Speed of Innovation Diffusion in Water Electrolysis

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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

Green hydrogen will help the European Green Deal achieve “net zero” greenhouse gas emissions by 2050. Green hydrogen is created through water electrolysis and is viewed by many as crucial in our energy transition to a low carbon future. However, lacking infrastructure, investments, and a complex supply chain has made it more expensive than its fossil fuel competitors. With more research focused on developing the technology itself, the green hydrogen ecosystem lacks findings on improving the innovation ecosystem to find pathways for faster diffusion.

This dissertation focuses on the challenge of diffusing novel electrolysis technologies through the green hydrogen supply chain. Sixteen case studies are examined using innovation ecosystem principles and a maturity model to estimate how fast these technologies will reach market saturation. Key parameters affecting the speed of innovation diffusion are also analysed. Results are then compared to 12 case studies on the green hydrogen supply chain to provide a holistic view of the green hydrogen ecosystem, followed by validation interviews.

The thesis is divided into a literature review, followed by finding informative water electrolysis case studies while analysing and developing outcomes using the maturity model and comparing with existing outcomes from green hydrogen supply chain case studies. The lack of maturity among water electrolysis case studies holds back the entire green hydrogen ecosystem was the conclusion drawn from this work. Degree of certification lacks in both sets of cases while population of investors rank high.

Keywords: Innovation Diffusion, Water Electrolysis, Green Hydrogen, Maturity levels, Innovation Ecosystems

RESUMO

O hidrogénio verde ajudará o Acordo Verde Europeu a alcançar "zero emissões líquidas" de gases com efeito de estufa até 2050. O hidrogénio verde é criado através da electrólise da água e é visto por muitos como crucial na nossa transição energética para um futuro de baixo carbono. No entanto, a falta de infra-estruturas, investimentos e uma complexa cadeia de abastecimento tornaram-no mais caro do que os seus concorrentes dos combustíveis fósseis. Com mais investigação centrada no desenvolvimento da própria tecnologia, o ecossistema de hidrogénio verde carece de descobertas sobre a melhoria do ecossistema de inovação para encontrar vias para uma difusão mais rápida.

Esta dissertação centra-se no desafio da difusão de novas tecnologias de electrólise através da cadeia de abastecimento de hidrogénio verde. Dezasseis estudos de caso são examinados utilizando os princípios do ecossistema de inovação e um modelo de maturidade para estimar a rapidez com que estas tecnologias atingirão a saturação do mercado. São também analisados parâmetros-chave que afectam a velocidade da difusão da inovação. Os resultados são então comparados com 12 estudos de caso sobre a cadeia de abastecimento de hidrogénio verde para fornecer uma visão holística do ecossistema de hidrogénio verde, seguidos de entrevistas de validação.

A tese é dividida numa revisão bibliográfica, seguida de estudos de caso informativos de electrólise da água enquanto se analisam e desenvolvem resultados utilizando o modelo de maturidade e comparando com os resultados existentes dos estudos de caso da cadeia de abastecimento de hidrogénio verde. A falta de maturidade entre os estudos de caso de electrólise da água atrasa todo o ecossistema do hidrogénio verde foi a conclusão retirada deste trabalho. O grau de certificação é insuficiente em ambos os conjuntos de casos, enquanto que a população de investidores é elevada.

Palavras-chave: Difusão da Inovação, Electrólise da Água, Hidrogénio Verde, Níveis de Maturidade, Ecossistemas de Inovação

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1. Introduction

1.1. Problem background and motivation

The effects of climate change are right at our doorstep, and we now face unfamiliar challenges in tackling it. Major world powers are scrambling their finances and resources to help tackle climate change by making ambitious plans toward carbon neutrality. With an ambitious plan to reduce greenhouse gases by 55% by 2030, the European Union is doing its part to achieve its long-term goal of carbon neutrality by 2050(IEA, 2019). A diverse mix of renewables is essential in bringing about an energy transition to tackle climate change.

Various methods can be employed to produce hydrogen. Steam reforming of natural gas, fermentation of biomass and biofuels, and thermochemical cycles of nuclear and solar energy are a few. Although a colourless gas, commercial hydrogen can be described using various colour codes to differentiate. Differentiation is done based on production methods. Though not a universal convention, these colour codes can also help determine the source of the hydrogen produced. Standard colour codes are green, grey, blue, brown, yellow, turquoise, pink and white.

Green hydrogen, or hydrogen produced from renewable energy, is a critical piece in our energy transition puzzle. Its ability to replace fossil fuel-based hydrogen for industrial purposes, transform the emission-intensive transport sector or act as an energy carrier for renewables asserts its role in climate neutrality. Water electrolysis, the process by which renewable electricity is used to split water into oxygen and hydrogen, produces hydrogen with zero carbon emissions and is deemed crucial in any decarbonized energy sector. With increasing fossil fuel prices and a need for energy security, green hydrogen's importance in the energy mix rises daily. However, a lack of infrastructure, investments, and a complex supply chain has made green hydrogen two to three times more expensive than its fossil fuel competitors.

Even though much advancement in the sector has been made with solid international policies backing green hydrogen, many roadblocks slow its diffusion. As the hydrogen economy is in its initial stages of growth, extensive analysis and study are needed to estimate factors key to the faster adoption of this technology to reach its desired targets.

This thesis focuses on the innovation diffusion of water electrolysis technologies. Determining how fast these technologies will reach market saturation using a maturity model involving 16 case studies and comparing them with 12 green hydrogen supply chain case studies to identify critical factors for accelerating diffusion forms the core of this work (Correia et al., 2022). This study is divided into finding informative water electrolysis case studies followed by analyzing and developing outcomes using the maturity model and comparing with existing outcomes from green hydrogen supply chain case studies to provide a holistic view while suggesting recommendations for future projects to achieve a higher diffusion rate. This work will help understand the factors crucial for the faster adoption of green hydrogen and the influence of its ecosystem in minimizing the time required to achieve adoption by the critical mass.

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1.2. Dissertation objectives

The goal of this dissertation is to develop a maturity model on innovations of water electrolysis technologies and their end uses, understand how it diffuses over time and present recommendations on the variables influencing diffusion to focus on future endeavours. This work also compares with the results obtained from green hydrogen supply chain case studies to provide a comprehensive take on the factors lacking in the green hydrogen ecosystem to improve its diffusion. This dissertation covers the first stages of a theoretical approach to the methodological and conceptual background as well as the practical application of the mathematical model. The following are the essential elements to comprehending the methods suggested to solve the issue:

- Review earlier studies on diffusion concepts and models, comprehend the assessment of innovation diffusion and learn how to use it to help with data retrieval and model creation.
- Identify case study projects of the technologies behind water electrolysis and its potential end use. Recognize these innovations as the primary focus and use the Diffusion of Innovations concepts to apply them precisely to a parametric simulation.
- Create the maturity model for case studies involving water electrolysis and analyze them.
- Compare the outcomes to case studies on the green hydrogen supply chain.
- Validate the model results using semi-structured interviews with specialists in energy and hydrogen.
- Recommend the significant actions and variables to consider when developing water electrolysis projects to reach mass adoption faster and more successfully.

1.3. Dissertation structure

The following six chapters make up this dissertation in order to accomplish the aforementioned goals:

1. **Introduction:** Contextualising the central subject of investigation and defining the main objectives, this chapter explains the project's structure and novelty.
2. **Problem Definition:** This chapter defines the major research question, the components that make it up, and the knowledge base needed to apply it to the thesis. Green Hydrogen, its role in the EU's energy transition and various end-use of green hydrogen is described here.
3. **Literature Review:** The state of art comprising the main concepts, methodologies, and results of the previous investigations is presented. The foundations of innovation diffusion, value networks, and previous methodologies used to model technological innovations and diffusion models are also discussed.
4. **Methodology Proposal:** This chapter describes the background and process for locating pertinent case studies. The maturity model in use, the case studies under discussion, and descriptions of the methodology developed based on the Bass Diffusion Model are covered (Bass, 2004).

5. **Results: Analysis, Validation and Discussion:** The implementation and analysis performed with the proposed model and methodological approach are described here. The innovation diffusion model's main outputs are discussed along with the comparison and analysis with the green hydrogen supply chain case studies. The final recommendations are then presented and discussed following the validation process.
6. **Conclusion and Future Developments:** The last chapter summarises the key findings of the thesis and exposes the most relevant features studied and the current state of the green hydrogen ecosystem. It also presents the future steps proposed in the development of upcoming research.

2. Literature review and problem definition

The core problem addressed in the dissertation is discussed in detail in the following chapter, along with information on the numerous components that comprises it. This also demonstrates how knowledge can be applied to the creation of the research question. The definitions of water electrolysis technologies, the significance of this innovation for the global and European energy transition, and a discussion of the numerous applications for the generated green hydrogen are all covered in the sections that follow.

The relevancy of this chapter is to recognize the base concepts involved in creating the methodology. It includes theoretical work along with research developments and the need and relevance of this work. The literature review clarifies the methodology involved in this dissertation using results of previous work by discussion significant scientific literature

The theory of the Diffusion of Innovations written by Everett M. Rogers forms the core basis of this study (Rogers, 1983). Following that, relevant concepts from Value Networks and Innovation Webs are discussed, as are pertinent research in Green Hydrogen Innovation Diffusion. It serves as the theoretical foundation for this theory.

2.1. EU decarbonization strategies

The European Union (EU) has set a goal of being climate-neutral by the year 2050, which entails an economy with net-zero greenhouse gas emissions, due to the rising global energy needs, climate change issues, and GHG emissions. The European Green Deal was introduced by the European Commission (EC) in 2019 in this regard (European Commission, 2019). This proposal offers environmental measures, such as funding the development of cleaner, less expensive, and environmentally friendly technologies. cleaner modes of private and public transportation, a decarbonized energy sector, more energy-efficient construction, and industry assistance for the development of green firms.

According to Tagliapietra et al. (2019), adopting revolutionary measures to decarbonize the transportation sector and preparing the electricity system for a significant rise in renewable sources are the top four objectives for implementing the EU's energy transition. The decarbonization of industry, transportation, and buildings are the other two priority, along with bolstering the EU's competitiveness in low-carbon technologies (Tagliapietra et al., 2019).

Subsequently, the role of hydrogen is considered pivotal in a clean, secure, and affordable energy future (IEA, 2019). It conveys a compelling solution to decarbonise various sectors from industry, transportation, and the energy sector , using it as fuel, an energy carrier, or energy storage (European Commission, 2020). As a result, the EU is investing heavily in developing multiple hydrogen-based projects to produce, distribute, and store renewable hydrogen on a large scale. The European Commission (EC) intends to accelerate the European technological lead by funding projects in two main application pillars, energy, and transport, in cross-cutting and overarching activities, with the establishment of the Horizon 2020 Fuel Cell and Hydrogen Joint Undertaking.

The EU Hydrogen Strategy was developed in 2020 by the European Commission. It outlines how the deployment and usage of renewable hydrogen will assist the decarbonisation of the EU in line with the

European Green Deal. The strategy prioritises green hydrogen. However, it additionally emphasises that other hydrogen production processes, like via natural gas, should also be promoted during the transitional period. The EU hopes that the Hydrogen Strategy will assist in the decarbonisation of hard-to-abate sectors and the better integration of wind and solar power by using hydrogen for storage (Directorate-General for Research and Innovation (European Commission), 2020). Overcoming the economic damage of the Covid-19 lockdown, creating new jobs, and combating migration by creating supply chains with countries outside the EU serves as additional bonuses (Axpo Holding AG, 2021). Hydrogen uptake is split into three phases: today to 2024, 2025 to 2030, and 2030 to 2050. These differ in their hydrogen production targets: 6GW by 2024 and 40GW by 2030. The first phase aims to scale up the manufacturing of electrolysers, decarbonise existing hydrogen installations, and facilitate the take-up of hydrogen in end-use applications. It is expected of green hydrogen to become cost-competitive with other hydrogen production forms and gradually increasing demand in new applications, with steel industries, transportation, and gas transition. In the second phase, in addition to using hydrogen production to balance energetic grid needs and supply heat for buildings, the so-called "Hydrogen Valleys," defined as regional clusters that produce hydrogen from decentralised renewable energy and mitigate local demand for industrial and transportation applications, will be developed (EGHAC, 2022). Renewable hydrogen technologies are predicted to mature and be developed on a significant scale during the final phase, from 2030 to 2050, reaching all hard-to-decarbonize sectors. Renewable energy sources will account for most of the energy output in this last phase, if not exceeding energy requirements. It is expected that around one-quarter of renewable electricity will be used to make hydrogen (European Commission, 2020).

Furthermore, regulatory frameworks will be established to ensure a well-functioning hydrogen market and planned transport infrastructure. In the second phase, until 2030, the planned infrastructure will be increasingly deployed. The strategy plans an EU-wide logistical infrastructure with large-scale storage and a pan-European hydrogen network. This could include the reuse of the existing gas infrastructure. By 2030, green hydrogen will reach cost competitiveness, and its technologies will reach maturity with large-scale deployment 2030 (Directorate-General for Research and Innovation (European Commission), 2020). Many member states in the EU released their own National Hydrogen Strategies and are currently developing these, as seen in Figure 1 (Hydrogen Europe, 2020). Some countries, like Germany, Norway, and the Netherlands, released their strategies before the EU Hydrogen Strategy was finalised.

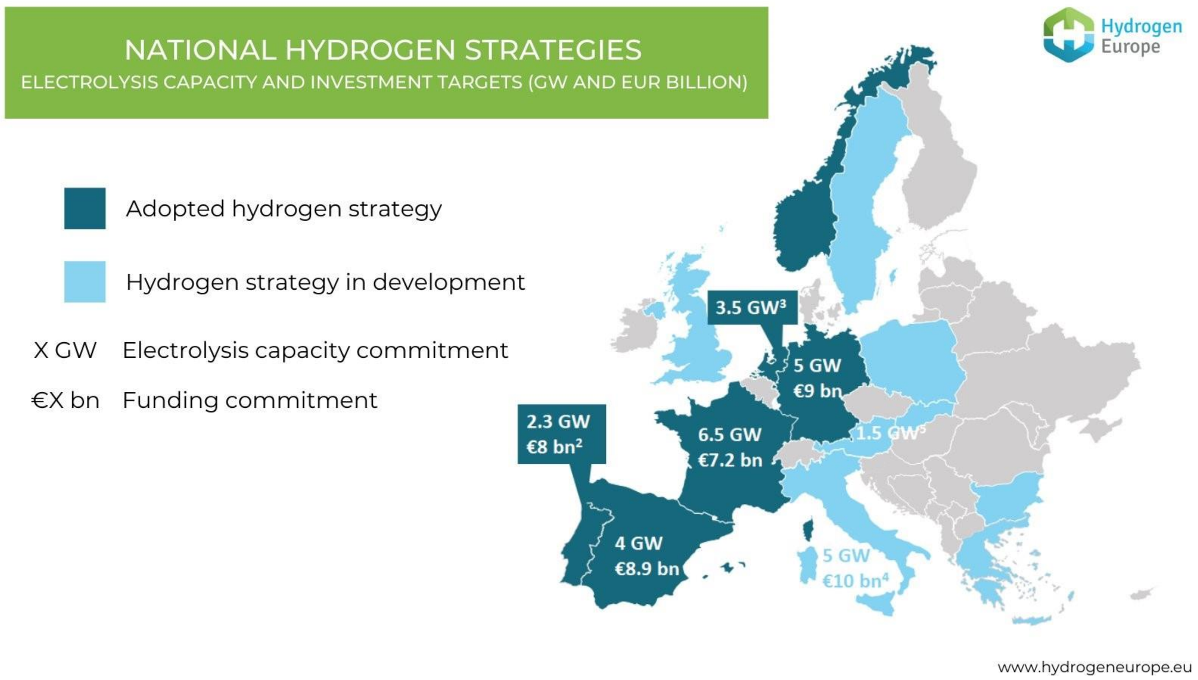


Figure 1: Hydrogen strategies of countries across Europe.(Hydrogen Europe, 2020)

According to an IRENA forecast, hydrogen could contribute to 18% of world final energy consumption, or 78EJ, by 2050 (IRENA, 2018). The new wave of awareness that is sweeping the EU is also spreading to countries where, in addition to the environmental benefits, the technology is more profitable due to the high availability of RES and economies of scale, and where the new industry will add value to the economy, such as China, Chile, Japan, the United States, and Australia (IRENA, 2020a).

The EU intends to facilitate a hydrogen economy by incentivizing both supply and demand, closing the cost gap between conventional and renewable hydrogen production, implementing appropriate governmental aid rules, and encouraging private and institutional investments in order to build a sustainable scale-up of hydrogen ecosystems (European Commission, 2020). Between 2020 and 2050, investments in manufacturing capacity are expected to total between 180 and 470 billion euros (€) in the EU alone (European Commission, 2020). In addition, as part of the new EU industrial strategy, the EC established the European Clean Hydrogen Alliance to assist these investments. and the development of the whole hydrogen ecosystem, from source to the final applicability (EGHAC, 2022; European Commission, 2020).

All presented, the EU shows a high degree of involvement to adopt green hydrogen into the energy mix. In order to bring novel hydrogen solutions to market, the EU must provide a large-scale infrastructure network and collaborate with other countries to build a global hydrogen supply chain. There needs to be an enormous growth from the 144 refuelling stations currently present across Europe to support the mass hydrogen adoption (European Parliamentary Research Service, 2021). Infrastructure and cost are major market factors slowing down progress, but progressive EU policies and ambitious targets by countries have laid down a pathway to handle these problems. Refuelling infrastructure is crucial for the growth of hydrogen in the mobility sector as it also helps balance the grid by seasonal storage of renewable energy. As of 2020, 11 gas infrastructure companies over nine member states started the

Hydrogen Backbone Initiative, making plans to create a 6800 km hydrogen infrastructure system to help achieve long term hydrogen goals as shown in Figure 2 (European Parliamentary Research Service, 2021). In 2021, a white paper was published by the European energy regulators on hydrogen network regulations regarding energy system integration. In the long term, the network is set to expand to 39700 km spanning across 21 countries by 2040. Scheming plans and devising strategies gives a sense of the goal, but it is putting them into action that destroys the roadblocks for the hydrogen economy.

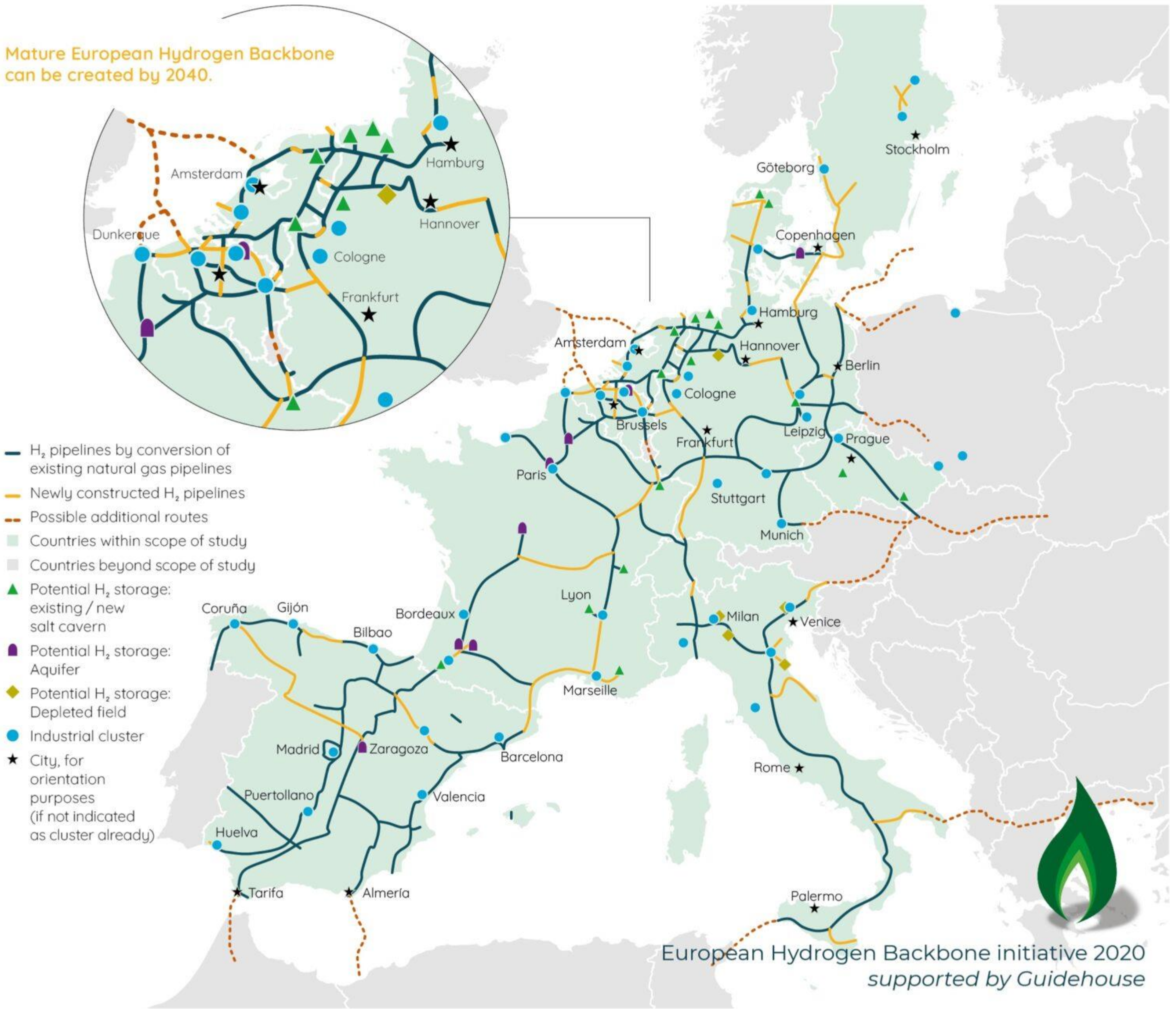


Figure 2: A Hydrogen Backbone created for the EU for deployment by 2040. (Pekic, 2021)

2.2. Hydrogen role in the energy transition

Climate change is not a problem for tomorrow but today. The effects of climate change are experienced throughout the world. The need for decarbonisation is rising and quick actions are to be taken. Green hydrogen is touted to 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, 2019).

