part of the ecosystem members to be addressed.

REFERENCES

Adner, Ron. 2006. “Match Your Innovation Strategy to Your Innovation Ecosystem.” *Harvard Business Review* 84(4).

Airbus. n.d. “ZEROe - Hydrogen - Airbus.” Retrieved June 5, 2021 (https://www.airbus.com/innovation/zero-emission/hydrogen/zeroe.html).

Allee, Verna. 2008. “Value Network Analysis and Value Conversion of Tangible and Intangible Assets.” *Journal of Intellectual Capital* 9(1):5–24. doi: 10.1108/14691930810845777.

Allee, Verna, and Oliver Scwabe. 2011. “Value Networks and the True Nature of Collaboration.” *ValueNet Works and Verna Allee Associates* 28(3):228–35. Retrieved May 27, 2021 (https://www.goodreads.com/book/show/26216692-value-networks-and-the-true-nature-of-collaboration).

Almansoori, A., and A. Betancourt-Torcat. 2016. “Design of Optimization Model for a Hydrogen Supply Chain under Emission Constraints - A Case Study of Germany.” *Energy* 111:414–29. doi: 10.1016/j.energy.2016.05.123.

Antonia, O., and G. Saur. 2012. “Wind to Hydrogen in California: Case Study Wind to Hydrogen in California: Case Study.” *National Renewable Energy Laboratory* (August):38.

Ashokan, Rashini, Gabriel Lopez Zenarosa, and Xiuli He. 2018. “Diffusion Model for the Adoption of Smartphone Brands under Competitive Pricing.” *International Journal of Trade, Economics and Finance* 9(3):96–99. doi: 10.18178/ijtef.2018.9.3.595.

Azzaro-Pantel, Catherine. 2018. *Hydrogen Supply Chains: Design, Deployment and Operation*.

Barile, Sergio, Mara Grimaldi, Francesca Loia, and Carlo Alessandro Sirianni. 2020. “Technology, Value Co-Creation and Innovation in Service Ecosystems: Toward Sustainable Co-Innovation.” *Sustainability (Switzerland)* 12(7). doi: 10.3390/su12072759.

Bass, Frank M. 1969. “A New Product Growth for Model Consumer Durables.” *Management Science* 15(5):215–27.

Bass, Portia Isaacson, and F. Bass. 2001. “Diffusion of Technology Generations: A Model of Adoption and Repeat Sales.”

BIGHIT. 2020. “BIG HIT.” Retrieved December 19, 2021 (https://www.bighit.eu/).

Biurrun, Rodrigo, Dennis Krieg, and Detlef Stolten. 2012. “Systemic Tradeoff Analysis of Fuel Cell Mobility Systems.” *International Journal of Hydrogen Energy* 37(17):12639–49. doi: 10.1016/j.ijhydene.2012.05.161.

Chapman, Andrew, Kenshi Itaoka, Katsuhiko Hirose, F. Todd Davidson, Kazunori Nagasawa, Alan C. Lloyd, Michael E. Webber, Zeynep Kurban, Shunsuke Managi, Tetsuya Tamaki, Michael C. Lewis, Robert E. Hebner, and Yasumasa Fujii. 2019. “A Review of Four Case Studies Assessing the Potential for Hydrogen Penetration of the Future Energy System.” *International Journal of Hydrogen Energy* 44(13):6371–82.

Chisholm, Greig, and Leroy Cronin. 2016. “Hydrogen From Water Electrolysis.” Pp. 315–43 in *Storing Energy: With Special Reference to Renewable Energy Sources*. Elsevier Inc.