It is reported that less than 0.1% of the hydrogen produced today is green hydrogen and the biggest issue is the cost. Only 25% of the world’s hydrogen projects are green hydrogen and only 18% of those operational but only in small scale with most of it in Europe or Australia due to their emission and renewable targets (Global Energy Infrastructure, 2021). Over 99% is produced from fossil fuel sources are green hydrogen is 2 to 3 times more expensive than its competitors. However, with a decrease in electricity prices to 40 USD /MWh, as shown in Figure 3 and a drastic reduction of investment costs to the range of 130 to 300 USD/kW installation, green hydrogen can be competitive with fossil fuels. Efficiency and flexibility in operations preventing low efficiency due to low loads can also help decrease costs. Another key factor in cost decrease is ambitious climate mitigation, creating a substantial energy transition. On aligning with international climate goals to limit global warming at 1.5˚C, electrolyzers, by 2030, are estimated to be cheaper by 40% (IRENA, 2020a).

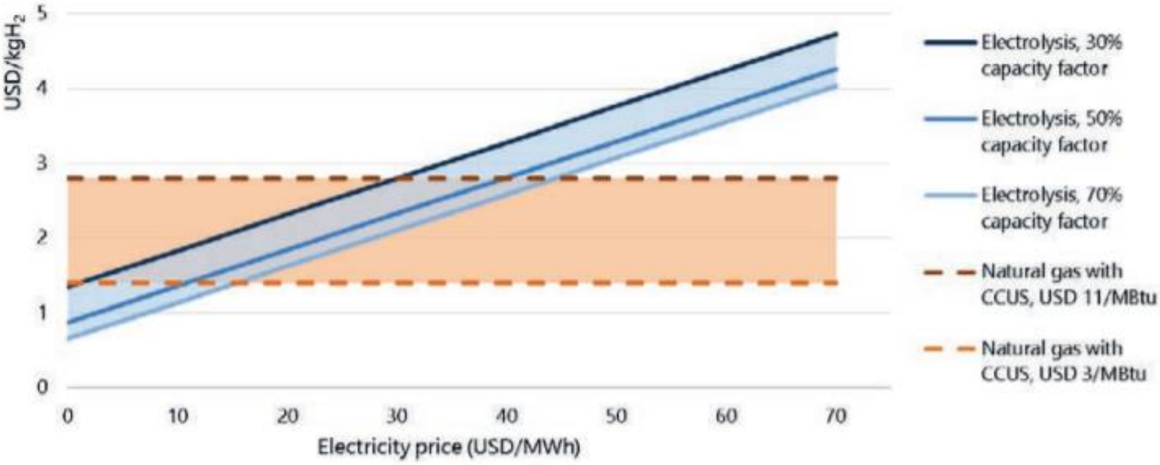


Figure 3: Variation of price of Green Hydrogen with Electricity price.

A massive increase in green hydrogen to curb the needs of the energy transition would also require an enormous increase in the renewable energy capacity. Renewable power output climbed by 45% to 280 GW in 2020, according to the IEA, and it was the only energy source to expand this year despite the pandemic's effects. It also predicted that the future share of renewable energy in the global energy mix would rise (IEA, 2021). Although renewable based generation has reached a record high, IEA states that the number has to be amped up at a faster rate in order to achieve net zero levels by 2050. By 2022, solar PV production will have increased by 162 GW, representing a 50% increase over 2019, while wind energy production will have increased by a record-breaking 114 GW in 2020, marking a 90% increase year on year (IEA, 2021). By 2030, solar PV is predicted to have 630 GW in net additions by 2030, thereby making it the cheapest cost option for electricity. Given the volatile nature of RES production in relation to the energy supply and demand, renewable hydrogen has been considered a possible energy storage technology, particularly for large amounts of energy over extended periods of time, via the electricity-hydrogen-electricity cycle (Power-to-Power). The creation of hydrogen from renewable energy sources (RES), storage, and reconversion into electricity for grid supply by fuel cells or gas turbines, presents a promising off-grid application, for example, in remote places or as backup power (IEA, 2019; McKinsey & Company, 2021). However, it does not appear to be practical currently due to the low full-cycle efficiency, which is now between 30% and 40% (Chapman et al., 2019).

Renewable energy costs have fallen drastically over the last decade and are continued to do so over the following years. Public environmental concerns and technological advancements are some of the reasons driving down this cost. National Renewable Energy Laboratory (NREL) has predicted a 45 to 65% reduction in the Levelized cost of energy (LCOE) of wind technologies and a 47% to 77% decrease for solar technologies by 2050 (Silvio Marcacci, 2020).

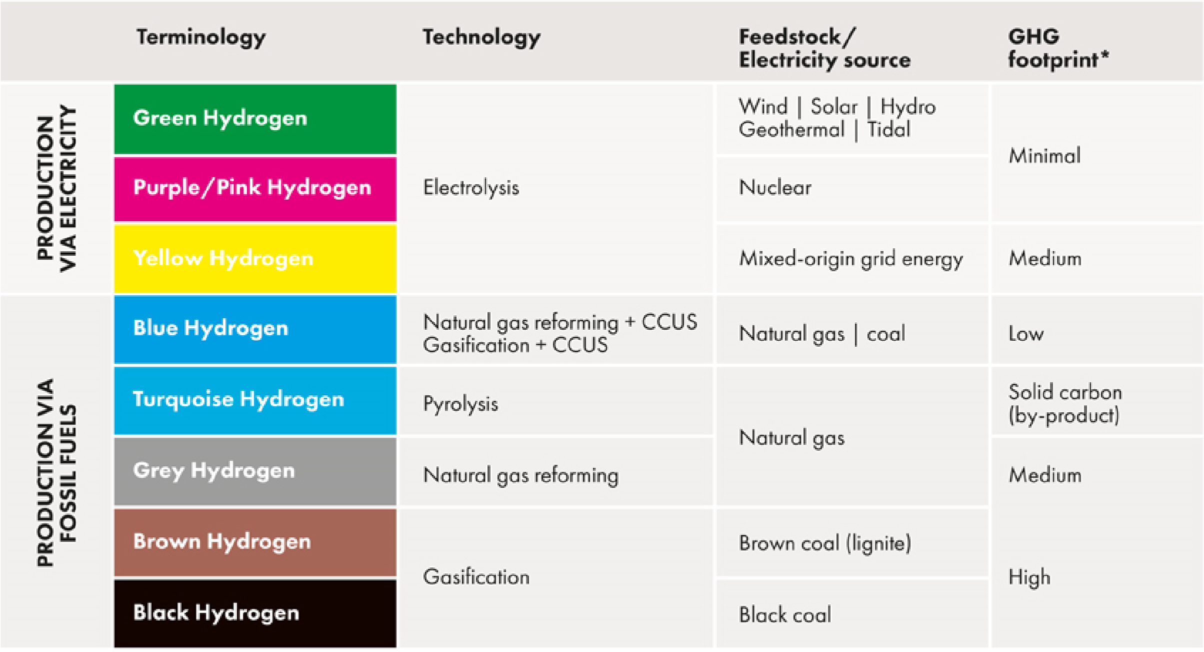
With transport accounting for close to 25% percent of the greenhouse emissions in the EU in 2018, the need for change is imminent as transport is the second-largest emitter in the energy sector. These emissions are alarming, with a 33% increase since 1990 and a 0.8% increase in 2019 alone. Hydrogen can prove to be a promising option, especially with heavy-duty transport. Fuel cells are forecasted to power 55% of trucks and 25% of buses by 2050. Light-duty vehicles and passenger cars, however, represent a whole different scenario. With increasing production volume and ever reducing battery costs, EV's seem to have an edge. The short refuelling times and the long driving ranges are promising as automobile companies such as BMW, Jaguar Land Rover, and Vauxhall are developing hydrogen fuel cell cars. But this seems to be a small part of the green transport mix, dominated primarily by electric vehicles.

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 (Maggio et al., 2019).

Green Hydrogen or hydrogen produced by renewable sources, is low carbon hydrogen produced via renewable electricity or low carbon power. Water electrolysis utilising renewable electricity in an electrolyzer is the most established technology for producing green hydrogen (Azzaro-Pantel, 2018).

Although a colourless gas, commercial hydrogen can be described using various colour codes to differentiate. Differentiation is done based on production methods. Though not a universal convention, these colour codes can also help determine the source of the hydrogen produced. Standard colour codes are green, grey, blue, brown, yellow, turquoise, pink and white (National Grid, 2021). Green hydrogen is produced using an electrolyser's clean electricity from renewable sources. Grey hydrogen is currently the most common form of hydrogen production worldwide. Hydrogen is produced from natural gas or methane using steam reformation. Blue hydrogen is the same as grey hydrogen, except blue hydrogen has some form of carbon capture and storage (CCS) to reduce emissions. It is a low-carbon form of hydrogen. Hydrogen produced from coal is known as brown hydrogen and commonly uses the process of gasification. It is the most environmentally damaging form of hydrogen. Pink hydrogen is generated using nuclear energy, whereas yellow hydrogen uses solar energy. Both forms are generated by electrolysis. Turquoise hydrogen is a reasonably new concept yet to be proven on a larger scale. It is generated using methane pyrolysis to produce solid carbon and hydrogen. This generation is also a low emission process, depending on whether renewables are used to power the thermal process and the storage or usage of the produced solid carbon. Extracting hydrogen from natural geographical locations through fracking constitutes white hydrogen. There are no current strategies for procuring hydrogen through this method (National Grid, 2021). Figure 4 shows the different shades of hydrogen along with their feedstock and footprint.



	Terminology	Technology	Feedstock/ Electricity source	GHG footprint*
PRODUCTION VIA ELECTRICITY	Green Hydrogen	Electrolysis	Wind | Solar | Hydro Geothermal | Tidal	Minimal
	Purple/Pink Hydrogen		Nuclear	
	Yellow Hydrogen		Mixed-origin grid energy	Medium
PRODUCTION VIA FOSSIL FUELS	Blue Hydrogen	Natural gas reforming + CCUS Gasification + CCUS	Natural gas | coal	Low
	Turquoise Hydrogen	Pyrolysis	Natural gas	Solid carbon (by-product)
	Grey Hydrogen	Natural gas reforming		Medium
	Brown Hydrogen	Gasification	Brown coal (lignite)	High
	Black Hydrogen		Black coal	

*GHG footprint given as a general guide but it is accepted that each category can be higher in some cases.

Figure 4: Terminologies of various “shades” of hydrogen.(Global Energy Infrastructure, 2021)

However, in addition to all of the problems associated with Grey Hydrogen, such as the use of limited natural resources (fossil fuels), Blue Hydrogen via CCS does not remove GHG emissions. Instead, it just reduces them because the capture efficiencies in the best-case scenarios are between 85-95%, and these emissions must still be stored somewhere (IRENA, 2020b). Grey hydrogen is projected to emit 5 to 10 kg of CO2 per kilogramme of hydrogen produced. Blue hydrogen, on the other hand, can emit 1 to 4 kg of CO2 per kg of hydrogen, which is less than grey hydrogen due to carbon capture systems. Furthermore, the CCS has substantial expenses associated with the transportation and storage of the residual CO2 as well as the inherent monitoring of the stored material (IRENA, 2020b).
As a result, hydrogen from renewable sources is a promising energy carrier for the energy shift. This technology is the subject of this thesis because it offers an innovative and environmentally friendly process for producing hydrogen and is still in its early phases of development, with several barriers to its widespread adoption. The following subchapters highlight the two differentiating variables for selecting case studies for review: (1) the electrolyzer, which produces hydrogen using electricity without releasing GHGs. (2) The final application of the created green hydrogen

2.3.1. Electrolyser

The electrolyser is a multistage electrochemical device that converts electricity into hydrogen in a power-to-gas (P2G) process based on water electrolysis. Electrolysis is a chemical process that involves breaking down water molecules (H2O) into oxygen (O2) and hydrogen (H2) by applying a direct electric current (Azzaro-Pantel, 2018). An electrolyte consists of an anode and a cathode in an electrolyte. The two electrodes are immersed in water and connected to a power source that delivers a direct current.

When the electrodes attract ions with opposite charges, hydrogen and oxygen are dissociated. Due to the effect of the applied electric current, an oxidation-reduction reaction occurs during electrolysis.
The first industrial water electrolyser was constructed in 1888 (Chisholm and Cronin, 2016). However, this technology has only recently attracted attention for its commercialisation potential, being used to meet the world's energy and climatic needs. There are three main kinds of electrolysers: proton exchange membrane (PEM), alkaline, solid oxide (SOE), and high temperature electrolysis (THE) which differ in the type of electrolyte employed.

1. **Alkaline Electrolyser:** A mature technology, alkaline electrolysis was employed by the chemical industry for non-energy generation uses as early as the 1920s. It functions by moving hydroxide ions (OH-) through the electrolyte at roughly 100 degrees Celsius, with hydrogen produced on the cathode side. This electrolyzer works with a liquid alkaline solution of sodium or potassium hydroxide. Newer trends, on the other hand, use solid alkaline exchange membranes as electrolytes. (US Department of Energy, 2021)An alkaline electrolyzer has twice the lifetime of a proton exchange membrane. Furthermore, its capital expense is cheaper than that of PEM on a per-kilowatt basis. Furthermore, this type of electrolyzer has a higher efficiency for a lower heating value (IRENA, 2018).
2. **Proton Exchange Membrane (PEM):** Also known as polymer electrolyte membrane electrolyser, where the electrolyte is a solid plastic material. Water reacts at the anode side of the electrolyser to create oxygen and positively charged protons. The electron flows through an external circuit, and hydrogen ions move to the cathode side. Simultaneously, the hydrogen ions are mixed with electrons from the external circuit to generate hydrogen gas at the cathode side. This operation occurs at temperatures around 70-90 degree Celsius.(US Department of Energy, 2021) PEM technology is growing exponentially and pushing for commercial deployment. Proton exchange membrane is more flexible when operated than alkaline electrolysers. As a result, it will allow PEM to grasp the different sources of revenue from various electricity markets due to its more comprehensive operating range and faster response time. In addition, polymer electrolyte membrane electrolyser can provide capacity for higher frequency without needing to sacrifice the available production capacity, meaning that it works as an ancillary service to the grid at the same time while supplying hydrogen (IRENA, 2018).
3. **Solid Oxide Electrolysers (SOEC):** The electrolyte consists of solid ceramic. It selectively conducts negatively charged oxygen ions at high temperatures (700-800 Celsius), which pass through the ceramic membrane and reacts at the anode to form oxygen gas and generate electrons for the external circuit. Afterwards, the stream on the cathode will combine with the electrons from the external circuit to generate hydrogen gas. Future developments could drop the temperature to around 500-600 Celsius. This kind of electrolyser is mainly used in nuclear energy to generate hydrogen (US Department of Energy, 2021). The SOEC method's efficiency is higher when compared to ALK and PEM methods, even though its technology is not as developed. Another possible application would be in onsite production at Concentrated Solar Plants due to their high temperatures (IRENA, 2018).
4. **High Temperature Electrolysis (HTE):** HTE is an electrolysis process that separates steam from H2 and O2 at temperatures ranging from 700 to 1000°C. System efficiency in electrolysis

grow as operating temperatures rise. As a result, the electrical energy required by HTE is less than that required by conventional electrolysis. The initial phase in HTE is to heat the water until it evaporates and then to operational temperatures, which needs a large amount of thermal energy. This thermal energy can be supplied directly to the electrolyzer by direct steam injection or indirectly via an external heat source. HTE creates hydrogen with practically negligible GHG emissions if the heat source is pure, such as geothermal, solar, or recovered heat (Acar and Dincer, 2018).

2.3. End uses for green hydrogen

Green hydrogen production is steamrolling across the world with major governments adopting it into their energy policies while backing them up with huge funds. Apart from being an energy carrier, green hydrogen also has various other uses that can help various sectors with their transiton to a low carbon one. The case studies under consideration are chosen with diverse end uses for their produced hydrogen.

2.3.1 Green Hydrogen for Steel production

The iron and steel sector is a substantial contributor to global CO2 emissions and thus a key driver of climate change. According to McKinsey, steel production averaged 8% of the global carbon emissions with a staggering 1.85 tons of carbon dioxide (McKinsey & Company, 2020). The use of renewable hydrogen over coal has gained traction over the recent decades with various promising developments across the EU to refine the transition. There are issues with the immediate rise in steel prices with a estimated increase by a third. But the gap is likely to disappear and reach parity by 2030. Producing green steel would also require a huge increase in renewable capacity (McKinsey & Company, 2020).

2.3.2 Green Hydrogen for Mobility

Green Hydrogen, along with battery technology pose a viable alternate for the transition of the mobility sector. While the world is moving towards electric power for shorter and smaller modes of transport, green hydrogen is being tried and tested for trucks, ships and even trains. But there have also been developments in the space of passenger cars. Widespread adoption, infrastructure and regulation are key for this sector. All though the current costs are high, there is a huge potential for cost reduction for the infrastructure necessary (IEA, 2019). Hydrogen based fuels are also a possible option for replacing fossil fuels in the maritime and aviation sectors and providing the opportunity to decarbonise the ports and airports.

2.3.3 Green Hydrogen as an energy carrier

The main area where green hydrogen is touted to have a major impact is in being an energy carrier. Green hydrogen works in perfect sync with the intermittent nature of most renewable sources (IEA, 2019). Green hydrogen can act as a seasonal storage option for renewables and can also be used to produced hydrogen-based fuels such ammonia and synthetic methane. Green hydrogen also has uses in off grid applications and can act as a backup storage for grid supplies. Flexible power generation and co-generation using ammonia are options to decarbonise existing power plants (IEA, 2019).

2.4. Diffusion of Innovations

Innovations ″a term for defining a series of vast changes in business activities, which will lead to firm performance improvement" are essential for any progressive environment (Tohidi and Jabbari, 2012). The explanation of how an idea or a product diffuses through a social system was developed as the Diffusion of Innovation theory by E.M. Rogers in 1962 (Rogers, 1983). Adopting an idea is not simultaneous but a process where some individuals are more likely to accept innovation than others. The perception of an idea as innovative is key for adoption.

The study of the diffusion of innovations was first introduced by Gabriel Tarde (1903), a French sociologist and legal scholar. In his book *The Laws of Imitation* on opinion leadership, various concepts used in modern day analysis like S-curve of diffusion and the importance of socio-economic status on interpersonal diffusion is defined (Djellal and Gallouj, 2014). Everett M. Rogers, an American communication theorist and sociologist, developed the foundation of research in the field of innovation since the mid-twentieth century based off Tarde’s work. With his book Diffusion of Innovations, Everett Rogers' theory (1983) has been recognised to be crucial in understanding how technical innovations become diffused and potentially accepted by individuals and organisations (Rogers, 1983). Rogers defines diffusion as the process by which an innovation is disseminated over time among members of a social system via specialised communication channels. This process connects the theory's four essential components: inventions, communication channels, time, and social systems. Every diffusion research study contains these elements. Throughout the years, the concept of innovation has evolved. However, the most prevalent definitions are centred on the concepts of novelty and utility or accomplishment in anything new (Granstrand and Holgersson, 2020).

Adopting an idea is not simultaneous but a process where some individuals are more likely to accept innovation than others. The perception of an idea as innovative is key for adoption. The key to adopting innovation to a specific target group involves understanding the attributes and needs of that target segment. The diffusion of an innovation will be accelerated if it meets the following criteria: it should provide significant benefits, it is compatible with existing economic and social behaviours, it has fewer complex aspects, it can be tested in controlled settings, and its effects are easily recognised (Rogers, 1983). With a focus on the innovation of the product/idea rather than a change in an individual, this theory pivots on products being "reinvented" or evolved to fit their target groups better. Time is a crucial factor when considering successful diffusion of an innovation. The time factor influences diffusion in the adoption rate of innovation in a social structure, in an individual's innovativeness, that is, how an entity adopts early innovation, and in influencing the innovation-decision process by which individual moves from knowledge to adoption or rejection of innovation. The third component is the Social System, which Rogers defines as a collection of interconnected units engaged in collaborative problem solving to achieve a common purpose. Individuals, informal groups, organisations, and subsystems are all examples of social system members (Rogers, 1983).

2.4.1. Innovation Attributes

Since users rely on these variables when selecting whether to adopt an innovation, its characteristics have a substantial influence on its adoption rate and serve as an assistance to understanding how it will disseminate over time. Diffusion of Innovation theory points to five major factors influencing the adoption of innovations.

1- Relative Advantage: The degree to which an innovation is regarded to be superior to the idea it replaces. The degree of relative advantage can be quantified in terms of intrinsic costs. Nonetheless, social prestige, convenience, and enjoyment are important factors—the higher the perceived relative advantage, the faster innovation is adopted.

2- Compatibility: The degree to which an innovation is regarded to be congruent with potential users' existing values, beliefs, and needs. An innovation that does not adhere to the principles of a specific social system will not be adopted as quickly.

3- Complexity: The degree to which an innovation is regarded to be difficult to grasp and apply. The degree of complexity of an innovation directly effects its adoption rate, as complex ideas spread more slowly due to the level of experience and abilities required for the individual to learn.

4- Trialability: The degree to which an innovation may have been tested on a small scale. A readily triable innovation reduces uncertainty for the individual when deciding on adoption, increasing the speed with which the concept spreads.

5- Observability: The extent to which the outcomes of an innovation are visible to individuals. The more easily adopters can check the outcomes 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, 1983).

2.4.2. Adopter Categories

The graphical representation of the adoption of innovations is derived from the percentage of adopters over a period of a social system which is represented via a sigmoidal curve. The S shaped curve for diffusion has a slower rate during the initial stages followed by a rapid acceleration until it reaches a saturation point where it beings to slow down as shown in Figure 5 (Rogers, 1983). The categorisation of the adopters starts with these curves.

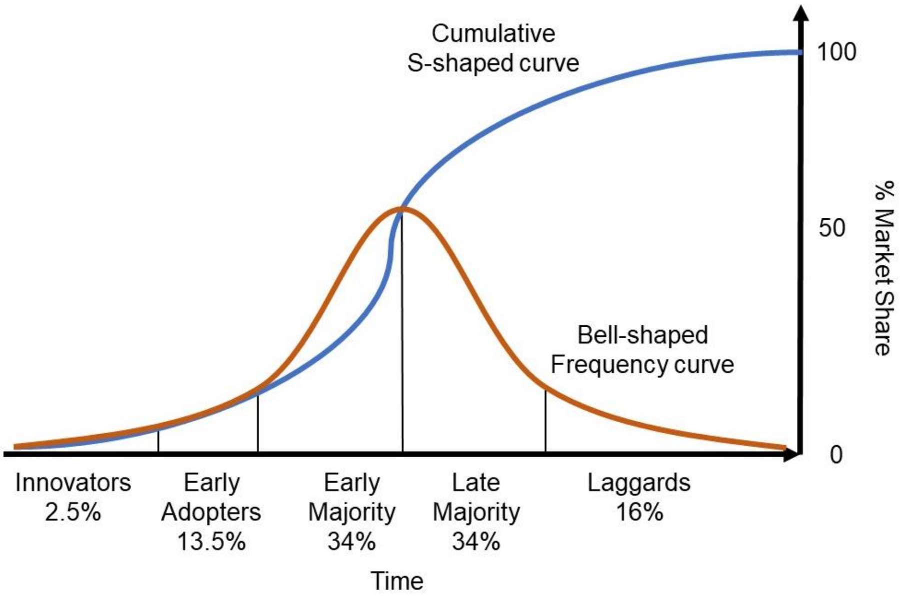


Figure 5: Bell-shaped, S-shaped curves and adopter categorization.

Innovativeness is the major criterion for the adopter categories. An individual can be categorised into one of the following five categories, based on how quickly they adopt the novel idea. The distinctions between categories are determined by standard deviations from the average time of adoption (Rogers, 1983). The theory also comes up with different population segments based on their resistance to adoption. Each group has its own" personality" with the most influencing factors being communication behaviour, socio-economic status, and personality variables. An innovation must satisfy the group's needs to achieve adoption. These categories form a framework for research used in this dissertation. Rogers proposed the following categorization of adopters as given in (Rogers, 1983):

1- **Innovators:** They are the first adopters of the system with interest in new ideas and a willingness to take risk being their traits. They are also independent from the system and usually do not have financial constraints when adopting an idea. Innovators are also okay with the setbacks that are involved with the adoption.
2- **Early Adopters:** They tend to be a part of the social system with a great degree of opinion in leadership in social systems. Early adopters can help fasten the rate of diffusion while providing guidance to the other segments on adoption.

3- **Early Majority:** They adopt an innovation quicker than an average individual and comprises of a third of the system. Even though they do not lead adoption, they provide for an important role by acting as a bridge between the early adopters and the late majority.

4- **Late Majority:** Scepticism is a key trait for this group as their motivation for adoption is usually economic requirements or an increasing peer pressure following the previous groups. This group is key when trying to achieve for high diffusion and market saturation (Schwabe et al., 2021).

5- **Laggards:** Referred to as traditionalists, this group is extremely cautious when it comes to adoption due to their low resources and risk aversion.

2.5. Value Networks and Innovation Ecosystems

A value network is a collection of interactions between organisations and individuals that benefit all parties involved (Allee, 2008). It allows participants to trade both tangible and intangible assets and to share information. Identifying the key partners and stakeholders, mapping the intangible and tangible exchanges while analysing value creating patterns for cost/benefit analysis forms the framework of the value network analysis (Allee et al., 2015). Interorganisational relations enable the spread of information and resources, thus a crucial role in the diffusion of innovations through value chains which allows for the better understanding of the roles and assets interchanged (Barile et al., 2020; Yang and Li, 2019). There has been an increasing interest in innovation ecosystems with business and strategy in mind over the past years (Gomes et al., 2018). Innovation ecosystems represent value networks related with innovations systems (Granstrand and Holgersson, 2020). Innovation ecosystem has been defined by Ron Adner as “the collaborative arrangements through which firms combine their individual offerings, into coherent, customer-facing solution” (Adner, 2006). Innovation ecosystem focuses on the players and stakeholders as much as the innovation itself (Granstrand and Holgersson, 2020). Strategies on the ecosystem can help companies to generate better value via platform leadership, open innovation, and hyperlinking organisations (Adner, 2006).

2.6. Modelling the Diffusion of Innovations

Various mathematical models have been used to make the diffusion theory practical in order to diffuse ideas better. There are a lot of diffusion models present for different uses and scenarios. The most widespread methods used are logistics and Gompertz models (Kumar, 2015). The Gompertz model is used for the analysis of empirical cases which assumes an asymmetric growth pattern in which the maturity is not compared with the introduction, take off and growth phases (Gompertz, 1825). The logistics models on the other hand characterises the S curve of growth. The logistics model has a long history of development where parameters are added to be applicable for different situations. The most used model for technological development and market research is the Bass diffusion model, which is a combination of both the logistic and the modified exponential model (Kumar, 2015). Recent studies, however, are creating methods of describing the principles of diffusion through more flexible models, with the goal of unifying the idea that innovations spread through an infectious rate of information-sharing that distinguishes adopters from non-adopters (Kumar, 2015). The bio-economic interactions between costs and prices, biological adoption rates, and carrying capacity are the most important considerations when evaluating diffusion models (Mehmood et al., 2016).

The areas of application of the diffusion models are plentiful including anthropology, public health, communication and so on (Kumar, 2015). Table 1 contains a summary of some of the main innovation studies, their authors, and applications:

Table 1: Summary of applications of diffusion models (Kumar 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

2.7. Innovation Diffusion in Hydrogen technologies

An early assessment of the future of the hydrogen economy was conducted by Barreto with a long-term approach to the global energy trends with respect to the diffusion of green hydrogen (Barreto et al., 2003). An hydrogen supported scenario was used for this analysis and rapid diffusion was achieved in this scenario. The interesting result of this study was that the more industrialised nations took longer for the diffusion of green hydrogen than the developing countries. Previous research has offered ways to speed up the green transition. One possibility is to remove the supply and demand diffusion barriers described by Hotte (Hötte, 2020). There is also the significant cost to adopting green technology on the demand side due to the internal procedures that are still immature. Although prior research has been done on the diffusion of hydrogen systems, the research has focused mainly on hydrogen as an energy carrier and hydrogen fuel cells for use in vehicles. A study conducted by Trencher uses interviews to find barriers in the diffusion of fuel cell electric vehicles (FCEV) in California, USA (Trencher, 2020).The study shows that stakeholder involvement is crucial, and strategies such as regulation, market and consumer incentives, and public-private coordination are essential. Another study by Hacking and Pearson analyses fuel cell innovation in the United Kingdom using event history analysis and interviews (Hacking et al., 2019). One common aspect both the studies focus on is the importance of policies for the widespread adoption of fuel cell electric vehicles (FCEV). Various studies have also come to conclusion about the importance of resilient infrastructure for better adoption rates (Chapman et al., 2019; IEA, 2019). Existing research provides quantitative analysis that hamper the diffusion of hydrogen based on future scenario-based modelling studies. Models either create scenarios where some parameters may be unrealistic to achieve or exclude political, geographical, and technological dynamics (Zandstra, 2022). This leads to a knowledge gap where the question of the impact of the barriers/ factors that hamper the better diffusion of green hydrogen and water electrolysis arises (Zandstra, 2022). With increased inclusiveness in energy roadmaps across the EU, it is safe to say that green hydrogen holds a vital role in most of the energy transition plans in the EU. With most research efforts going into the innovation of the product, there needs to be increased focus on improving the innovation ecosystem to find new pathways of faster diffusion due to the rapid rise in importance of green hydrogen for energy transition.

2.8. Problem Definition

The primary challenge present on developing an efficient hydrogen infrastructure is overcoming the cost barrier. High production and transportation costs along with an increased need for renewable capacity makes green hydrogen an expensive alternate at this point. Even hydrogen-based fuels such as synthetic aviation fuels are estimated to be eight times more expensive than conventional fuels. Development of dedicated infrastructure goes hand in hand with the cost issue. Strides have been taken in improving technology to facilitate an increased development in infrastructure like blending hydrogen in natural gas pipelines but there still is a major lack when compared to natural gas pipelines. There is also the issue of energy loss during electrolysis by 30- 35% (IRENA, 2020a). Lack of targets and incentives also inhibit the growth of this technology and thus limiting its downstream demand.

However, most of the issues addressed are due to the sudden rise in global importance of green hydrogen. It is conceivable to interpret the need to comprehend what can be done in the EU as a holistic approach to influencing a seamless, energetic transition in the many downstream uses to the set goals in such a short time.

The EU's goals for achieving a climate-neutrality by 2050 are strikingly clear, as are the investments in expertise, funding, resources, and materials, with a structured strategy to grow hydrogen economies toward large-scale applicability and mass consumption. The hydrogen economy is still in its early phases, with a long road ahead in terms of infrastructure, cost reductions, supply and demand variables, and scientific and technological breakthroughs. With increased inclusiveness in energy roadmaps across the EU, it is safe to say that green hydrogen holds a vital role in most of the energy transition plans in the EU. With most research efforts going into the innovation of the product, there needs to be increased focus on improving the innovation ecosystem to find new pathways of faster diffusion due to the rapid rise in importance of green hydrogen for energy transition. 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)

This will be the focus of the dissertation, to understand the evolution of the technology from an innovation standpoint over time, specifically how it can be successful in the EU, and reach the targets set for hydrogen technologies by assessing different cases of water electrolysis through the maturity model and understanding how fast diffusion and adoption happen, what variables influence them, and what actions should be put in place to enable the deployment. The combined assessment with green hydrogen supply chain case studies will provide for a holistic view on the entire green hydrogen ecosystem to find out the lacking factors needed for the overall acceleration of these technologies.

3. Research Design and Thesis Methodology

The current chapter attempts to clarify the preceding data with the methodologies used to construct this dissertation based on the information presented in the literature review. Specifically, the genesis of data retrieval, the primary variables in the study, and an explanation of the diffusion model employed in the dissertation's subsequent steps are explained here. This chapter will also cover the case studies explored in water electrolysis technologies that will be applied to the same model, before closing with the general dissertation presented approach that will be used in the following steps.

3.1. Bass Diffusion Model

The theoretical foundation of the tool for analysis used in this dissertation is the Bass Diffusion Model (Bass, 2004). This is the model of choice to put into practice the Diffusion of Innovations theory and analyse the diffusion of green hydrogen and water electrolysis technologies. The model investigated the adoption of new technology by segmenting the cycle into parts with varying adoption rates and segmenting customers into distinct characteristic groups based on the stage of the cycle at which they embrace the technology. This model has been used in numerous studies to forecast the growth of various fields within telecommunications and other technological sectors (Boucher, 2019). The modal follows a s shaped curve which is broken up into three segments namely new product, maturing product and standardised product. This method assumes that a combination of innovation and imitation carries out adoption. Influences and imitation drive innovation by positive word of mouth.

Two coefficients, the coefficient of innovation (p) and the coefficient of imitation (q) are used to estimate the degree of impact of influences on the rate of adoption (Schwabe et al., 2021). In theory, the number of new innovators decline with time as there is an increase in the number of imitators until they peak. The mathematical form is as follows (Schwabe et al., 2021).

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

The equation represents the growth of adopters N throughout time t. The equation can be broken down to two 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 (Schwabe et al., 2021).

The model has a history of providing results close to real adoption rates. Bass applied his model to study the growth and diffusion of consumer variables in the 1960's with recent evidence showing that the initial predictions were indeed close to the real adoption rates (Ashokan et al., 2018; Bass and Bass, 2001). The Bass diffusion model has been used extensively in the energy sector as well. From understanding alternative fuel vehicle sales to learning the diffusion mechanism of renewable energy technologies in Europe (Paschalia, 2021). Diffusion pathways have also been explored for ambitious climate policy targets, household PV systems and the environmental and material implications of circular economy (Batista da Silva et al., 2020; Sigüenza et al., 2021; Uidhir et al., 2022).

3.2. Litmus Test

The Innovation Diffusion Litmus Test, developed by Dr. Oliver Schwabe, is used in this dissertation to understand to speed of diffusion of a technological innovation from ideation to market saturation while identifying the key variables and their interdependence in the ecosystem. It enables you to estimate the speed of diffusion and maturity levels of an innovation (Correia et al., 2022). The test is formulated using the Diffusion of Innovations theory and other literary works such as Value Networks and the Bass Diffusion model.(Allee et al., 2015; Bass, 2004; Rogers, 1983) The test is a Microsoft™ Excel based maturity model with a set of questions that helps recognize the level of maturity of an innovation ecosystem. The critical components of the test are the roles played by the players of an ecosystem while they interchange tangible and intangible deliverables (Correia et al., 2022).

Innovation Webs form the core idea behind the Litmus test and represent the spread of an innovation through the stakeholders in the ecosystem (Schwabe, 2019; Schwabe et al., 2021). An idea is usually diffused through research, socialisation, market validation and commercialisation (Correia et al., 2022). With different roles such as Buyer, Commercializer, Funder, Innovator, Marketeer, Product Packager, User and Web weaver, each architype forms an interaction with the other roles in the ecosystem. Considering the innovation web/ ecosystem as a living being the idea proposed in the Litmus test is to diffuse the innovation as quickly as possible. The innovation web is crucial to an innovation and helps understand how an idea diffuses through its own ecosystem (Schwabe et al., 2021). The research tool assesses the underlying innovation diffusion web model depicted in Figure 6.

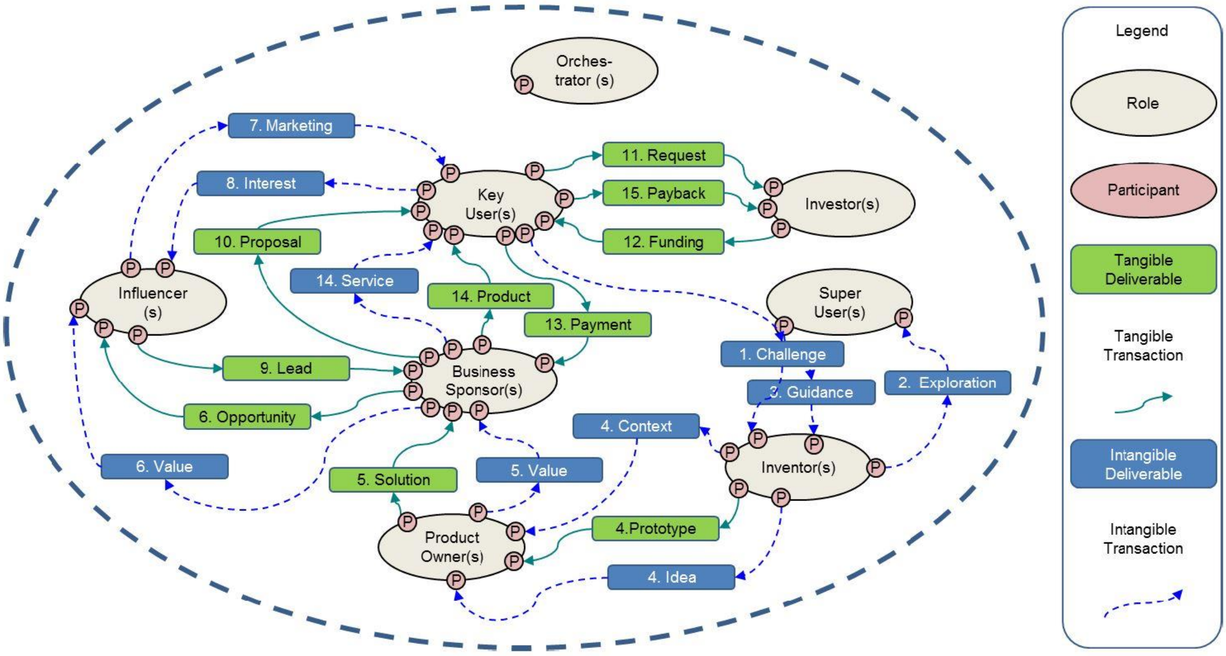


Figure 6: Value Network of Innovation Diffusion to Late Adopters [Schwabe et al. 2020]

The key elements are of the innovation web are the roles of individual participants, the participants themselves and the tangible and intangible deliverables exchanged amongst themselves.

The series of relations and exchanges between the stakeholders and the roles they play are as displayed in Figure 6. When the Inventor(s) receives an intangible challenge from the Key User, the Innovation Web begins. Inventor(s) examine the issue with Super User(s) and create a tangible prototype that is given to the Product Owner as a viable solution to the problem (Schwabe et al., 2021). The Product Owner(s) develop the prototype into a practical solution while generating value for the consumer. Following that, the Business Sponsor shares the solution and potential value creation with the Influencer, who reshapes the solution (Schwabe et al., 2021). The Influencer(s) commercialise the solution and give a value proposition to the Key User(s), resulting in an intangible expression of interest that the Influencer(s) converts into a tangible asset that is passed through to the Business Sponsor (s). The Business Sponsor(s) present a concrete commercial proposal to the Key User for selling the solution (s). Following receipt of the proposal, they seek funding from the Investor(s), which is ideally supplied as payment for the concrete solution to the Business Sponsor (s). Following receipt of the required payment, the Business Sponsor(s) returns the produced solution and associated intangible services to the Key User(s) (Schwabe et al., 2021). Key User(s) eventually use the product to solve the initially disclosed problem/need and then supply the feedback and assets required for relevant adjustments in exchange for funding from the Investor(s) (Schwabe et al., 2021). The roles are divided in core and accelerator. The core roles such as, Key User, Inventor, Product Owner, and Business Sponsor are responsible for starting the initial innovation development. Accelerator roles such as Investor, Influencer, Super User and Moderator increase the momentum of diffusion to reach 84% of adoption in the proposed schedule (Schwabe et al., 2021).

Innovations suffer a high level of uncertainty through their lifetime due to lack of adaptation of highly regulated designs and technical solutions by value chains and ecosystems that can’t keep up. Assuming the ecosystem is living with a constant exchange of assets between stakeholders is important when taking this modular ecosystem approach the key thought in this ecosystem is to also assume the idea as a “virus”, aiming to diffuse it as quickly as possible through the entire system. An innovation is considered to achieve market saturation if it has achieved adoption to the late majority or 84% of the total market to continue providing value to the stakeholders to achieve sustainable use and create enough value for continued stakeholder investment (Rogers, 1983; Schwabe et al., 2021).

The Litmus test is a series of semi-structured interviews evaluating the factors influencing diffusion, considering the degree of commitment from the roles and players in the ecosystem. The qualitative evaluation is based out of a Likert scale from 0 meaning not at all to 5 meaning very high. 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 are the factors under consideration for innovation (Correia et al., 2022). In terms of the population, the factors weigh in on their behaviour in the innovation web, focusing on urgency, priority, motivation, expertise, collaboration, and if they are voluntarily engaging. The test also considers the subjective confidence by taking in a confidence score from the user during evaluation. 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 (Correia et al., 2022). The assessment of each case study is done via the public information present on the internet that includes websites, deliverables, articles and project based information from the stakeholders in the ecosystem.