Cross, Robert Lee, and Andrew Parker. 2004. *The Hidden Power of Social Networks: Understanding How Work Really Gets Done ... - Robert Lee Cross, Robert L. Cross, Andrew Parker - Google*

Livros.
Daimler. n.d. “Hydrogen | Daimler.” Retrieved June 7, 2021 (https://www.daimler.com/innovation/drive-systems/hydrogen/).
Dincer, Ibrahim. 2012. “Green Methods for Hydrogen Production.” *International Journal of Hydrogen Energy* 37(2):1954–71. doi: 10.1016/J.IJHYDENE.2011.03.173.
Djellal, Faridah, and Faïz Gallouj. 2017. “The Laws of Imitation and Invention: Gabriel Tarde and the Evolutionary Economics of Innovation.” *Revue Economique* 68(4):643–71. doi: 10.3917/reco.684.0643.
ECHA. n.d. “European Clean Hydrogen Alliance.” Retrieved June 5, 2021 (https://www.ech2a.eu/missionandvision).
EGHAC. 2022. “EGHAC - The European Green Hydrogen Acceleration Center.” Retrieved April 3, 2022 (https://eghac.com/).
ELY4OFF. 2021. “ELY4OFF - PEM ElectroLYsers FOR Operation with OFFgrid Renewable Installations.” *2021*. Retrieved January 19, 2022 (http://ely4off.eu/).
Escobar-Yonoff, Rony, Daniel Maestre-Cambronel, Sebastián Charry, Adriana Rincón-Montenegro, and Ivan Portnoy. 2021. “Performance Assessment and Economic Perspectives of Integrated PEM Fuel Cell and PEM Electrolyzer for Electric Power Generation.” *Heliyon* 7(3):e06506. doi: 10.1016/j.heliyon.2021.e06506.
European Comission. 2020a. “A European Green Deal.” *New Circular Economy Action Plan* (December 2019):1–4. Retrieved May 19, 2021 (https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en).
European Comission. 2020b. *A Hydrogen Strategy for a Climate-Neutral Europe*. Brussels.
European Commission. 2020. “Making Europe’s Businesses Future-Ready: A New Industrial Strategy for a Globally Competitive, Green and Digital Europe (Press Release).” (March 2020):1–5.
European Union. 2021. *KEY DRIVER OF THE HYDROGEN STRATEGY*.
FCH EU. 2020a. “HYShip DEMONSTRATING LIQUID HYDROGEN FOR THE MARITIME SECTOR | Www.Fch.Europa.Eu.” Retrieved June 5, 2021 (https://www.fch.europa.eu/project/demonstrating-liquid-hydrogen-maritime-sector).
FCH EU. 2020b. *MARITIME HYDROGEN: THE NEXT BIG WAVE*.
Fuel Cells and Hydrogen EU. 2020. “All H2020 Projects | Www.Fch.Europa.Eu.” Retrieved June 3, 2021 (https://www.fch.europa.eu/fchju-projects/h2020).
Gomes, Leonardo Augusto de Vasconcelos, Ana Lucia Figueiredo Facin, Mario Sergio Salerno, and Rodrigo Kazuo Ikenami. 2018. “Unpacking the Innovation Ecosystem Construct: Evolution, Gaps and Trends.” *Technological Forecasting and Social Change* 136:30–48. doi: 10.1016/j.techfore.2016.11.009.
Gomes, Rafael, and Sema Seyfi Osman. 2019. *Managing Organizational Adoption of IoT Revisiting Rogers’ Diffusion of Innovation Theory*.
Gompertz, Benjamin. 1825. *On the Nature of the Function Expressive of the Law of Human Mortality, and on a New Mode of Determining the Value of Life Contingencies*. Vol. 115.
Grammelis, Panagiotis, Nikolaos Margaritis, and Dimitrios Sotirios Kourkoumpas. 2018. “Pyrolysis Energy Conversion Systems.” *Comprehensive Energy Systems* 4–5:1065–1106. doi:

10.1016/B978-0-12-809597-3.00445-4.

Granstrand, Ove, and Marcus Holgersson. 2020. “Innovation Ecosystems: A Conceptual Review and a New Definition.” *Technovation* 90–91(February). doi: 10.1016/j.technovation.2019.102098.

H2FUTURE PROJECT. n.d. “H2FUTURE PROJECT - FCH EU.” Retrieved (https://www.h2future-project.eu/).

H2Haul. 2021. “H2Haul.” *2021*. Retrieved January 18, 2022 (https://www.h2haul.eu/).

H2Haul. n.d. “H2Haul - FCH EU.” Retrieved June 5, 2021 (https://www.h2haul.eu/).