The level of maturity reached is estimated from the case study assessment tool which 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 (Correia et al., 2022). The more the maturity level, the faster and better the diffusion rates. The six layered maturity levels were appropriate for this analysis based on a previous work from Schwabe et.al concerning diffusion rates for high value manufacturing. Total market size and the time forecast of the project are important parameters when modelling the maturity levels (Schwabe et al., 2021).

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)), through the following equations adapted from the Bass Diffusion base equation (Schwabe et al., 2021):

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

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

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

The assumption here is 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 (Schwabe et al., 2021).

The main outcome of the test is as follows:

1. Evaluation of the Innovation's maturity level
2. Evaluation of the Population's maturity level
3. Assessment of the overall maturity level of the project
4. Forecast on the time period necessary to reach the late majority share of the population relative to the expected project schedule and initial time frame
5. Identification of the aspects needed for the better acceleration of diffusion to reach sustainable market growth.

3.3. Case Studies

Data retrieval consists of finding relevant case studies to understand the speed of diffusion of these cases and their overall maturity levels to understand the factors key to speed and adoption of these projects. The cases under consideration are practical innovations that are in various stages of development with some in ideation while some fully commercialised. The cases are defined and strutted by the technology used to produce hydrogen and the end use of the produced hydrogen. The cases were chosen from the IEA hydrogen projects database and the Fuel Cells and Joint Hydrogen Undertaking (FCH JU) list of invested projects (IEA, 2022). Key words of "electrolysis projects in EU" and “green hydrogen projects in EU” were used while searching for case studies. The cases were considered with practicality of finding relevant data to make informed decisions. Only cases with adequate information about its size, the type of electrolyser used, the stakeholders and their contribution to the project and the roadmap and outcome of the project were considered. The key component of these cases is establishing and defining the ecosystem and stakeholder present to implement them. These data sets are then further structured and defined to provide necessary information on the hydrogen production technology used in the project and the condition of the ecosystem of partners (companies, research, and governmental organizations) behind the project.

Over 100 projects were taken into consideration at an early stage before deciding upon 16 case studies to meet the minimum number of combinations of the four casual variables considered for the analysis (Simister N, 2015). The selection process included understanding the product and the technology behind it, identifying the participants in the ecosystem and assigning them roles with adequate relevancy The case studies were further subjected to a questionnaire on the project's intent and the roles played by the ecosystem players to provide information on the maturity scores and diffusion forecast.

With projects in various stages of development and different timelines, an element of variety is added to the case study set. The cases selected also varied in their method of water electrolysis technology used and the final end use of the green hydrogen produced in order to cover a spectrum. All the cases taken are in the European continent as the EU is actively developing a hydrogen economy and understanding the diffusion barriers in this geographical location would provide qualitative answers. The case studies used are the following 16, a brief explanation of each one is provided in the following while information on the stakeholders and type of electrolyzer used is in the appendix under Table A-3.

1- **The ANIONE PROJECT (2020)**

The aim of this project is to develop a sustainable and efficient solution for the storage of renewable power via green hydrogen. The process of electrolysis used here is anion exchange membrane. The ANIONE project combines proton exchange membrane and liquid electrolyte alkaline technology to validate a 2-kW electrolyser. (ANIONE, 2020)

2- **The Channel EU Project (2020)**

This project aims to construct and anion exchange membrane with low-cost materials. The goal is to create an electrolyser as efficient as a proton exchange membrane electrolyser with a CAPEX equal or below of that an alkaline electrolyser. This, along with the ANIONE project aims to form a anion exchange membrane hub with a common goal of advancing this technology. (CHANNEL, 2020)

3- **DEMO4GRID (2017)**

The project aims to create a commercial setup and demonstrate the use of a pressurised alkaline electrolyser. The 4 MW plant is to be setup in Völs, Austria. The electrolyser is to regulate the regional electricity network from the supplier TIWAG and heat the Therese Mölk Bakery. Surplus hydro-power energy from a station currently near the electrolysis plant will also be used. This demonstration hopes to create a business case for scaling up the technology. (Demo4Grid, 2017)

4- **ELY4OFF (2016)**

The ELY4OFF project intends to develop a fully integrated off-grid green hydrogen production system via a direct coupling photovoltaic generation installation in northern Spain. The final industrial prototype has a maximum capacity of 50 kW and serves as the foundation for development, validation, and demonstration. A PEM electrolyser manufacturer, research organisations, and enterprises specialising in power electronics, control and communications systems are all part of the consortium. The goal of this project is to develop and demonstrate an autonomous small-scale off-grid electrolysis system linked to track the solar photovoltaic source with a cold start and rapid response while considering electric grid changes, with the possibility of replication and serving as a new business model on a larger scale. (ELY4OFF, 2016)

5- **Haeolus Project (2018)**

This project uses a PEM electrolyser within Raggovidda wind farm in Norway for remote applications. Electricity storage, mini grids and fuel production are the main purposes of the project. Multiple strategies are being used from selling hydrogen to creating mini grids to make the project appealing to investors. The prototype uses a 2.5 MW electrolyser with remote operation due to the plant’s location. As it is an innovation project, dissemination of information is also a key feature of this project.(Haeolus, 2018)

6- **H2FUTURE (2017)**

H2FUTURE uses a PEM electrolyser to produce green hydrogen. A 6 MW test system is to be installed in Voestalpine Linz steel plant in Austria. The project builds on the expertise of its partners in order to make an impact on the steel industry. The ultimate goal of the project is to be able to replace fossil fuels with green hydrogen in the steel making process. (H2Future, 2017)

7- **Glomfjord Hydrogen AS (2020)**

The Glomfjord site in Norway has a rich history with green hydrogen by being the site of the world’s largest electrolyser which was operational from 1949 to 1993. Alkaline electrolysers are preferred in this project with a capacity of 20 MW. The produced hydrogen is intended to be used for mobility in the neighbouring areas in the maritime and transport sectors. (Glomfjord Hydrogen, 2020)

8- **EFarm (2019)**

The project eFarm is the biggest green hydrogen mobility project in Germany to date. The eFarm Hydrogen Valley focuses on creating a modularly expandable green hydrogen infrastructure in the region, covering the production of renewables and green hydrogen to setting up refuelling stations and fleets. (eFarm, 2019)

9- **HyDeploy (2017)**

Green hydrogen is produced with a 0.5 MW PEM electrolyser in Great Britain. The project aims to deliver low carbon heating solutions by blending green hydrogen into the existing gas networks. The project is divided into three trials with the first two stages completed showing promising results. 20% blend was achieved in the first trial at Keele University. With the project in its third face of working with the UK government to make a decision on blending green hydrogen into the gas networks all over the country.(HyDeploy, 2017)

10- **Methycentre (2019)**

This project in Céré-la-Ronde, France uses the concept of power to gas. A PEM electrolyser with a quoted capacity of 0.25 MW is used for this project. The project is to use the network to power the electrolyser with the adequate guarantee certificates of renewable origin. The produced green hydrogen is combined with the carbon dioxide produced from a methanation process involving bio waste from farms around the site. The result, methane will be used as a fuel for mobility and industrial processes. The project uses waste from nearby farms. . (Methycentre, 2019)

11- **SALCOS (2015)**

Another green hydrogen project that aims to decarbonise the steel industry with a PEM electrolyser in Salzgitter, Germany. The process uses hydrogen to reduce the iron ore with the help of an electric arc furnace. The electrolyser will be wind powered with a capacity of 30 MW. By 2030, the project hopes to achieve a 95% reduction in their production process. Research and dissemination is also a key aspect of this project. (SALCOS®, 2015)

12- **HyBridge (2023)**

Power to gas technology is implemented in this project to convert 100 MW worth of electric power to hydrogen in Germany between Lower Saxony and North Rhine-Westphalia. With plans to convert the nearby gas network exclusively for hydrogen, this project also has plans of blending hydrogen within regulation and creating methane via methanation for commercial distribution. Technological pre-requisites are in play and plant is set for operation by 2023.(Hybridge, 2019)

13- **GrInHy 2.0 (2019)**

This is a subproject within the SALCOS program described earlier. High temperature electrolysis using Solid oxide electrolysis cells is the preferred method for green hydrogen production. This would be the first implementation of a high temperature electrolyser in the MW scale with a production capacity of 200 Nm^3/h of green hydrogen. The project will supply hydrogen to the SALCOS steel production plant. The project has other objectives like scaling up and reducing CAPEX costs basis for this technology. The WindH2 project using its wind turbines would provide the renewable power necessary for this project.("GrInHy2.0," 2019)

14- **GAMER (2018)**

This project aims to develop a Proton Ceramic Electrolyser (PCE) to produce dry pressurized hydrogen. The technology is novel, and the aim is to create a cost-effective tubular stack and increase to a TRL 5. The electrolyser will be thermally coupled to waste heat from industries and renewables. The pilot test is a 10-kW plant. GAMER is a technical project to develop the simulations and modelling along with all the risk management. (GAMER, 2018)

15- **PrometH2 (2020)**

The project's objective is to develop a PEM electrolyser for the production of renewable methanol using a 25 kW pilot plant in Germany. With a consortium of 12 industry and academic organisation, this project aims to produce hydrogen at the lowest CAPEX ever achieved of between 500 to 700 euros per kilowatt.(PrometH2, 2020)

16- **HyBalance (2015)**

The purpose of HyBalance project is to demonstrate the feasibility of producing renewable hydrogen using wind power in Denmark. The end use of the produced hydrogen is grid balancing and industrial sector usage. The plant has also been used to identify potential revenue streams for the power to gas concept. The plant uses a PEM electrolyser with a capacity to produce 180 tons annually. (HyBalance, 2015)

3.4. Dissertation Methodology

The theoretical foundations organise this dissertation, as do the intrinsic methodological procedures to complete it, as well as the practical relevance of the Litmus Test to the various cases studied. The fundamental goal is for innovation to spread quickly to late adopters. Its success is dependent on capturing 84% of the potential target market for Green Hydrogen technology. Finally, the study work will provide recommendations and key factors to focus on while designing technological innovation in the various stages of Green Hydrogen ecosystem and water electrolysis technologies, allowing them to diffuse as soon as practicable.

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

1. **Case Studies and Data retrieval** – Research and identification of sixteen relevant Case Studies with various water electrolysis production technologies and end users of the produced hydrogen, specifically technological innovations occurring in the EU. This also includes the retrieval of relevant data for use in the model and its validation, namely in the Innovation's Characteristics and Ecosystem (Population).
2. **Model development** – Customize and adapt 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.

   The interviewees were previously given a questionnaire describing the general results, as shown in APPENDIX A, for them to understand the methodology, interpret the outcomes, and then form a supported argument about how the factors align with real projects or their experience with practical hydrogen applications. The interviews were conducted as an open dialogue in which both parties were free to respond to whatever thoughts arose, with no tight script to inquire but rather than acquire a genuine knowledge and interpretation of the model and the major outcomes.

   To demonstrate the model's flexibility to different areas of application, the interviewees who participated in the validation represent various areas of expertise and understanding of the field, from project management in hydrogen infrastructures to being proficient in innovations and strategic product development.

4. **Results Analysis and Discussion** – Analysing the output data from the model to form recommendations for the better diffusion of water electrolysis technology project. Comparison of the output data with existing case study outputs of the hydrogen supply chain from Correia et.al to provide a holistic view on the green hydrogen ecosystem and the factors key for its diffusion (Correia et al., 2022).

Additionally, the dissertation methodology is summarized through the Input/Output model present on Figure 7. to achieve the described outputs as presented in the subsequent Chapter 5 – Results.

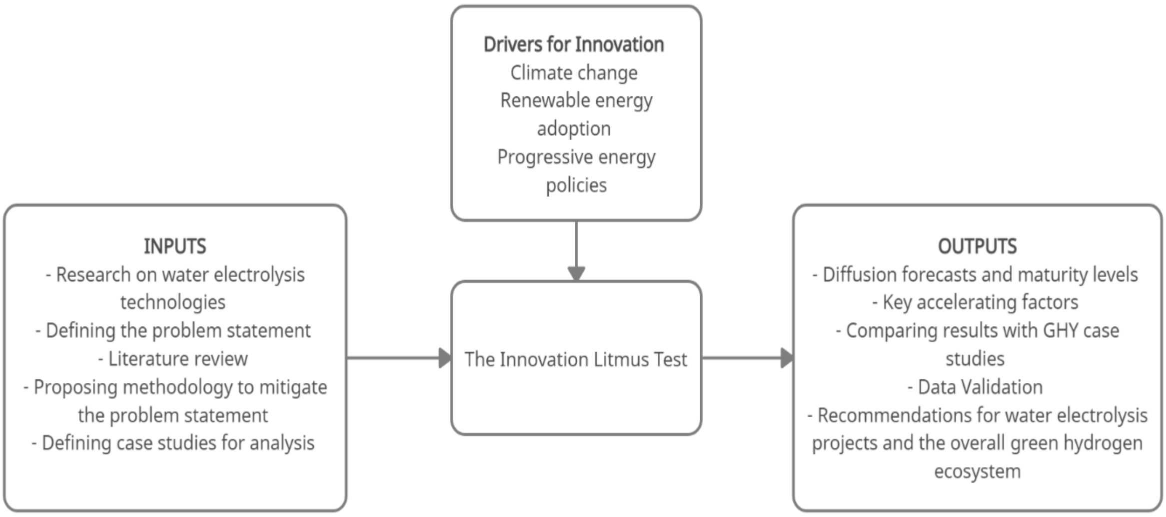


Figure 7: Input/Output Model for the Dissertation Methodology.

4. Results

4.1. Wider Case Study Results

The subchapter that precedes illustrates the model's analytical and qualitative conclusions from the Case Studies perspective, illustrating the maturity of each case and the total outputs from the Innovation Factors perspective. Table 2 summarises the findings for each scenario, including innovation maturity, population maturity, overall maturity, adherence to the anticipated timetable versus the previously expected timetable, and model input confidence level. The overall Case Study results in Table 2 also indicate the first Case Study, which is E. Rogers' Reference Model, with optimal diffusion throughout the value network, resulting in 100% on all outputs. This reference model transforms Rogers' sigmoidal curve, seen in Figure 8, into the foundation for comparing the ideal diffusion rates for innovation to achieve widespread adoption and the requisite 84% of adopters sooner. Furthermore, Figure 9 depicts the cumulative values for each scenario as a function of adherence to the targeted timeline.

Table 2 – Wider Case Study Results

Number	Case	Idea Maturity	Population Maturity	Overall Maturity	Schedule Forecast	Assessment Confidence
0	Reference model	100%	100%	100%	1	100%
1	ANIONE	62%	35%	52%	3	63%
2	Channel Project	51%	53%	52%	2.8	70%
3	DEMO4GRID	48%	76%	59%	2.8	76%
4	Ely4off	48%	76%	59%	2.8	72%
5	Heaolus	52%	73%	60%	2.8	76%
6	H2Future	53%	67%	59%	2.8	73%
7	Glomfjord	49%	34%	44%	3	61%
8	Efarm	43%	50%	46%	3	60%
9	HyDeploy	44%	67%	53%	2.8	70%
10	Methycentre	46%	60%	52%	2.8	67%
11	SALCOS	46%	60%	52%	3	67%
12	HyBridge	49%	49%	49%	3	64%
13	GrInHy 2.0	50%	72%	59%	2.8	73%
14	GAMER	51%	70%	59%	2.8	73%
15	PrometH2	53%	77%	63%	2.6	77%
16	HyBalance	52%	80%	63%	2	80%

Considering the overall results of the Case Studies reported in Table 2, high values for Population Maturity can be observed, with the majority of the instances falling in the middle of the maturity spectrum. The case studies evaluated provide a comprehensive perspective of the electrolysis process; hence, given the technology, an enhanced level of maturity in green hydrogen water electrolysis projects may be interpreted. In terms of idea maturity, there are lower values of maturity in the projects' generality compared to the population maturity scores, with the majority falling in the lower part of the idea maturity spectrum. The average for the 12 case studies in terms of idea maturity population maturity and overall maturity mentioned in table 2 are 50%,62% and 55%. These scores make sense with the reality of the water electrolysis sphere with the amount of companies and organisations rushing in to capture market value while the technology still lacks in terms of the plans and policies proposed by governmental organisations. The ideas are not mature enough to be commercialised successfully and adopted by the masses but due to economic and financial incentives backed by the global climate and energy crisis, water electrolysis is pushed forward as a solution for the present. The schedule forecast factor represents the time needed for an innovation to reach 84% of the total adopters when compared to the initially aspired schedule. In simpler terms, the factor compares the speed of adoption to the initial reference model while giving insights into the adoption rates affecting the success of the case. There is a correlation between the scheduled forecast and the overall maturity of the project. Projects/cases that have a smaller scheduled forecast tend to be of higher maturity scores. Projects such as ProMetH2 and HyBalance have a lower scheduled forecast (260% and 200% respectively) and have higher overall maturity scores than rest (63% for both). The rest of the cases shift between 280% and 300% which coincides with the relatively low overall maturity scores (52% to 60%). These scores are way higher than the reference bass diffusion values understandably as the model is an ideal case. The Confidence level introduced in the Litmus Test evaluation greatly determines the Overall Maturity; this component

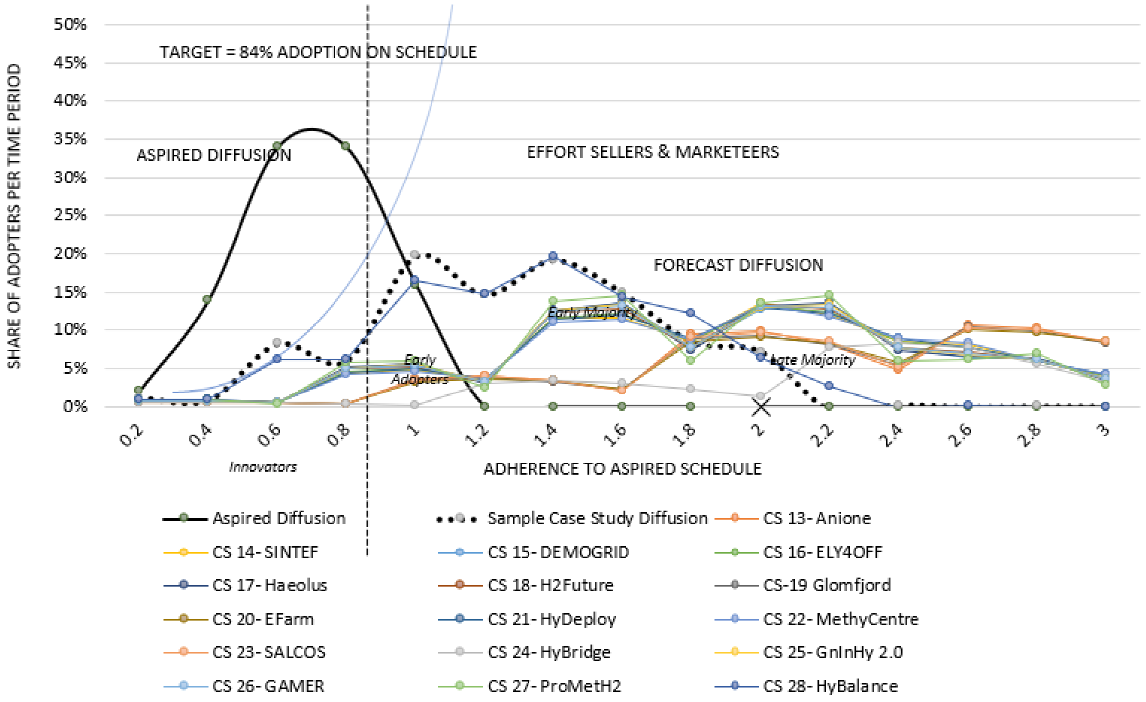


Figure 8 – Share of Adopters per Time Schedule for the Reference Model and the 16 Case Studies

is influenced by the availability of information, uncertainty about the case under consideration, and the innovation factors studied. In the majority of circumstances, the confidence evaluation has a negative impact on the overall maturity of the projects as the lack of concrete and educated information affects the impact of the results. 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.

The graph on Figure 8 shows the distinct forecasts of diffusion for the 16 Case Studies. An interesting point to observe is that certain projects such as ANIONE, Glomfjord, Efarm, SALCOS and Hybridge do not gain the share of late adopters even at 300% adherence to the schedule factor. Lower maturity levels are associated to these projects as they do not diffuse to the late adopters through the estimated time period of observation. HyBalance has the fastest scheduled factor of 200% coinciding with the highest maturity of 63%. HyBalance is also a project that has finished completion and its main partner Air Liquide is using the project to produce hydrogen for their needs which amounts for its high maturity. HyBalance is the only project that reaches 100% of the market share with some of them not diffusing to the laggards' part of the adopters. The curve has an initial slower rate in adoption but picks up speed over the second curve due to the higher overall number of adopters in the region.

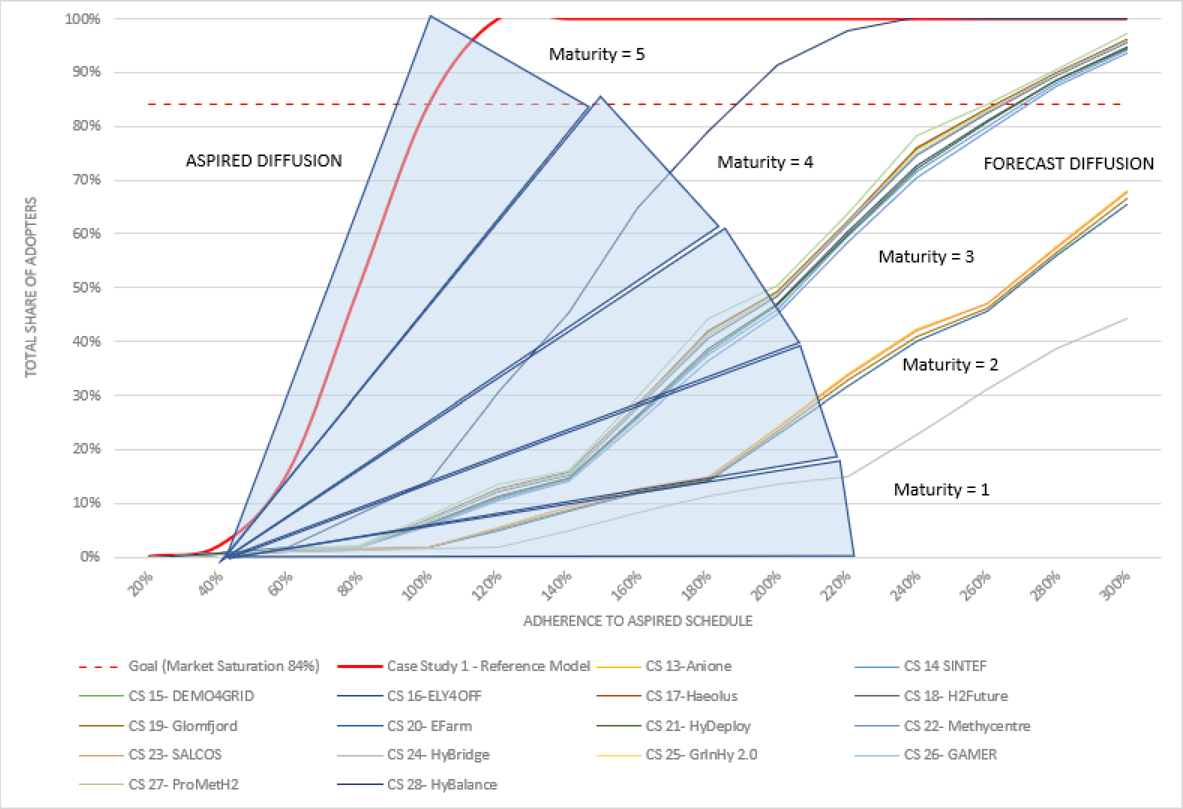
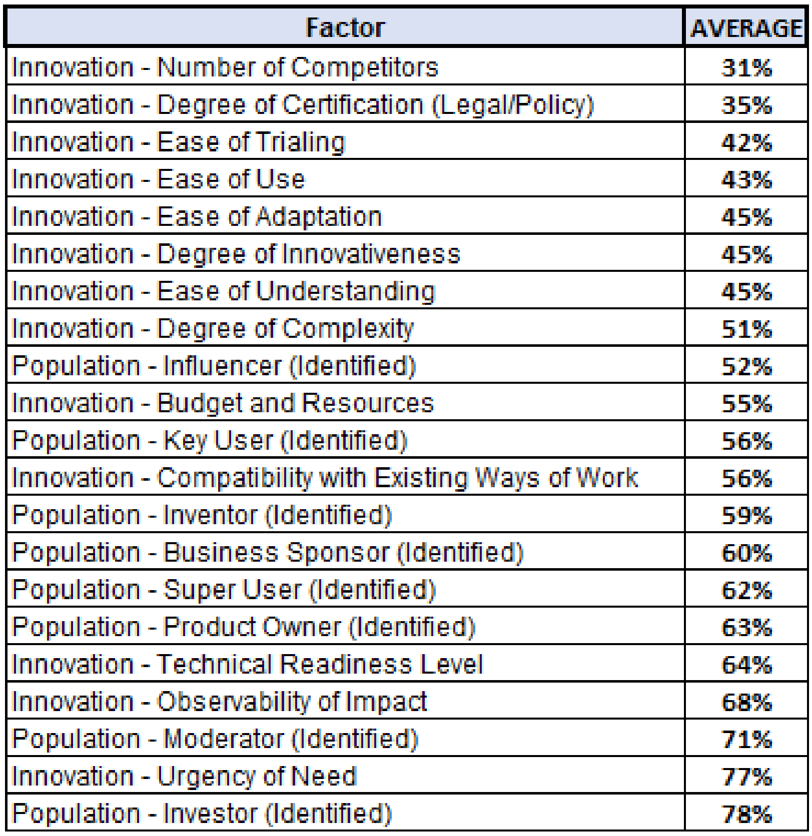


Figure 9 – Cumulative Share of Adopters for the Reference Model and the 16 Case Studies

The mentioned pattern is more explicitly reflected on the Figure 8 as the cumulative equivalent, where it is easy to discern that none of the patterns will go to market on time when compared to the aspired diffusion curve on red (Case Study 1 – Reference Model). It is a conclusive assertion because this curve defines the ideal diffusion rate without any limits to its diffusion process and thus measures 100% on the model's assessment. Nonetheless, the discrepancy between the ideal curve and the remaining CS curves demonstrates the possible space for development to achieve higher and faster diffusion, as none of the CS outcomes reached market saturation on time.In addition, the cumulative share of adopters over time in Figure 9, where the Reference Model also serves as the foundation for the desired diffusion, provides an easier method of evaluating the results, with the closer the curve of each case is to the reference, the faster the rate of diffusion. Figure 9's blue area denotes the five maturity levels where the cumulative share of the cases are positioned at each period. At lower maturity levels (1 and 2), the lower curves begin to diffuse. Following that, they gain speed, climbing to Level 3 and finishing with an Overall Maturity of Level 4, reaching market saturation at roughly 260% of the desired timeline. Even though the upper curves begin on the lower Level 3, they acquire speed faster with greater rates of diffusion and stable on Level 4 about 100% of the time and achieve the 84% share of adopters, the line objective, at around 180% of the time. The model's questionnaire assesses the various aspects that affect diffusion, and the results are shown on a Pareto analysis, in which the factors that contribute the most to the success of the innovation are projected on the benefit supplied to the diffusion. This emphasises the top and bottom issues that must be addressed in order to address the lower maturity of specific Case Studies. As seen here, a majority of the cases lie between the maturity levels 2 and 3 with just one case with a maturity for 4 and one with 1.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 4 with the performance results of the factors in Table 3 comprising of the average scores among all the case studies under consideration. The impact of each variable is equal, and the key is to maintain the degree and value of the better performing factors while improving the lower performing factors to achieve faster diffusion results.

Table 3 – Case Studies ranked by overall factor average maturity



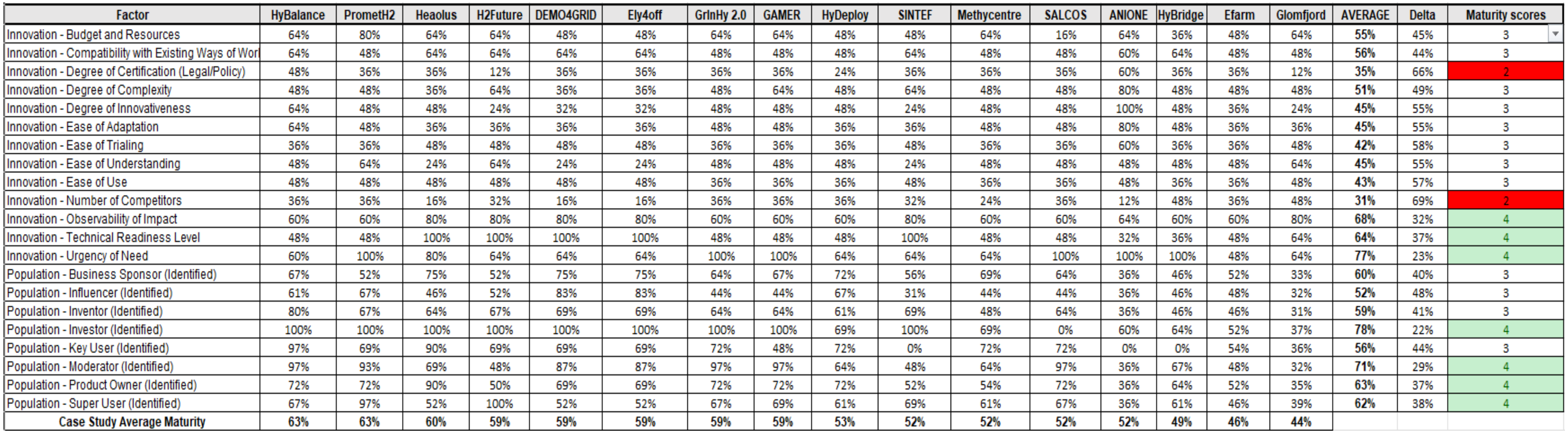
Factor	AVERAGE
Innovation - Number of Competitors	31%
Innovation - Degree of Certification (Legal/Policy)	35%
Innovation - Ease of Trialing	42%
Innovation - Ease of Use	43%
Innovation - Ease of Adaptation	45%
Innovation - Degree of Innovativeness	45%
Innovation - Ease of Understanding	45%
Innovation - Degree of Complexity	51%
Population - Influencer (Identified)	52%
Innovation - Budget and Resources	55%
Population - Key User (Identified)	56%
Innovation - Compatibility with Existing Ways of Work	56%
Population - Inventor (Identified)	59%
Population - Business Sponsor (Identified)	60%
Population - Super User (Identified)	62%
Population - Product Owner (Identified)	63%
Innovation - Technical Readiness Level	64%
Innovation - Observability of Impact	68%
Population - Moderator (Identified)	71%
Innovation - Urgency of Need	77%
Population - Investor (Identified)	78%

Table 4 – 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 3. Each value represents the maturity reached by each factor (Table 3) modelled during the assessment of the Water Electrolysis Case Studies. On Table 3 the values are displayed from lowest to highest level of maturity, where the bottom 20% or the four lowest maturities achieved are the number of competitors, degree of certification, ease of trialling and ease of use. All these factors are innovation or idea related factors which account to the overall lower maturity score for innovation as described earlier. The factors with the highest scores are investors, urgency in need, moderators, and observability in impact. Table 4 shows the ideas taken into account behind the factors.

Table 5 – Detailed results of maturity for the 12 Case Studies and respective factors



Factor	HyBalance	PrometH2	Heaolus	H2Future	DEMO4GRID	Ely4off	GrInHy 2.0	GAMER	HyDeploy	SINTEF	Methycentre	SALCOS	ANIONE	HyBridge	Efarm	Glomfjord	AVERAGE	Delta	Maturity scores
Innovation - Budget and Resources	64%	80%	64%	64%	48%	48%	64%	64%	48%	48%	64%	16%	64%	36%	48%	64%	**55%**	45%	3
Innovation - Compatibility with Existing Ways of Worl	64%	48%	64%	64%	64%	64%	48%	48%	48%	64%	48%	48%	60%	64%	48%	48%	**56%**	44%	3
Innovation - Degree of Certification (Legal/Policy)	48%	36%	36%	12%	36%	36%	36%	36%	24%	36%	36%	36%	60%	36%	36%	12%	**35%**	66%	2
Innovation - Degree of Complexity	48%	48%	36%	64%	36%	36%	48%	64%	48%	64%	48%	48%	80%	48%	48%	48%	**51%**	49%	3
Innovation - Degree of Innovativeness	64%	48%	48%	24%	32%	32%	48%	48%	48%	24%	48%	48%	100%	48%	36%	24%	**45%**	55%	3
Innovation - Ease of Adaptation	64%	48%	36%	36%	36%	36%	48%	48%	36%	36%	48%	48%	80%	48%	36%	36%	**45%**	55%	3
Innovation - Ease of Trialing	36%	36%	48%	48%	48%	48%	36%	36%	36%	48%	36%	36%	60%	36%	36%	48%	**42%**	58%	3
Innovation - Ease of Understanding	48%	64%	24%	64%	24%	24%	48%	48%	48%	24%	48%	48%	48%	48%	48%	64%	**45%**	55%	3
Innovation - Ease of Use	48%	48%	48%	48%	48%	48%	36%	36%	36%	48%	36%	36%	48%	36%	36%	48%	**43%**	57%	3
Innovation - Number of Competitors	36%	36%	16%	32%	16%	16%	36%	36%	36%	32%	24%	36%	12%	48%	36%	48%	**31%**	69%	2
Innovation - Observability of Impact	60%	60%	80%	80%	80%	80%	60%	60%	60%	80%	60%	60%	64%	60%	60%	80%	**68%**	32%	4
Innovation - Technical Readiness Level	48%	48%	100%	100%	100%	100%	48%	48%	48%	100%	48%	48%	32%	36%	48%	64%	**64%**	37%	4
Innovation - Urgency of Need	60%	100%	80%	64%	64%	64%	100%	100%	64%	64%	64%	100%	100%	100%	48%	64%	**77%**	23%	4
Population - Business Sponsor (Identified)	67%	52%	75%	52%	75%	75%	64%	67%	72%	56%	69%	64%	36%	46%	52%	33%	**60%**	40%	3
Population - Influencer (Identified)	61%	67%	46%	52%	83%	83%	44%	44%	67%	31%	44%	44%	36%	46%	48%	32%	**52%**	48%	3
Population - Inventor (Identified)	80%	67%	64%	67%	69%	69%	64%	64%	61%	69%	48%	64%	36%	46%	46%	31%	**59%**	41%	3
Population - Investor (Identified)	100%	100%	100%	100%	100%	100%	100%	100%	69%	100%	69%	0%	60%	64%	52%	37%	**78%**	22%	4
Population - Key User (Identified)	97%	69%	90%	69%	69%	69%	72%	48%	72%	0%	72%	72%	0%	0%	54%	36%	**56%**	44%	3
Population - Moderator (Identified)	97%	93%	69%	48%	87%	87%	97%	97%	64%	48%	64%	97%	36%	67%	48%	32%	**71%**	29%	4
Population - Product Owner (Identified)	72%	72%	90%	50%	69%	69%	72%	72%	72%	52%	54%	72%	36%	64%	52%	35%	**63%**	37%	4
Population - Super User (Identified)	67%	97%	52%	100%	52%	52%	67%	69%	61%	69%	61%	67%	36%	61%	46%	39%	**62%**	38%	4
Case Study Average Maturity	**63%**	**63%**	**60%**	**59%**	**59%**	**59%**	**59%**	**59%**	**53%**	**52%**	**52%**	**52%**	**52%**	**49%**	**46%**	**44%**			

4.2. Water Electrolysis case studies

The cases under consideration are based in the European case studies. The evaluation is via public information available on the internet which includes project and organisation's websites, scientific works and other articles. The choice of production method of green hydrogen and the availability of public information to make an educated evaluation was two important criteria in picking cases. Most cases fell under the maturity level of 3(40% to 60%). This proves green hydrogen's presence in the society and shows it to be "upcoming but not quite there yet." The case studies have an average innovation maturity score of 3 and an average population score of 4 as discussed earlier showing the lack in technological advancement with the increased population of the ecosystem.

The population of Investors and Moderators, along with Innovation in Urgency of need, hold the highest maturity scores, which tells a complete story of the current state of electrolysis projects. Climate change is not a problem for tomorrow but today. As years go by, the effects of climate change are visible drastically around the earth and are affecting the livelihoods of people and economics at a scale not seen before. The way around this crisis is shifting to a greener way of life and green hydrogen fits right into that pocket. The threat of energy security is another issue that has taken governments, especially in the European continent by surprise. It has become imperative for countries to have their source of energy and not be completely dependent on other nations. As green hydrogen provides a valuable option as an energy carrier, this option becomes attractive for adoption. With green hydrogen offering a pathway to fight the pressing problems faced by the EU, players are fighting to enter the space and capture the market early. Energy companies along with other industry users of hydrogen are looking to develop and invest projects with funding and expertise to gain share in this evolving market. With many policies and grants in place for green hydrogen, the sphere is an exciting investment for these companies. Companies such as SINTEF, Salzgitter and Air Liquide are involved in more than one project and are making swift moves in the green hydrogen space. The European Clean Hydrogen Alliance announced that more than 600 projects will be operational by 2025.(European Commission, 2021a)

Degree of certification, number of competitors and ease of trialling hold the lowest scores. The foundation for success lies in the framework around an innovation's implementation. Certification and regulation become key after the initial implementation in order to maintain standards. There is currently a lack in certification as the world moves towards a hydrogen economic barring a few such as CertifHy. Legal barriers along with technological regulations are key to form a base for better diffusion for this factor while ensuring quality and adequate safety standards.(Freymann et al., 2020) But this isn't a pressing concern just yet due to relatively late emergence of the green hydrogen sector with this space gaining traction over the last few years. With lesser number of competitors from an innovation point of view, there is a stagnancy when it comes to technological progression of water electrolysis hence creating low maturity levels in that domain. But there is a need to innovate at a faster rate for the progression of water electrolysis as the scale of technological advancement in the field is not a match for the influx of population and emergency of favouring policies. This also happens to be the reason for the betterment of this factor as it will force for a faster diffusion through this area. Ease of trialling also appears to be of a low maturity level. The emergence of green hydrogen and its alternate uses for mobility and renewable energy storage has been popularised over the few years, but hydrogen has been used in industries and in forms such as ammonia for a long time. Most industries using vast amounts of hydrogen have their own facility to produce hydrogen. A rapid shift to electrolysers is not economically and practically feasible with the scale of hydrogen needed. Hydrogen is usually produced via natural gas using processes like steam methane reforming and accompanying it with some sort of carbon capture and storage seems like a feasible option than completely shifting to green hydrogen. The current renewable capacity around the world along with the state of electrolysers at the present makes green hydrogen not very appealing for now. There are also issues with the transport of the produced hydrogen Many questions over the years have been asked from the transmission point of view. With issues in using existing pipelines for hydrogen, repurposing is a viable option as it is cheaper than building newer ones.(European Commission, 2021b) The blending of hydrogen into natural gas networks has also been carried out in various European projects. However, it comes with issues like pipes' embrittlement and leakage concerns.(Mahajan et al., 2022)

4.3. Green Hydrogen supply chain case studies

The cases for assessment have been obtained from the work of Correia et al on the speed of innovation diffusion of the green hydrogen supply chain.(Correia et al., 2022) The work focusses on projects of innovation across the entire green hydrogen supply chain ranging from the production to the transportation and storage of green hydrogen. These cases were taken into consideration following a similar methodology to the one proposed in this dissertation with a focus on various elements and innovative areas in the entire green hydrogen supply chain. Cases range from the technical feasibility of underground storage for green hydrogen to the development of hydrogen heavy duty mobility vehicles. His work showed an 87% idea maturity and a 79% population maturity, which is drastically higher values than the one obtained for water electrolysis case studies. With most of the cases between the maturity levels of 3 and 4, the entire green hydrogen supply chain is a fast-progressing ecosystem with highly mature projects as shown in Figure 10. The higher average case study maturity also means that the cases have a lower scheduled forecast. The analysis also points out that innovation in degree of certification, degree of complexity and compatibility with existing ways of work are the least mature factors while innovation in degree of innovativeness, number of competitors and the population of investors as the factors with the highest maturity levels (Correia et al., 2022).