H2ME. 2021. “Hydrogen Mobility Europe.” *2021*. Retrieved January 18, 2022 (https://h2me.eu/).

H2Ref. n.d. “About H2Ref | H2Ref.” *2020*. Retrieved January 17, 2022 (http://www.h2ref.eu/about-h2ref/).

Homans, George C. 1958. “Social Behavior as Exchange.” *American Journal of Sociology* 63(6):597–606. doi: 10.1086/222355.

HPEM2GAS. n.d. “Homepage - HPEM2GAS | HPEM2GAS.” *2020*. Retrieved January 18, 2022 (https://hpem2gas.eu/).

HySTOC. 2020. “HySTOC.” Retrieved January 18, 2022 (https://www.hystoc.eu/).

Hystories. 2021. “Hystories - Hydrogen Storage in European Subsurface - Hystories.” *2021*. Retrieved January 18, 2022 (https://hystories.eu/).

Hyunday. n.d. “All-New Hyundai NEXO | Hydrogen Fuel Cell SUV.” *2021*. Retrieved June 7, 2021 (https://www.hyundai.co.uk/new-cars/nexo).

Iberdrola, Fertiberia. n.d. “Puertollano Green Hydrogen Plant - Iberdrola.” *2020*. Retrieved June 5, 2021 (https://www.iberdrola.com/about-us/lines-business/flagship-projects/puertollano-green-hydrogen-plant).

IEA. 2019a. “The Future of Hydrogen.” *The Future of Hydrogen* (June). doi: 10.1787/1e0514c4-en.

IEA. 2019b. *The Future of Hydrogen*.

International Energy Agency, Iea. 2021. *Renewable Energy Market Update - Outlook for 2021 and 2022*.

IRENA. 2018. *Hydrogen From Renewable Power: Technology Outlook for the Energy Transition*.

IRENA. 2019. “RENEWABLE POWER-TO-HYDROGEN INNOVATION LANDSCAPE BRIEF.”

IRENA. 2020. *Green Hydrogen: A Guide to Policy Making*. Vol. 2.

IRENA. 2022. “The Geopolitics of Energy Transformation. The Hydrogen Factor.” *Stiftung Wissenschaft Und Politik*.

Kakoulaki, G., I. Kougias, N. Taylor, F. Dolci, J. Moya, and A. Jäger-Waldau. 2021. “Green Hydrogen in Europe – A Regional Assessment: Substituting Existing Production with Electrolysis Powered by Renewables.” *Energy Conversion and Management* 228:113649. doi: 10.1016/j.enconman.2020.113649.

Maggio, G., A. Nicita, and G. Squadrito. 2019. “How the Hydrogen Production from RES Could Change Energy and Fuel Markets: A Review of Recent Literature.” *International Journal of Hydrogen Energy* 44(23):11371–84.

McKinsey, and Hydrogen Council. 2021. “Hydrogen Insights.” (February).

Mehmood, Yasir, Nicola Barbieri, and Francesco Bonchi. 2016. “Modeling Adoptions and the Stages of the Diffusion of Innovations.” *Knowledge and Information Systems* 48:1–27. doi:

10.1007/s10115-015-0889-5.
Meyer, Patrick E., and James J. Winebrake. 2009. “Modeling Technology Diffusion of Complementary Goods: The Case of Hydrogen Vehicles and Refueling Infrastructure.” *Technovation* 29(2):77–91. doi: 10.1016/j.technovation.2008.05.004.
Miller, John, and Scott E. Page. 2007. *Complex Adaptive System. An Introduction to Computational Models of Social Life*.
Moore, J. F. 1993. “Predators and Prey: A New Ecology of Competition.” *Harvard Business Review* 71(3):75–86.
Neptune. 2021. “Neptune FCH JU.” *2021*. Retrieved January 18, 2022 (https://www.neptune-pem.eu/en/).
NorthH2. 2020. “NortH2 | Kickstarting the Green Hydrogen Economy.” Retrieved December 3, 2021 (https://www.north2.eu/en/).
Quinlan, Christina, William Zikmund, Barry Babbin, and John C. Carr. 2019. *Business Research Methods*.
Qumar, Naresh. 2015. “Review of Innovation Diffusion Models.”
REFHYNE. 2022. “REFHYNE – Clean Refinery Hydrogen for Europe.” *2022*. Retrieved January 19, 2022 (https://refhyne.eu/).
Renault Press. 2019. “Renault Runs on Hydrogen With Master Z.E. Hydrogen and Kangoo Z.E. Hydrogen.” 33(0):1–14.
Rogers, Everett M., Arvind Singhal, and Margaret M. Quinlan. 1983. *Diffusion of Innovations*.
Schwabe, Oliver. 2019a. “Exploring the First Innovation Web: The Research Archetype.” Retrieved June 2, 2021 (https://open-european-innovation-network.blogspot.com/2019/06/exploring-first-innovation-web-research.html).
Schwabe, Oliver. 2019b. “Exploring the Fourth Innovation Web: The Commercialization Archetype.” Retrieved June 2, 2021 (https://open-european-innovation-network.blogspot.com/2019/06/exploring-fourth-innovation-web.html).
Schwabe, Oliver. 2019c. “Exploring the Second Innovation Web: The Socialization (Community Building) Archetype.” Retrieved June 2, 2021 (https://open-european-innovation-network.blogspot.com/2019/06/exploring-second-innovation-web.html).
Schwabe, Oliver. 2019d. “Exploring the Third Innovation Web: The Market Validation Archetype.” Retrieved June 2, 2021 (https://open-european-innovation-network.blogspot.com/2019/06/exploring-third-innovation-web-market.html).
Schwabe, Oliver. 2020a. “The Innovation Diffusion Litmus Test.” Retrieved June 2, 2021 (https://open-european-innovation-network.blogspot.com/2020/04/the-innovation-diffusion-litmus-test.html).
Schwabe, Oliver. 2020b. “The Narrative for Generic Diffusion of Innovation.” Retrieved May 31, 2021 (https://open-european-innovation-network.blogspot.com/2020/01/the-narrative-for-generic-diffusion-of.html).
Schwabe, Oliver, Pinar Bilge, Andreas Hoessler, Taner Tunc, Daniel Gaspar, Nigel Price, Lee Sharir, Edna Pasher, John Erkoyuncu, Nuno Marques De Almeida, Piero Formica, Lynne Schneider, Franz Dietrich, and Essam Shehab. 2020. “A Maturity Model for Rapid Diffusion of Innovation in High Value Manufacturing.” *Procedia CIRP* 96:195–200. doi: 10.1016/j.procir.2021.01.074.

Schwabe, Oliver, Lynne Schneider, Nuno Marques de Almeida, and Ana Filipa Salvado. 2021. “A Framework for Accelerating Innovation Through Innovation Webs.” Pp. 205–10 in.

Sun, Fu, Jingshan Qin, Zhiyu Wang, Mengzhou Yu, Xianhong Wu, Xiaoming Sun, and Jieshan Qiu. 2021. “Energy-Saving Hydrogen Production by Chlorine-Free Hybrid Seawater Splitting Coupling Hydrazine Degradation.” *Nature Communications* 12(1). doi: 10.1038/s41467-021-24529-3.

Tagliapietra, Simone, Georg Zachmann, Ottmar Edenhofer, Jean Michel Glachant, Pedro Linares, and Andreas Loeschel. 2019. “The European Union Energy Transition: Key Priorities for the next Five Years.” *Energy Policy* 132:950–54. doi: 10.1016/j.enpol.2019.06.060.

Tarde, Gabriel. 1903. “The Laws of Imitation.”

Toyota. 2021. “Toyota Mirai Fuel Cell Vehicle.” *Toyota US Official Website*. Retrieved June 7, 2021 (https://www.toyota.com/mirai/).

Valkokari, Katri, Marko Seppänen, Maria Mäntylä, and Simo Jylhä-Ollila. 2017. “Orchestrating Innovation Ecosystems: A Qualitative Analysis of Ecosystem Positioning Strategies.” *Technology Innovation Management Review* 7(3):12–24. doi: 10.22215/timreview/1061.

Yang, Qian, and Cheng Li. 2019. “User Roles and Contributions in User Innovation Community.” *American Journal of Industrial and Business Management* 09(06):1318–31. doi: 10.4236/ajibm.2019.96087.

APPENDIX

APPENDIX A – Questionnaire provided to field experts as a basis for the interviews

Interview for validation of results in the Litmus Test applied to Green Hydrogen Case Studies

Student: Lourenço Horta Correia – lourenco.correia@tecnico.ulisboa.pt
Supervisor(s): Dr. Oliver Schwabe, Prof. Nuno Marques de Almeida

This interview takes part in the development of a master thesis in Industrial Engineering and Management at Instituto Superior Técnico (Lisbon) designated 'Speed of Innovation Diffusion in Green Hydrogen Technologies – Variables and their Interdependence'.

An Innovation Diffusion model (Litmus Test) was applied to 12 Case Studies in different levels of the Green Hydrogen Supply Chain. These cases are located in Europe, are related to different sectors from R&D to commercialization and the diffusion of the technology and are mainly sponsored by the European Union through the Horizon 2020 fund in Fuel Cells and Hydrogen Joint Undertaking. The model considers the innovation itself and its ease to diffuse in the current environment, while also focusing on the ecosystem of stakeholders (innovation web) that take part in the various transactions influencing the possible adoption of the innovation. The outputs of the model are the diffusion forecasts of the time it takes to reach the late majority of adopters compared to the aspired schedule of diffusion of each project, a maturity level (1 to 5) and identify the factors that influence the diffusion and the need of improvements. The objective of this interview is to validate the results obtained so far applied to the referred cases, assess the robustness of the model and to understand what recommendations can be obtained from the experts to improve the application of the model and what conclusions can be made to accelerate the diffusion.

In order to evaluate why some projects, seem to outperform others we compared the case studies with highest maturity levels to the ones with the lowest maturity. In the comparison we looked for the factors with the biggest difference for the case of NorthH2 (higher maturity) compared with HPem2Gas (lowest maturity) hence, the factors which show the biggest difference should be the ones that lead to slower diffusion rates on the HPem2Gas and need to be developed. The top three factors that have higher differences and influence the most the speed of diffusion are:

- Compatibility with existing ways of work – regarding the innovation itself and how it engages with the environment and the conventional technologies used.
- Ease of trialling – how easily the innovation can be tried by consumers in its possible end uses.
- Observability of Impact – how the results shown by the innovation can be observed, and how these influence the original problem set to be resolved.

Please see in the following pages, Table 1 with a brief explanation of the factors studied (from the innovation and the ecosystem members), the complete data table that we can discuss in Table 2 listing all the case studies with their assessed maturity levels (the higher the maturity the more likely they are to be successful) and shows the assessment scores for the 21 factors increasing from lowest to highest and in Figure 1 a general overview of the innovation web of how the key roles interact in the diffusion of innovations to late adopters. We would like to have a conversation with you to discuss if these results make sense and are aligned with real life projects in the field of Green Hydrogen.

Thank you,
Lourenço Horta Correia

	Factor	Description
Innovation	Budget and Resources	Budget and resources available within the funding and raw materials available for the development of the innovation
	Compatibility with Existing Ways of Work	Regarding the innovation itself and how it engages with the technological environment and the conventional ways used in the field
	Degree of Certification (Legal/Policy)	Legal certification and level of suitability to the policies present in the region/state being developed
	Degree of Complexity	The level of complexity in the development of the innovation as well as how complex it is seen by the different stakeholders
	Degree of Innovativeness	Level of innovativeness in the conventional ecosystem where the innovation is being developed
	Ease of Adaptation	How easily the innovation adapts to changes in the ecosystem that affect its development
	Ease of Trialing	How easily the innovation can be experimented by consumers in its possible end uses
	Ease of Understanding	How easily the different stakeholders understand the innovation and its benefits
	Ease of Use	How easily the innovation can be used in real life situation
	Number of Competitors	The threat of being overtaken by competitors or replaced by other technologies
	Observability of Impact	How the results shown by the innovation can be observed, and how these influence the original problem set to be solved
	Technical Readiness Level	Degree to which the innovation is ready to be deployed, to mass markets and large scale adoption
	Urgency of Need	How urgent the development of the innovation is, considering the current ecosystem and technologies
Population	Business Sponsor	Shapes the solution and value proposition from the Product Owner, into a tangible opportunity and transact it with the Influencer
	Influencer	Market the solution from the Business Sponsor to the Key User in order to generate na intangible expression of interest
	Inventor	Entity who receives an intangible challenge from the Key User and develops an idea to solve the identified need/problem
	Investor	Entity providing funding to the project
	Key User	Individual in an organization using the technology providing a challenge/need that is intended for use by late adoption market
	Moderator	Entity orchestrating and moderating the development of the project with the different stakeholders
	Product Owner	Transforms the input from the inventor into a potential tangible solution, accompanied by a value proposition
	Super User	A Key User receiving the challenge and providing guidance for the development of the innovation by the Inventor