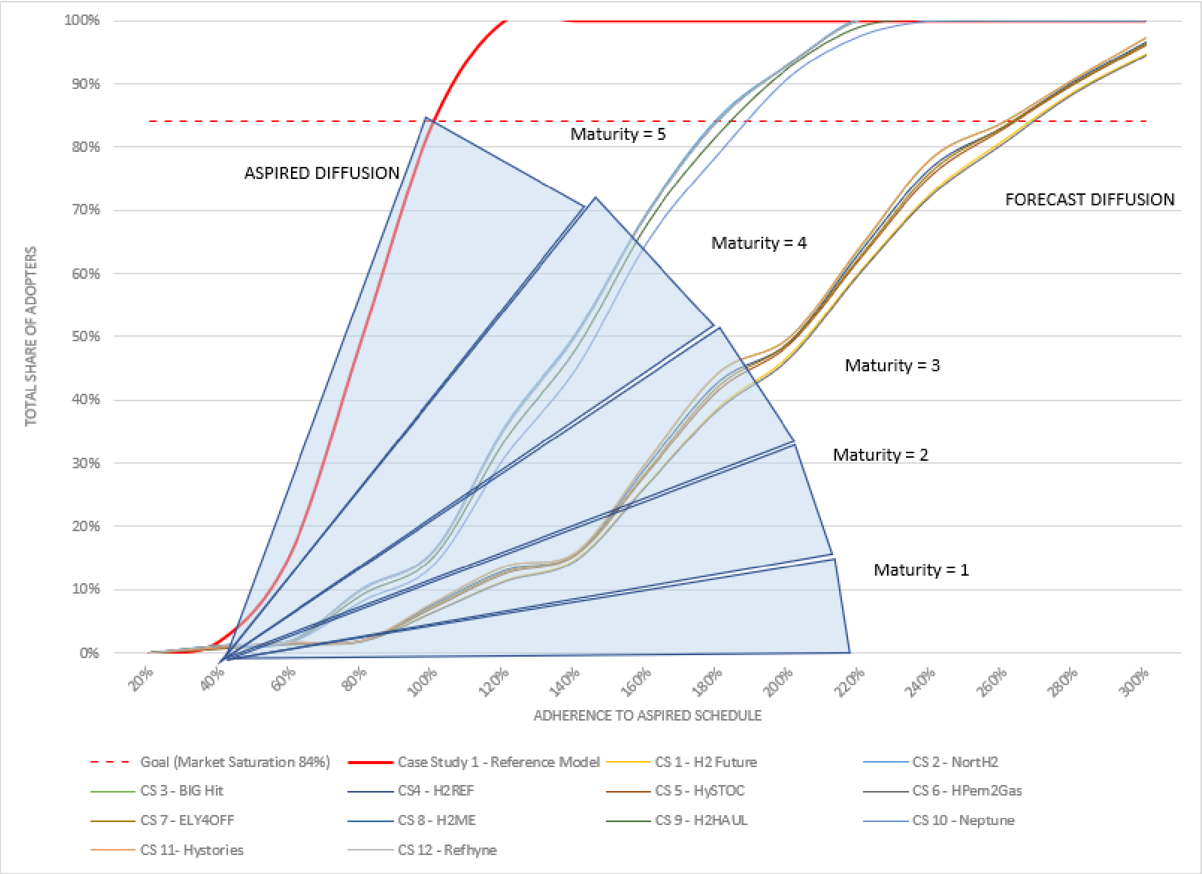


Figure 10 – Cumulative Share of Adopters for the Reference Model and the 12 Green Hydrogen Supply Chain Case Studies.

4.4. Holistic analysis

The novelty of this study lies in providing a holistic view to the speed of innovation diffusion of the entire green hydrogen ecosystem by analysing the water electrolysis case studies along with the green hydrogen supply chain case studies to cover the entire green hydrogen space. This approach has been considered as validated by the results, water electrolysis forms the core of the green hydrogen ecosystem and is also the lacking factor when it comes to the innovation diffusion of the entire green hydrogen ecosystem. The evaluation of the lacking factors of the green hydrogen supply chain case studies along with a focus on the water electrolysis case studies would provide a holistic view on the entire green hydrogen ecosystem. Table 6 shows the top and bottom three maturity scores of factors affecting diffusion of both case studies.

With none of the cases maturing in time as seen in the ideal case, it is evident that adequate steps need to be taken to assess the factors crucial for faster diffusion. The low innovation maturity emphasises the importance of developing the maturity of the technological aspects and effects of the innovation in an ecosystem where the population is more mature.

On analysis of both sets of case studies, there are certain factors that are commonly mature across both the cases. Investor population ranks high in both sets of cases. This factor is an obvious high due to to the amount of funding pumped into the green hydrogen sector. Hydrogen especially low carbon hydrogen is deemed key to the EU for achieving its goals of reducing greenhouse gas emissions by

55% by 2030. The European Clean Hydrogen Alliance, set up in 2020, brings 1500 stakeholders including industry players, research organisations and public authorities to create a European hydrogen consortium. The organisations cover all parts of the green hydrogen supply chain. As of September 2022, the European Commission has announced a 5.12 billion euro in public funding for the better and faster development of low carbon hydrogen technologies.(Reuters, 2022) The Commission has also set up Hydrogen Public Funding Compass to guide stakeholders to find public funding sources for their hydrogen projects.(European Commission, 2022) The key aspect of this program being the availability of information to make educated decisions as dissemination forms the key to faster adoption. The International Energy Agency (IEA) emphasizes that the next ten years are crucial for hydrogen penetration into our energy sectors in terms of policies.(IEA, 2019) Efforts to create long-term policy targets and mitigate investment risks are proving to be a deal breaker as investors and moderators flood in. There are initial steps taken in the right direction with EU Horizon 2020 and the public-private partnership on Fuel Cell and Hydrogen (FCH JU).(European Commission, 2018)

Observability of Impact also scores high among both sets of cases. A factor which portrays how much of a difference the innovation to the original problem, observability of impact is key for people as when the masses as well as stakeholders of the ecosystem start seeing the intended results, they are more likely to put in more effort for improving its adoption. In both sets of studies, they have a maturity level of 4 meaning the impact of green hydrogen and water electrolysis technologies is quite evident. With increasing stress on mitigating the effects of climate change and moving away from fossil-based fuels, green hydrogen is slowing increasing its market share. Even though this rate is very low at the moment due to wide use of other low carbon hydrogen forms, this rate is slowly increasing with the influx of policies and subsidies. Urgency of need and moderator also rank high among both data sets which as discussed earlier with gaining market share and mitigating climate change plays major roles.

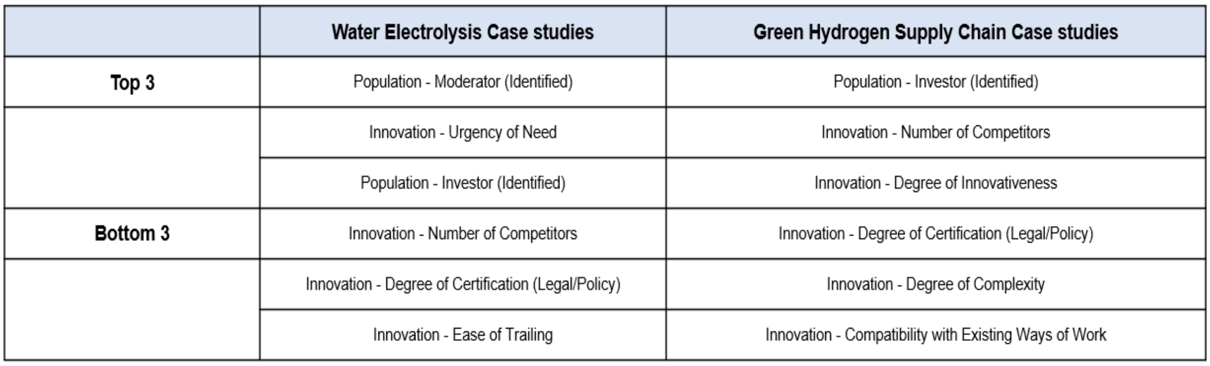
Degree of certification ranks low in both sets of case studies. Certification is a critical factor that makes or breaks this domain. The origin and certification of renewable electricity are essential for green hydrogen. Energy utility companies and grid providers have switched to labelling to ensure transparency and adequate tracking. Most of the case studies under consideration have their direct source of green electricity like the Haeolus Project powered by the Raggovidda wind park and H2Future, a project in partnership with the Austrian Power Grid and Verbund for their green electricity. The Greenhouse Gas Protocol 2 requires electricity and heat certificates to be used in the same energy market where they are produced. As the market for green hydrogen expands, the protocol is set to extend to the green hydrogen sector, countries have already started proposing projects for green hydrogen certification.(IRENA, 2022)

An example is CertifHy, which aims to create a standard definition for green hydrogen across the European Union. One of its main objectives is to ensure the compatibility between EU legislation and Green Hydrogen Guarantees of Origin (GO). To increase transparency and liquidity the scheme has three categories, green, low carbon, and grey hydrogen, depending on greenhouse gas intensity. Maintaining a transparent market for green hydrogen will help better measure emissions and set standards for a successful energy transition. The GnInH 2.0 project has been following the CertifHy scheme.(Freymann et al., 2020)

Compatibility with existing way also ranks low in both sets. A good reasoning would be the well implemented existing blue hydrogen plants around the world specifically for industrial purposes. The best alternate to save capital would be to introduce carbon capture in these plants rather than a whole new shift to green hydrogen as explained earlier. Better development of the downstream aspect of the supply chain is also required. The low maturity levels of the population of key user and super users in the ecosystem also support this statement. A recommendation would be an increased engagement between the upstream and downstream stakeholders of the green hydrogen ecosystem.

An interesting conclusion from the analysis is the dissimilarity when it comes to the innovation in the number of competitors. It ranks high in the supply chain case studies but quite low in the water electrolysis case studies. With more established companies coming into play with regards to the entire supply chain, there is a bigger set of competitors forcing better innovation to gain market share in their area of expertise. The downstream domain of the produced green hydrogen is much bigger than the upstream production criteria. That is not the case with water electrolysis. The number of companies with the capability to build electrolysers is limited when compared to the rest of the supply chain. There are also lesser competitors as the different types of electrolysers is limited. Many water electrolyser projects are also research projects with no clear motive for the end use of the produced green hydrogen which also accounts for the low key users and super user maturity levels. Competition is key for innovation and this factor should improve with time.

Table 6– Factors with the highest and lowest maturity levels in both sets of case studies



	Water Electrolysis Case studies	Green Hydrogen Supply Chain Case studies
Top 3	Population - Moderator (Identified)	Population - Investor (Identified)
	Innovation - Urgency of Need	Innovation - Number of Competitors
	Population - Investor (Identified)	Innovation - Degree of Innovativeness
Bottom 3	Innovation - Number of Competitors	Innovation - Degree of Certification (Legal/Policy)
	Innovation - Degree of Certification (Legal/Policy)	Innovation - Degree of Complexity
	Innovation - Ease of Trailing	Innovation - Compatibility with Existing Ways of Work

4.5. Results Validation

The results previously presented, which were achieved from modelling the Litmus Test with the Case Studies on water electrolysis 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 these cases.

4.5.1. Interviews

Interview 1: Mr Marwane El Alioui

Mr Marwane El Alioui has a masters specializing in gas engineering and management from École des Mines de Paris and specializes in the European hydrogen market with a focus on France. He currently works for Prodeval, as a Strategic Project Manager. With his expertise in project management, business development, market research and risk analysis, Mr Marwane has help set up and manage the hydrogen production plant for gasification for Prodeval. He also has vast experience in conducting market studies for green hydrogen and resilience studies for different production routes. Mr Marwane has also helped find competitive solutions and partnerships for producing syn gas. He currently works on product development for renewable gases and various hydrogen production methods such as electrolysis, electrocatalysis and steam methane reforming.

With respect to use of hydrogen, Mr Marwane emphasises on the importance of the industrial sector, especially for decarbonising the steel industry. The market for green hydrogen is competitive with companies trying to gather market share as soon as possible. He mentions how green hydrogen is not the solution to our energy crisis and will just form a part of it. The policies and targets set by the EU and various countries for green hydrogen production is still not achievable at this point in time due to the lack of technological advancement. Hence, diversifying the hydrogen portfolio remains the answer. The production of “low carbon” hydrogen will act as key he mentions. Low carbon hydrogen includes green hydrogen as well as hydrogen produced using natural gas with carbon capture in place. By 2030 at least, the prominence of steam methane reforming will remain while green hydrogen continues to grow is what he expects. An important point he points out is the issue with cost. CAPEX electrolyser costs are too high at the moment for a switch, but the surprising cause is the cost of renewable power. The lack of high renewable generation capacity and its high cost hinders the diffusion of water electrolysis as 80% of the operational costs includes the electricity needed to power electrolysers. Hence, a conclusion was reached with water electrolysis holding back the adoption speed of the entire green hydrogen ecosystem, as shown in the results earlier.

Mr Marwane was perplexed with the fact that the population of investors were high despite the high degree of complexity, but a conclusion was reached due to the policies, backing and funding provided by the EU to promote electrolysis. To support this, he mentioned France has 8 billion euros in subsidies for green hydrogen until 2030 to promote the growth of green hydrogen. He talked about how hydrogen for mobility is not a viable solution as we are yet to crack the electric vehicles case. Industrial use, especially steel industry is green hydrogen's best bet. Even though the technological readiness level of the process is low, it is necessary for the industry to adopt green hydrogen as it is a big carbon emitter. Other existing industrial have huge methane reforming plants set up and shifting to electrolysis is not a economically feasible option for them which coincides with one of the results of the study. Mr Marwane also explained the importance of certification in the industry, which according to this analysis is lacking for diffusion. He mentioned how the green hydrogen industry can look to the electricity sector on building a foundation for certification.

In conclusion, Mr Marwane agreed with the results of this analysis which offering market-based explanations to how the reality is and why the results make sense in the current scenario. He had also mentioned the impact of the current war on Ukraine and the importance of energy security and renewable gases and how this has caused a setback in the energy goals but a better political mindset.

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Interview 2: Prof. Daniel Gaspar

Prof. Daniel Gaspar is a mechanical engineer and is currently a professor in the Mechanical engineering and industrial management division of Polytechnic Institute of Viseu, Portugal. He has worked in the petrochemical industry with experience dealing with refineries. Daniel has also worked with water treatment in the pharmaceutical industry. His current expertise deals with reliability studies, strategic management and planning, new product development and innovation and has published many works in asset management and reliability studies. Mr Gaspar has also used the Innovation Diffusion Litmus Test, as used in this model, for previous analysis of his and is familiar with its workings.

Mr Gaspar agreed with the overlying conclusion of water electrolysis technologies holding back the speed of diffusion of the entire green hydrogen ecosystem. He reasoned with the idea that this might be the case due to the relatively new increase in scale of electrolysis in order to act as a solution for the energy crisis. He had also mentioned that the supply chain cases had a higher maturity due to its similarity in structure and foundation with the supply chain of natural gas. On further analysing the results he pondered over how a company wise analysis would turn out as there are quite a number of recurring companies/organisations in the various water electrolysis cases. He suggested adding a analysis depicting the co dependence of factors and how scores of one factor influence the others. He gave an example of how a higher observation of impact can give rise to higher population of investors as seen in the analysis conducted.

With respect to the results obtained. Mr Gasper stressed on the importance of number of competitors for the growth and adoption of an innovation. Mr Gaspar cited the few manufacturers of electrolysers along with limited technological advance could be the case for the water electrolysis cases whereas higher number of stake holders along the supply chain makes for a higher maturity in the case of the supply chain case studies. Larger number of competitors also accounts for the overall interest shown in the area, which again is crucial to the adoption of the innovation. Mr Gaspar mentions the importance of certification for this industry. Making it more appealing for stake holders is key for adoption and with the economic stability that certification brings to this domain, both participants agreed on its importance.

He reasoned this with the current price of green hydrogen being higher than its other fossil fuel-based counterparts. Certification also creates a foundation, one that is important to attract further funding based on the technological performance rather than an urgency of need. He mentioned how certification also protects the integrity of the technology, forming a “concrete structure” around it. He also spoke about how with more renewables integrating into the supply chain, the more complex the role of factors gets as seen in the supply chain case study results.

When asked about ways to improve diffusion speeds, he mentioned better lobbying and acting from the government and other organisations perspective. Mr Gaspar concluded the interview by adding that a cluster analysis could give more insights into the data sets and validation interviews from industrial manufacture to provide a perspective from their end.

4.6. Results Discussion

The advancement of the innovation diffusion methodologies used on the Litmus Test and applied to various case studies of water electrolysis projects in Europe, yielding 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 maturity of the factor through the Pareto analysis. This subchapter aligns the model outputs with the validation that occurred and is intended to achieve an understanding of what lessons can be gained from those mentioned above while searching for valuable insights on how to act quickly and what measures must be considered when developing innovative water electrolysis projects and the overall green hydrogen ecosystem.

Water electrolysis remain the most common method for producing green hydrogen, forming an integral and vital part of the green hydrogen supply chain. The combined analysis of the water electrolysis case studies and the green hydrogen supply chain case studies from Correia provides a holistic inspection of the entire green hydrogen ecosystem, thereby reasonably observing the factors that accelerate the speed of diffusion for this ecosystem. (Correia et al., 2022)The data used for the model is retrieved from data sets comprising relevant case studies of various hydrogen projects across the European continent using water electrolysis to produce hydrogen. Results show that water electrolysis case studies have a lesser maturity level than the green hydrogen supply chain cases. The urgency in need fuelled by the rising effects of climate change has expedited the diffusion of the various innovations in the supply chain even though the concept of electrolysis has existed over the last century. The lower maturity of electrolysis shows the process's importance for the ecosystem's overall advancement.

5. Conclusion & Future Developments

A comprehensive review of the role of green hydrogen was provided after analysing the topic at hand and what scientific literature exists behind the notions of a maturity model produced in this dissertation. Given the European energy paradigm, green hydrogen was presented, along with the many methods of water electrolysis and the end use for the created green hydrogen. Understanding the importance of these technologies in attaining green and sustainable economic growth, as well as demonstrating the necessity of spreading the hydrogen economy not only in the EU but globally, was understood, and the context to investigate was determined as a result. It is critical to note that hydrogen should not be regarded as the sole solution to the world's energy concerns, nor will it be the only solution to the transportation sector's problems. These issues may be overcome by a variety of solutions working together as one to meet the impending environmental targets. Green hydrogen, on the other hand, will be critical in decarbonizing difficult-to-electrify and carbon-intensive sectors such as the steel industry. By emphasising the importance of hydrogen technical advancements spreading successfully over the next few decades, climate targets will be met with greater speed.

Following a review of the literature on the diffusion of innovations concepts, value networks, and models used to assess distribution, it is possible to conclude the importance that innovation webs hold on understanding how innovations are adopted by the various stakeholders. Also understood was the importance of balance between an innovation’s technological attributes with the population of the stakeholders and their intentions on the innovation. Furthermore, the concepts evaluated in the state of the art align with the technology defined in the problem definition to achieve the dissertation’s goal, the application of the Litmus Test, to assess the maturity levels of the referred innovations and what variables influence their adoption, with special emphasis on achieving the fastest diffusion possible from ideation to market saturation. The analysis then concluded with a comparison in results with the green hydrogen supply chain case studies to find factors affecting the adoption of the entire green hydrogen ecosystem.

5.1. Main findings and Implications

Assessments have shown a maturity level of 3 for the water electrolysis case studies where the population maturity level outranked the innovation maturity level, thereby perfectly reflecting the current state of water electrolysis. The highest-ranking factors were investor and moderator population along with innovation in urgency in need. Degree of certification, number of competitors and innovation in ease of trialling ranked among the bottom three of the factors assessed. These factors emphasised the factors crucial for diffusion that are the most and least mature with the factors that are holding this technology behind. At the same time, the accelerating factors must be enhanced for a complete diffusion.

On comparing with the supply chain case studies, certain common factors were obtained. Investor population was high in both sets of case. Number of competitors were in the bottom for water electrolysis while it ranked in the higher maturity levels for the supply chain case studies. Degree of certification ranks in the bottom three for both sets of case studies.

This research work benefits the green hydrogen industry by creating a basis for using diffusion models to scrutinize the factors crucial for diffusion. The outcome of the work can also be generalised that the most innovative technology may be the one that is holding back the entire ecosystem's diffusion potential. Green hydrogen is on the up and will be a key part of the future energy mix as investments and policy decisions back it up. Hence finding pathways for better diffusion guarantees success of this crucial innovation. This work also creates a focus on water electrolysis projects, a part of the supply chain that is lacking in maturity as seen earlier in the results. Hence evidence for the factors holding back its diffusion as shown in this work may act as a small foundation while developing the much-needed green hydrogen framework. The quality of data gathered with the litmus test taking into account the subjective confidence scores along with the conduction of validation interviews adds affirmation to the results gathered and analysed.

5.2. Limitations and recommendation for future research

When implemented to the cases of interest, the research approach, in conjunction with the assessments of the selected change factors, results in an initially acknowledged strong validation of the selected diffusion theory. There also needs to be a constant monitoring of cases to confirm the validation of results. A larger data set will also increase the robustness of the results. The lack of publicly available information, even though it is integrated into the model, causes a slight change in results as a project might be commercially successful but with mostly privatised information. Keeping in mind the preceding, the recommendations for prospective future research are in the development of innovation. Furthermore, there is a need to investigate additional elements such as value network intent and value network/ecosystem performance.

Furthermore, the geographical variable must be addressed in addition to the TRL in different regions throughout the world with additional availability and compatibility with hydrogen technology. The role of the regulator and policymakers on various industries of hydrogen application (e.g., aviation, long haul, energy storage) is also underlined as necessary to consider in future study as part of the ecosystem members to be addressed. Another recommendation is to analyse the industry to which green hydrogen can create the most practical impact in order for complete practical adoption. There is a better chance of making a significant impact in an industry where green hydrogen can penetrate better and focus on that industry rather than generalizing the cause.