Table A-1 – Innovation factors and brief description

Factor	NorthH2	H2Me	Refhyne	H2Haul	H2Future	Neptune	HyStories	BIG Hit	H2Ref	Ely4Off	HySTOC	HPem2Gas	AVERAGE
Innovation - Degree of Certification (Legal/Policy)	64%	60%	64%	48%	60%	60%	48%	36%	48%	32%	36%	48%	**50%**
Innovation - Degree of Complexity	64%	60%	48%	64%	64%	60%	48%	48%	48%	48%	48%	48%	**54%**
Innovation - Compatibility with Existing Ways of Work	80%	40%	80%	60%	60%	48%	64%	64%	80%	24%	60%	32%	**58%**
Population - Super User (Identified)	75%	59%	67%	54%	61%	72%	54%	50%	44%	48%	69%	44%	**58%**
Population - Key User (Identified)	72%	53%	69%	69%	64%	52%	46%	48%	56%	50%	69%	61%	**59%**
Innovation - Ease of Use	64%	80%	64%	80%	60%	60%	32%	48%	64%	48%	64%	48%	**59%**
Population - Influencer (Identified)	72%	69%	52%	69%	67%	48%	50%	67%	67%	61%	46%	48%	**60%**
Innovation - Budget and Resources	64%	48%	80%	60%	64%	64%	60%	64%	80%	48%	48%	48%	**61%**
Innovation - Ease of Adaptation	64%	60%	60%	80%	80%	80%	48%	60%	48%	48%	64%	36%	**61%**
Innovation - Technical Readiness Level	80%	80%	80%	48%	48%	48%	48%	64%	48%	80%	48%	60%	**61%**
Innovation - Ease of Trialing	80%	100%	80%	60%	80%	48%	80%	80%	64%	48%	48%	36%	**67%**
Population - Business Sponsor (Identified)	90%	97%	67%	67%	56%	67%	75%	75%	72%	50%	64%	52%	**69%**
Population - Inventor (Identified)	72%	93%	75%	69%	56%	54%	75%	72%	59%	90%	52%	64%	**69%**
Innovation - Ease of Understanding	64%	80%	64%	64%	100%	80%	80%	64%	100%	48%	36%	64%	**70%**
Population - Product Owner (Identified)	72%	67%	90%	69%	69%	69%	75%	90%	48%	69%	72%	69%	**72%**
Innovation - Urgency of Need	80%	100%	80%	100%	80%	80%	60%	48%	80%	80%	64%	60%	**76%**
Innovation - Observability of Impact	100%	80%	100%	80%	64%	80%	80%	60%	64%	100%	60%	48%	**76%**
Population - Moderator (Identified)	72%	97%	93%	90%	60%	77%	93%	75%	75%	75%	75%	75%	**80%**
Population - Investor (Identified)	90%	80%	90%	90%	72%	87%	72%	75%	77%	97%	75%	56%	**80%**
Innovation - Number of Competitors	100%	100%	100%	100%	60%	80%	100%	80%	60%	60%	60%	100%	**83%**
Innovation - Degree of Innovativeness	100%	100%	100%	80%	80%	80%	80%	80%	60%	80%	100%	80%	**85%**
Case Study Average Maturity	**77%**	**76%**	**76%**	**72%**	**67%**	**66%**	**65%**	**64%**	**64%**	**61%**	**60%**	**56%**	

Table A-2 – Maturity results for the 12 Case Studies and respective factors studied

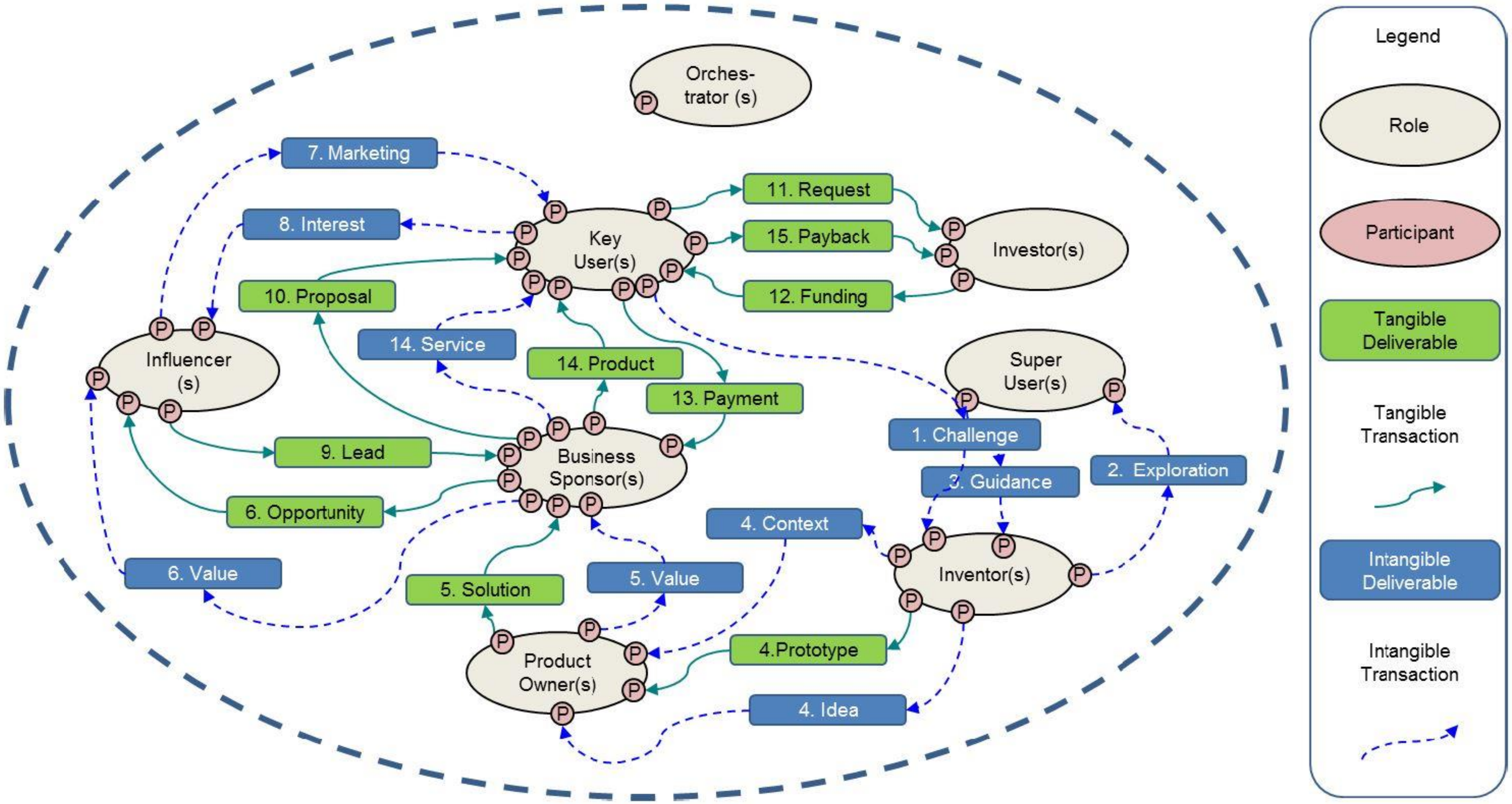

Figure A-1 – Value Network of Innovation Diffusion to Late Adopters [Schwabe et al. 2020]