Research may also take the route of using the method of associating cases to causal conditions put forward by Schwabe et.al. (Schwabe et al., 2021)Applying qualitative comparative analysis to the ecosystem, intent with regard to sustainable development, innovation diffusion and its performance can help figure out the conditions most feasible to form a catenations creating the most value. The identified case studies are to be placed in a specific causal code based on the crisp score of the factors Solution Maturity(S), Role maturity (R), Intent(I)and Performance (P) along with their sustainability potential that is calculated judgementally and through interactions with experienced investors. The crisp scores are created via fuzzy scores for each evaluation. In the case of water electrolysis case studies, the crisp score for solution maturity and role maturity comes with the evaluation of innovation maturity and population maturity of each case study as shown in the results of this dissertation. While SDG analysis are underway with respect to the achievement of a case study with respect to each factor of all the Sustainable Development Goals (SDG), efforts need to be shifted to monitor the performance of these case studies to finalise the parameters under consideration for the Performance(P) factor. The theory behind this work is that a unique causal code along with a high sustainability potential will create the highest value, but there is no specific pattern behind it yet. Cases with different causal codes but a high sustainability potential can also reach high value as there might be additional changes in the codes over time. Hence constant monitoring and variable interference is needed at appropriate times to facilitate better diffusion. This research methodology plays perfectly for water electrolysis and the green hydrogen ecosystem due to its early nature and high urgency of need. As the supply chain becomes more complex and technological and market-based advances enter water electrolysis, different pathways need to be assessed at different points in the timeline for faster diffusion rates. Hence the foundation of framework and certification can also be revisited and modified accordingly which plays into the hands of the results and discussions of this dissertation. Looking at the case studies from this perspective of diffusion can call for a different approach to reaching the desired diffusion rates.

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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 Water Electrolysis Case Studies to provide a comprehensive assessment of the green hydrogen ecosystem

Student: Dhakshin Kumar – dhakshin.kumar@tecnico.ulisboa.pt
Supervisor(s): Dr. Oliver Schwabe, Prof. Nuno Marques de Almeida

I am Dhakshin Kumar, a double-degree renewable energy master's student at Instituto Superior Técnico, Lisbon. This mail concerns my master thesis and a senior innovation manager from Rolls Royce Aerospace. This interview request takes part in developing a master thesis," Speed of Innovation Diffusion of Water Electrolysis Technologies."

An Innovation Diffusion model (Litmus Test) was applied to 16 Case Studies of European water electrolysis projects. These cases 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 participate 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 identifying the factors that influence the diffusion and the need for improvements. The work also compares existing results on case studies of the green hydrogen supply chain to provide a holistic view of the state of the entire hydrogen ecosystem. This interview aims to validate the results obtained so far applied to the referred cases, assess the model's robustness, and discuss with experts in the field the recommendations on the results and the model itself.

To evaluate why some projects outperform others, we compared the case studies with the highest maturity levels to the ones with the lowest maturity. In the comparison, we looked for the factors with the most significant difference for the case of HyBalance (higher maturity) compared with Glomfjord (lowest maturity); hence, the factors which show the most significant difference should be the ones that lead to slower diffusion rates on the Glomfjord and need to be developed. The population of Investors and Moderators, along with Innovation in Urgency of need, hold the highest maturity scores.

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. I 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. The list of cases used are listed below for your reference

(1) HyBalance - https://hybalance.eu/

(2) PrometH2 - http://promet-h2.eu/

(3) Heaolus - https://www.haeolus.eu/

(4) H2Future - https://www.h2future-project.eu/technology

(5) DEMO4GRID - https://www.demo4grid.eu/

(6) Ely4off - http://ely4off.eu/

(7) GrInHy 2.0 - https://www.green-industrial-hydrogen.com/

(8) GAMER - https://www.sintef.no/projectweb/gamer/

(9) HyDeploy - https://hydeploy.co.uk/

(10) Channel - https://www.sintef.no/projectweb/channel-fch/

(11) Methycentre - https://methycentre.eu/

(12) SALCOS - https://salcos.salzgitter-ag.com/en/salcos.html#c141547

(13) ANIONE - https://anione.eu/

(14) HyBridge - https://www.hybridge.net/index-2.html

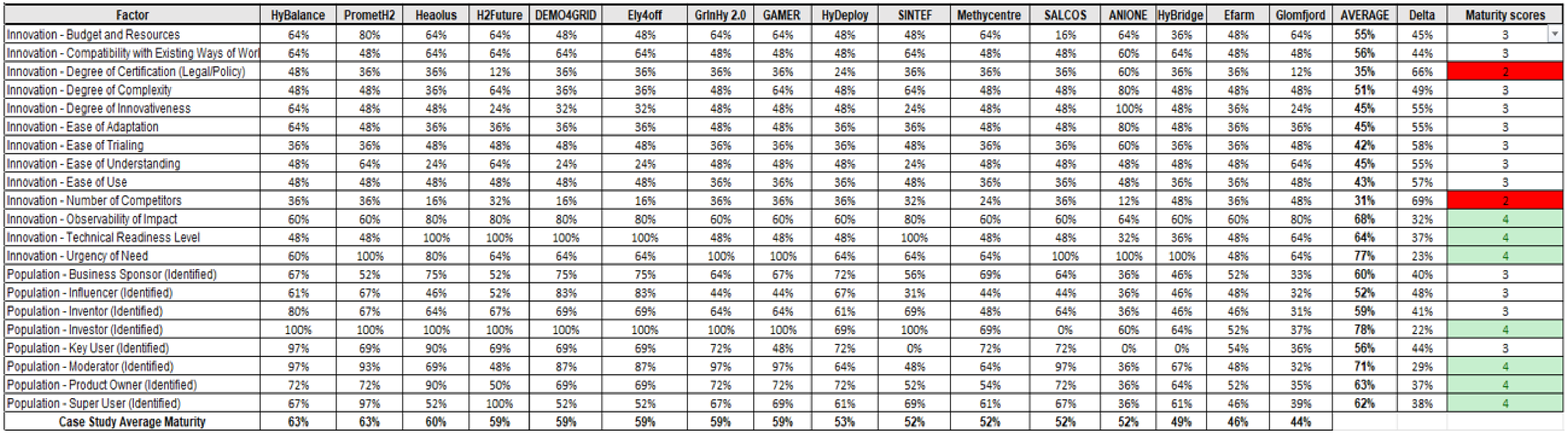
(15) Efarm - https://www.h2v.eu/analysis/best-practices/efarm

(16) Glomfjord - https://www.glomfjordhydrogen.no/ac/glomfjord-hydrogen-as. .

Thank you,
Dhakshin Kumar.

	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	HyBalance	PrometH2	Heaolus	H2Future	DEMO4GRID	Ely4off	GrInHy 2.0	GAMER	HyDeploy	SINTEF	Methycentre	SALCOS	ANIONE	HyBridge	Efarm	Glomfjord	AVERAGE	Delta	Maturity scores
Innovation - Budget and Resources	64%	80%	64%	64%	48%	48%	64%	64%	48%	48%	64%	16%	64%	36%	48%	64%	**55%**	45%	3
Innovation - Compatibility with Existing Ways of Worl	64%	48%	64%	64%	64%	64%	48%	48%	48%	64%	48%	48%	60%	64%	48%	48%	**56%**	44%	3
Innovation - Degree of Certification (Legal/Policy)	48%	36%	36%	12%	36%	36%	36%	36%	24%	36%	36%	36%	60%	36%	36%	12%	**35%**	66%	2
Innovation - Degree of Complexity	48%	48%	36%	64%	36%	36%	48%	64%	48%	64%	48%	48%	80%	48%	48%	48%	**51%**	49%	3
Innovation - Degree of Innovativeness	64%	48%	48%	24%	32%	32%	48%	48%	48%	24%	48%	48%	100%	48%	36%	24%	**45%**	55%	3
Innovation - Ease of Adaptation	64%	48%	36%	36%	36%	36%	48%	48%	36%	36%	48%	48%	80%	48%	36%	36%	**45%**	55%	3
Innovation - Ease of Trialing	36%	36%	48%	48%	48%	48%	36%	36%	36%	48%	36%	36%	60%	36%	36%	48%	**42%**	58%	3
Innovation - Ease of Understanding	48%	64%	24%	64%	24%	24%	48%	48%	48%	24%	48%	48%	48%	48%	48%	64%	**45%**	55%	3
Innovation - Ease of Use	48%	48%	48%	48%	48%	48%	36%	36%	36%	48%	36%	36%	48%	36%	36%	48%	**43%**	57%	3
Innovation - Number of Competitors	36%	36%	16%	32%	16%	16%	36%	36%	36%	32%	24%	36%	12%	48%	36%	48%	**31%**	69%	2
Innovation - Observability of Impact	60%	60%	80%	80%	80%	80%	60%	60%	60%	80%	60%	60%	64%	60%	60%	80%	**68%**	32%	4
Innovation - Technical Readiness Level	48%	48%	100%	100%	100%	100%	48%	48%	48%	100%	48%	48%	32%	36%	48%	64%	**64%**	37%	4
Innovation - Urgency of Need	60%	100%	80%	64%	64%	64%	100%	100%	64%	64%	64%	100%	100%	100%	48%	64%	**77%**	23%	4
Population - Business Sponsor (Identified)	67%	52%	75%	52%	75%	75%	64%	67%	72%	56%	69%	64%	36%	46%	52%	33%	**60%**	40%	3
Population - Influencer (Identified)	61%	67%	46%	52%	83%	83%	44%	44%	67%	31%	44%	44%	36%	46%	48%	32%	**52%**	48%	3
Population - Inventor (Identified)	80%	67%	64%	67%	69%	69%	64%	64%	61%	69%	48%	64%	36%	46%	46%	31%	**59%**	41%	3
Population - Investor (Identified)	100%	100%	100%	100%	100%	100%	100%	100%	69%	100%	69%	0%	60%	64%	52%	37%	**78%**	22%	4
Population - Key User (Identified)	97%	69%	90%	69%	69%	69%	72%	48%	72%	0%	72%	72%	0%	0%	54%	36%	**56%**	44%	3
Population - Moderator (Identified)	97%	93%	69%	48%	87%	87%	97%	97%	64%	48%	64%	97%	36%	67%	48%	32%	**71%**	29%	4
Population - Product Owner (Identified)	72%	72%	90%	50%	69%	69%	72%	72%	72%	52%	54%	72%	36%	64%	52%	35%	**63%**	37%	4
Population - Super User (Identified)	67%	97%	52%	100%	52%	52%	67%	69%	61%	69%	61%	67%	36%	61%	46%	39%	**62%**	38%	4
Case Study Average Maturity	**63%**	**63%**	**60%**	**59%**	**59%**	**59%**	**59%**	**59%**	**53%**	**52%**	**52%**	**52%**	**52%**	**49%**	**46%**	**44%**			

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

No.	Case study	Start Date	Electrolyser used	Partners
1	Anione	2020	Anione Exchange Membrane	• Fuel Cells and Hydrogen 2 Joint Undertaking • Consiglio Nazionale Delle Ricerche (CNR-ITAE) • Centre National de la Recherche Scientifique CNRS (CNRS) • HydroLite • TFP Hydrogen (TFP H2) • IRD Fuel Cells A/S (IRD) • Hydrogenics Europe NV (Hydrogenics) – Acquired by Cummins Inc • Uniresearch BV (UNR)
2	The Channel EU Project	2020	Anione Exchange Membrane	• SINTEF • EVONIK • ENAPTER • NTNU • Forschungszentrum Jülich • Shell

3	DEMO4GRID	2017	Pressuirzed Alkaline	• MPREIS • Aragon Hydrogen Foundation • INYCOM Innovation Technologies • Diadikasia • Fen Systems • Sunfire Renewables • Fuel Cells and Hydrogen 2 Joint Undertaking
4	ELY4OFF	2016	Proton Exchange Membrane	• ITM Power • Aragon Hydrogen Foundation • INYCOM Innovation Technologies • Liten CEA Tech • Epic Power • CEA
5	Haeolus Project	2018	Proton Exchange Membrane	• Sintef • UBFC • Tecnalia • University of Sannio • Varanger Kraft • Hydrogenics • KES • Fuel Cells and Hydrogen 2 Joint Undertaking

6	H2FUTURE	2017	Proton Exchange Membrane	• VERBUND • Voestalpine • Siemens Energy • Austrian Power Grid AG (APG) • K1-MET • ECN(Part of TNO) • Fuel Cells and Hydrogen 2 Joint Undertaking
7	Glomfjord Hydrogen AS	2020	Alkaline	• NEL • Greenstat AS • Meløy energi • Troms Kraft AS • Air Liquide
8	EFarm	2019	Proton Exchange Membrane	• GP Joule • H-TEC Systems • National Innovation Programme Hydrogen and Fuel Cell Technology • NOW GmbH
9	HyDeploy	2017	Proton Exchange Membrane	• ITM Power • Northern Gas Networks • keele university • Cadent • HSE • Progressive Energy • Ofgem’s Network Innovation Competition
10	Methycentre	2019	Proton Exchange Membrane	• Storenergy • Khimod • PRODEVAL • CEA • Elogen French Environment and Energy Agency

11	SALCOS	2015	Proton Exchange Membrane	• Fraunhofer-Gesellschaft • Avacon Natur GmbH • Tenova S.p.A. / • Sunfire GmbH • Rhenus Logistics • Uniper SE • Paul Wurth S.A. • Salzgitter
12	HyBridge	2023	Proton Exchange Membrane and Alkaline are considered	• Amprion • Open Grid Europe
13	GrInHy 2.0	2019	High Temperature Electrolysis	• Salzgitter Mannesmann Forschung GmbH • Salzgitter Flachstahl GmbH • Sunfire GmbH • Paul Wurth S.A. • Tenova • Commissariat à l’énergie atomique • Fuel Cells and Hydrogen 2 Joint Undertaking
14	GAMER	2018	High Temperature Electrolysis	• SINTEF • Carbon Recycling International • CSIC, Instituto de Tecnología Química • Coorstek Membrane Science AS • University of Oslo • MC2 Ingenieria y Sistemas SL • Shell • Fuel Cells and Hydrogen 2 Joint Undertaking

15	PrometH2	2020	Proton Exchange Membrane	• Air Liquide • The Chemours Company • CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS (CSIC) • The National Council of Research-Italy (CNR) • CENmat • The Institute of Engineering Thermodynamics at the German Aerospace Center • Forschungszentrum Jülich • The Foundation for the Development of New Hydrogen Technologies in Aragon • The SME iGas energy GmbH • MONOLITHOS Catalysts & Recycling Ltd. • Nel Hydrogen • The SME ProPuls • Fuel Cells and Hydrogen 2 Joint Undertaking
16	HyBalance	2015	Proton Exchange Membrane	• Fuel Cells and Hydrogen 2 Joint Undertaking • AIR LIQUIDE • Copenhagen Hydrogen Network (CHN) • Hydrogenics • Centrica • HYDROGEN VALLEY (FORMER CEMTEC) • LUDWIG-BÖLKOW-SYSTEMTECHNIK (LBST)

Table A-3: Case study projects with their stakeholders list and electrolyser type.

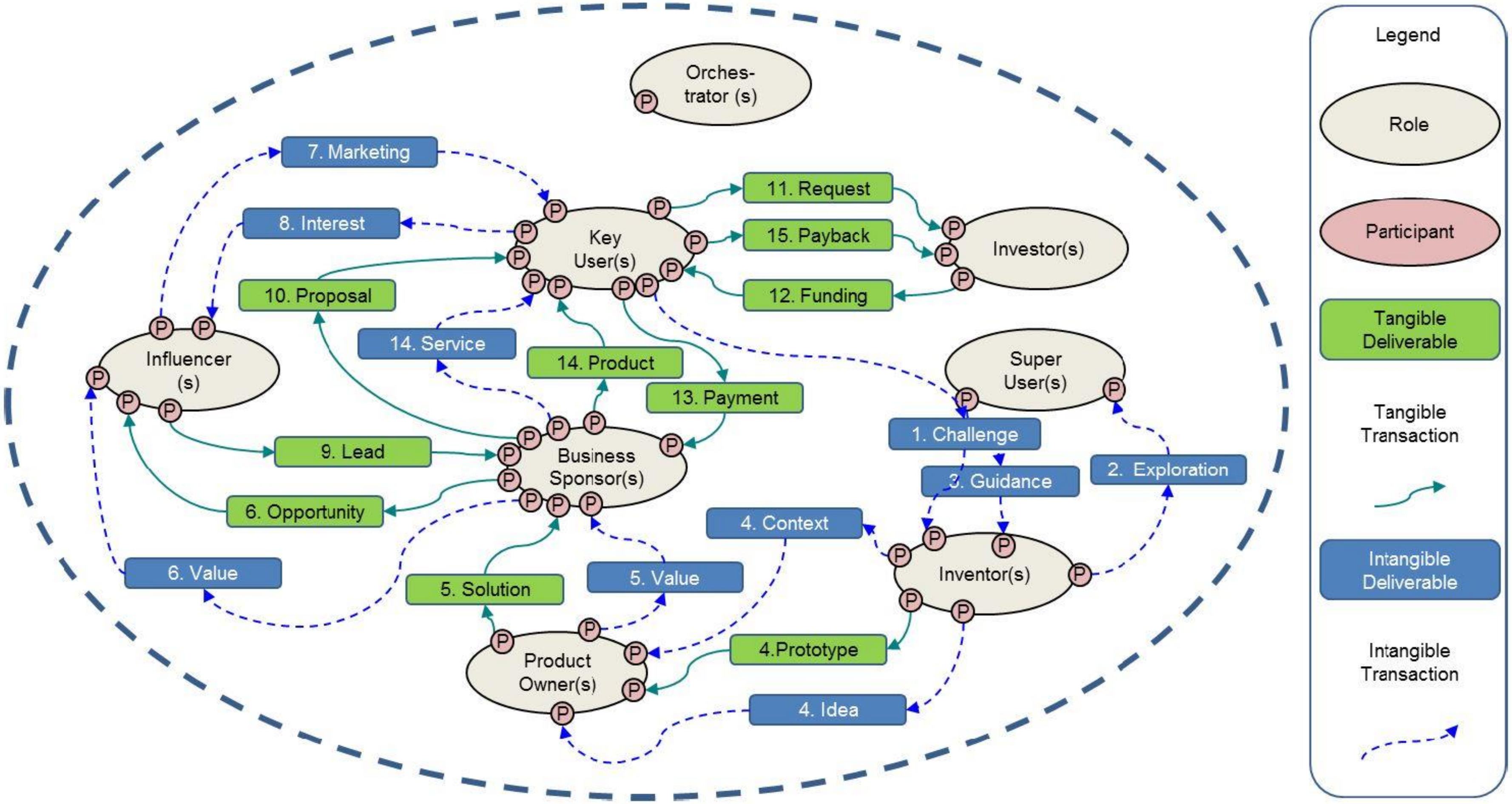
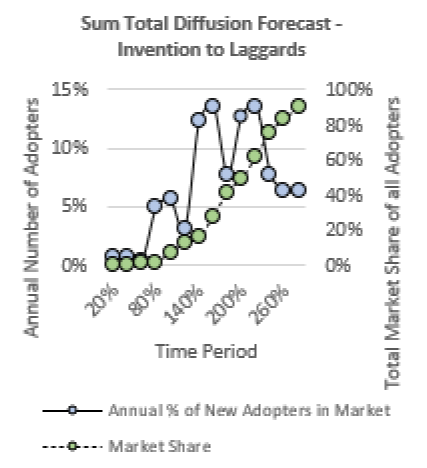
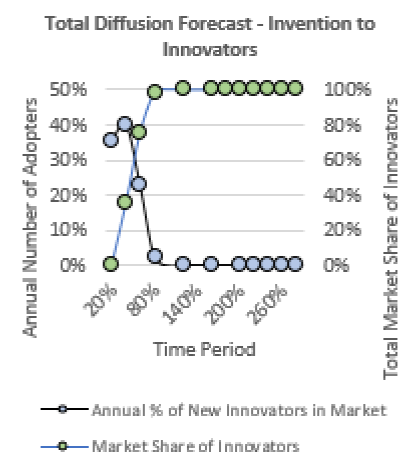


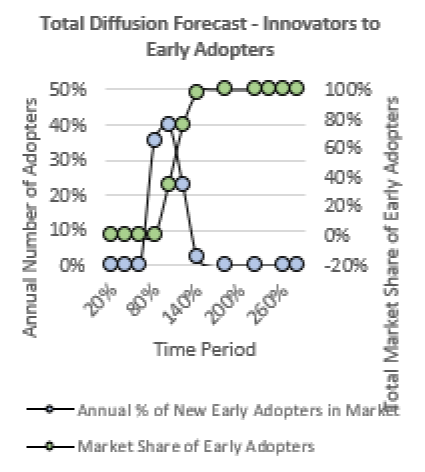
Figure A-1 – Value Network of Innovation Diffusion to Late Adopters [Schwabe et al. 2020]

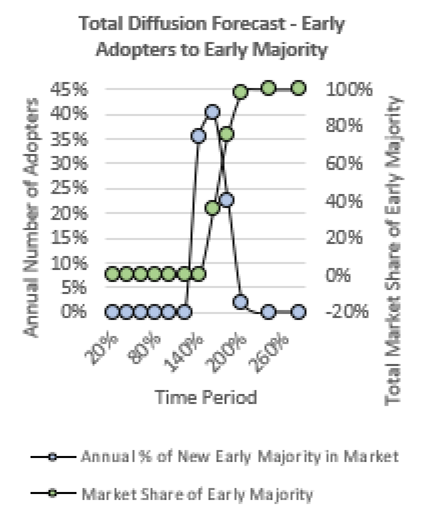
Innovation Diffusion Litmus Test - Detail Diffusion Forecast

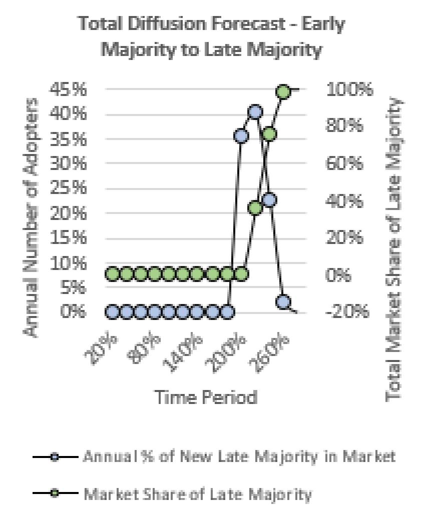
(Note: Blue cells can be manipulated by the user)

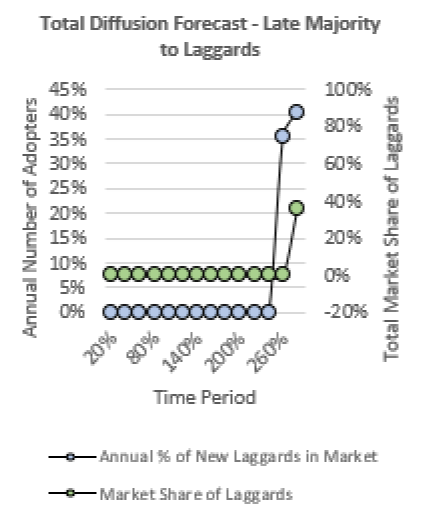


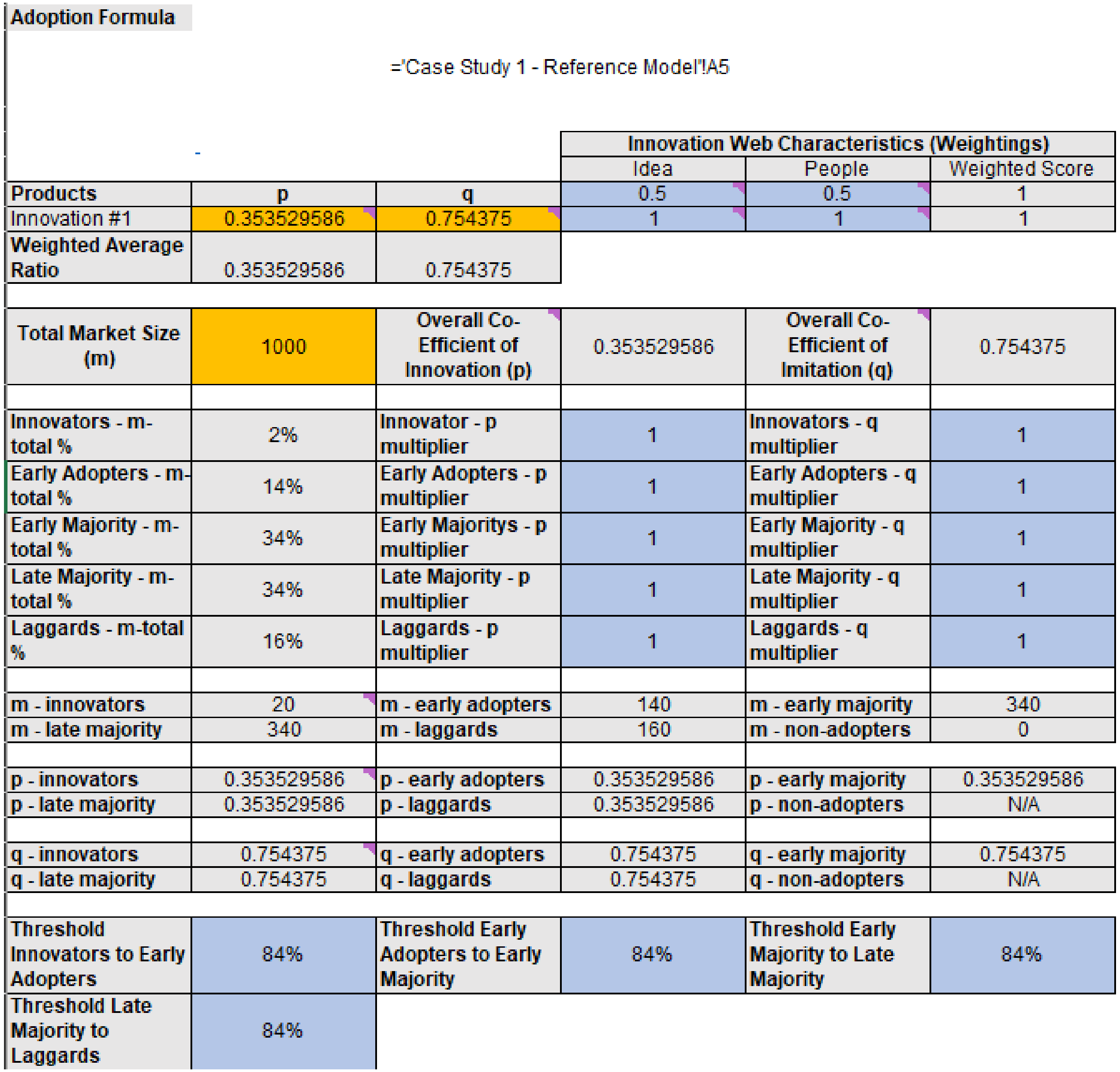








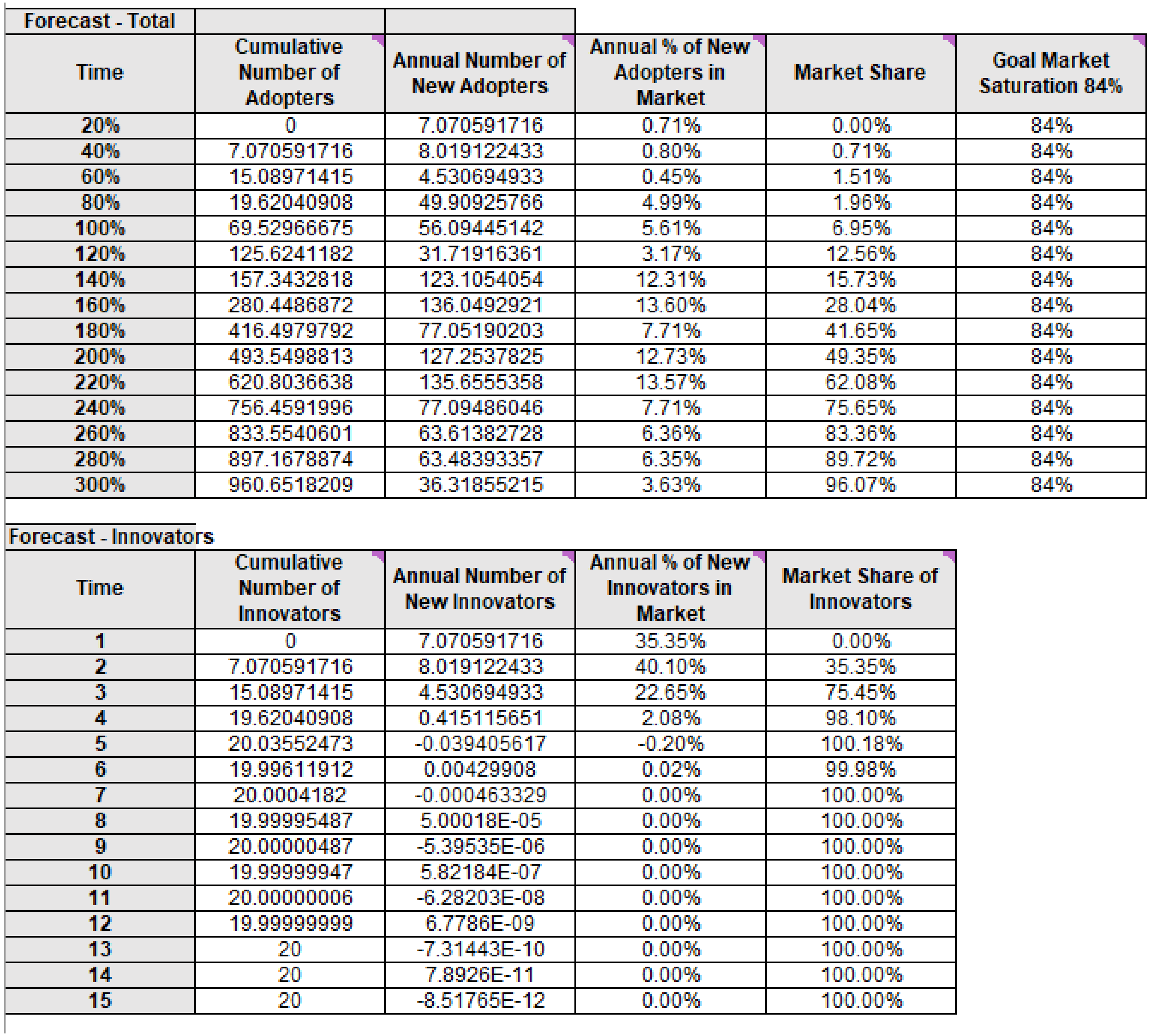




Adoption Formula

='Case Study 1 - Reference Model'!A5

			Innovation Web Characteristics (Weightings)		
			Idea	People	Weighted Score
Products	p	q	0.5	0.5	1
Innovation #1	0.353529586	0.754375	1	1	1
Weighted Average Ratio	0.353529586	0.754375			
Total Market Size (m)	1000	**Overall Co-Efficient of Innovation (p)**	0.353529586	**Overall Co-Efficient of Imitation (q)**	0.754375
Innovators - m-total %	2%	**Innovator - p multiplier**	1	**Innovators - q multiplier**	1
Early Adopters - m-total %	14%	**Early Adopters - p multiplier**	1	**Early Adopters - q multiplier**	1
Early Majority - m-total %	34%	**Early Majoritys - p multiplier**	1	**Early Majority - q multiplier**	1
Late Majority - m-total %	34%	**Late Majority - p multiplier**	1	**Late Majority - q multiplier**	1
Laggards - m-total %	16%	**Laggards - p multiplier**	1	**Laggards - q multiplier**	1
m - innovators	20	**m - early adopters**	140	**m - early majority**	340
m - late majority	340	**m - laggards**	160	**m - non-adopters**	0
p - innovators	0.353529586	**p - early adopters**	0.353529586	**p - early majority**	0.353529586
p - late majority	0.353529586	**p - laggards**	0.353529586	**p - non-adopters**	N/A
q - innovators	0.754375	**q - early adopters**	0.754375	**q - early majority**	0.754375
q - late majority	0.754375	**q - laggards**	0.754375	**q - non-adopters**	N/A
Threshold Innovators to Early Adopters	84%	**Threshold Early Adopters to Early Majority**	84%	**Threshold Early Majority to Late Majority**	84%
Threshold Late Majority to Laggards	84%				



Forecast - Total

Time	Cumulative Number of Adopters	Annual Number of New Adopters	Annual % of New Adopters in Market	Market Share	Goal Market Saturation 84%
20%	0	7.070591716	0.71%	0.00%	84%
40%	7.070591716	8.019122433	0.80%	0.71%	84%
60%	15.08971415	4.530694933	0.45%	1.51%	84%
80%	19.62040908	49.90925766	4.99%	1.96%	84%
100%	69.52966675	56.09445142	5.61%	6.95%	84%
120%	125.6241182	31.71916361	3.17%	12.56%	84%
140%	157.3432818	123.1054054	12.31%	15.73%	84%
160%	280.4486872	136.0492921	13.60%	28.04%	84%
180%	416.4979792	77.05190203	7.71%	41.65%	84%
200%	493.5498813	127.2537825	12.73%	49.35%	84%
220%	620.8036638	135.6555358	13.57%	62.08%	84%
240%	756.4591996	77.09486046	7.71%	75.65%	84%
260%	833.5540601	63.61382728	6.36%	83.36%	84%
280%	897.1678874	63.48393357	6.35%	89.72%	84%
300%	960.6518209	36.31855215	3.63%	96.07%	84%

Forecast - Innovators

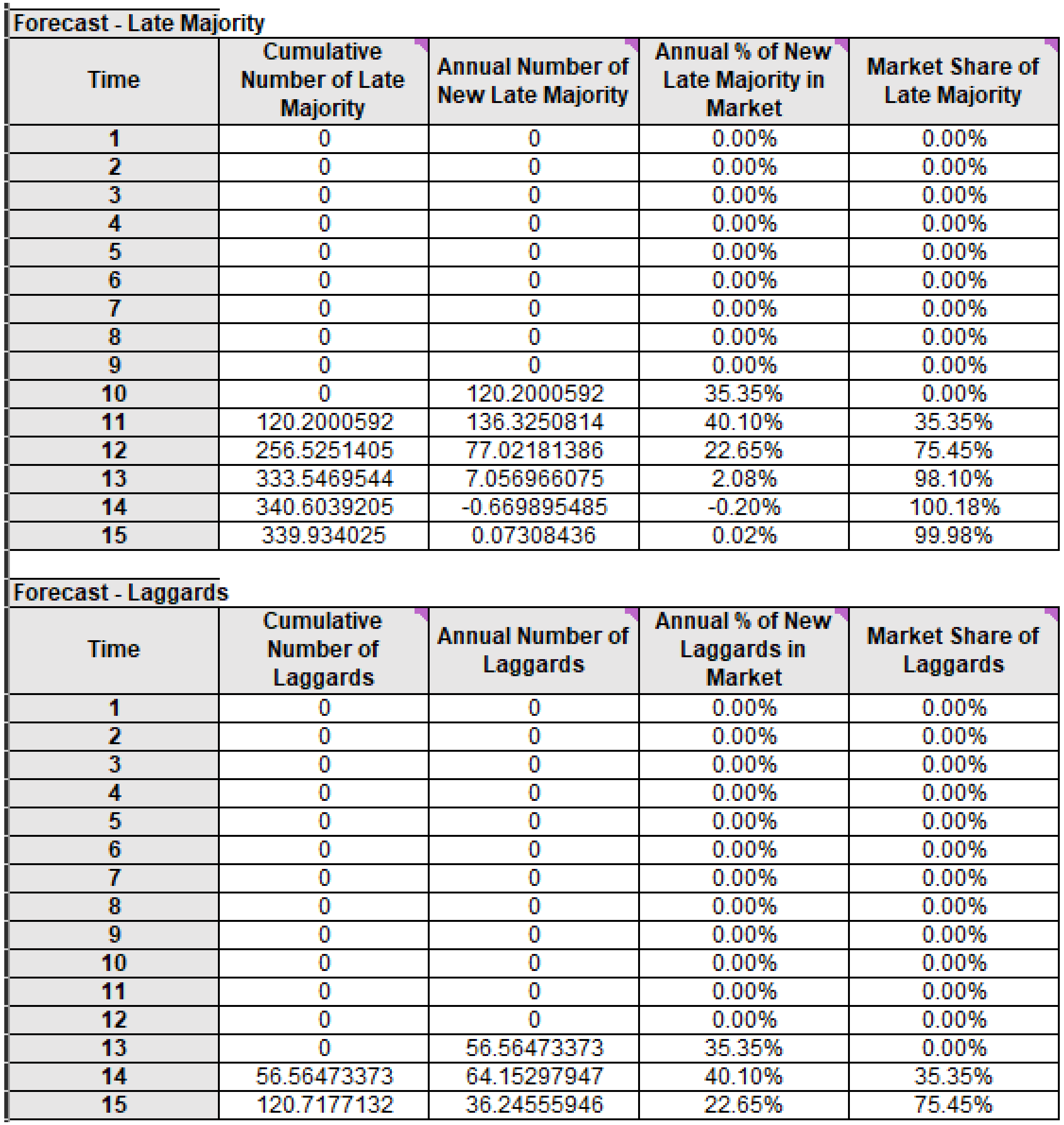
Time	Cumulative Number of Innovators	Annual Number of New Innovators	Annual % of New Innovators in Market	Market Share of Innovators
1	0	7.070591716	35.35%	0.00%
2	7.070591716	8.019122433	40.10%	35.35%
3	15.08971415	4.530694933	22.65%	75.45%
4	19.62040908	0.415115651	2.08%	98.10%
5	20.03552473	-0.039405617	-0.20%	100.18%
6	19.99611912	0.00429908	0.02%	99.98%
7	20.0004182	-0.000463329	0.00%	100.00%
8	19.99995487	5.00018E-05	0.00%	100.00%
9	20.00000487	-5.39535E-06	0.00%	100.00%
10	19.99999947	5.82184E-07	0.00%	100.00%
11	20.00000006	-6.28203E-08	0.00%	100.00%
12	19.99999999	6.7786E-09	0.00%	100.00%
13	20	-7.31443E-10	0.00%	100.00%
14	20	7.8926E-11	0.00%	100.00%
15	20	-8.51765E-12	0.00%	100.00%

Forecast - Early Adopters

Time	Cumulative Number of Early Adopters	Annual Number of New Early Adopters	Annual % of New Early Adopters in Market	Market Share of Early Adopters
1	0	0	0.00%	0.00%
2	0	0	0.00%	0.00%
3	0	0	0.00%	0.00%
4	0	49.49414201	35.35%	0.00%
5	49.49414201	56.13385703	40.10%	35.35%
6	105.627999	31.71486453	22.65%	75.45%
7	137.3428636	2.90580956	2.08%	98.10%
8	140.2486731	-0.275839318	-0.20%	100.18%
9	139.9728338	0.03009356	0.02%	99.98%
10	140.0029274	-0.003243303	0.00%	100.00%
11	139.9996841	0.000350013	0.00%	100.00%
12	140.0000341	-3.77675E-05	0.00%	100.00%
13	139.9999963	4.07529E-06	0.00%	100.00%
14	140.0000004	-4.39742E-07	0.00%	100.00%
15	140	4.74502E-08	0.00%	100.00%

Forecast - Early Majority

Time	Cumulative Number of Early Majority	Annual Number of New Early Majority	Annual % of New Early Majority in Market	Market Share of Early Majority
1	0	0	0.00%	0.00%
2	0	0	0.00%	0.00%
3	0	0	0.00%	0.00%
4	0	0	0.00%	0.00%
5	0	0	0.00%	0.00%
6	0	0	0.00%	0.00%
7	0	120.2000592	35.35%	0.00%
8	120.2000592	136.3250814	40.10%	35.35%
9	256.5251405	77.02181386	22.65%	75.45%
10	333.5469544	7.056966075	2.08%	98.10%
11	340.6039205	-0.669895485	-0.20%	100.18%
12	339.934025	0.07308436	0.02%	99.98%
13	340.0071093	-0.007876592	0.00%	100.00%
14	339.9992328	0.000850031	0.00%	100.00%
15	340.0000828	-9.1721E-05	0.00%	100.00%



Forecast - Late Majority

Time	Cumulative Number of Late Majority	Annual Number of New Late Majority	Annual % of New Late Majority in Market	Market Share of Late Majority
1	0	0	0.00%	0.00%
2	0	0	0.00%	0.00%
3	0	0	0.00%	0.00%
4	0	0	0.00%	0.00%
5	0	0	0.00%	0.00%
6	0	0	0.00%	0.00%
7	0	0	0.00%	0.00%
8	0	0	0.00%	0.00%
9	0	0	0.00%	0.00%
10	0	120.2000592	35.35%	0.00%
11	120.2000592	136.3250814	40.10%	35.35%
12	256.5251405	77.02181386	22.65%	75.45%
13	333.5469544	7.056966075	2.08%	98.10%
14	340.6039205	-0.669895485	-0.20%	100.18%
15	339.934025	0.07308436	0.02%	99.98%

Forecast - Laggards

Time	Cumulative Number of Laggards	Annual Number of Laggards	Annual % of New Laggards in Market	Market Share of Laggards
1	0	0	0.00%	0.00%
2	0	0	0.00%	0.00%
3	0	0	0.00%	0.00%
4	0	0	0.00%	0.00%
5	0	0	0.00%	0.00%
6	0	0	0.00%	0.00%
7	0	0	0.00%	0.00%
8	0	0	0.00%	0.00%
9	0	0	0.00%	0.00%
10	0	0	0.00%	0.00%
11	0	0	0.00%	0.00%
12	0	0	0.00%	0.00%
13	0	56.56473373	35.35%	0.00%
14	56.56473373	64.15297947	40.10%	35.35%
15	120.7177132	36.24555946	22.65%	75.45%

Innovation Diffusion Litmus Test

Idea for Diffusion

On a Scale of 0 (Not at all) to 5 (Very High) estimate the degree to which the idea…

Attributes of the Idea	Degree of Innovativeness	Technical Readiness Level	Budget and Resources	Number of Competitors	Degree of Complexity	Compatibility with Existing Ways of Work	Ease of Understanding	Ease of Use	Ease of Adaptation	Ease of Trialing	Oberservability of Impact	Urgency of Need	Degree of Certification (Legal / Policy Alignment)
Is your idea ready to diffuse rapidly to late adopters?	4	5	3	2	3	4	3	3	3	3	5	4	3
How confident are you in your above assessment of the idea?	2	5	4	2	3	4	2	4	3	4	4	4	3
											3.461538	3.384615	0.468639

Roles and Participants

On a Scale of 0 (Not at all) to 5 (Very High) estimate the degree to which the individual...

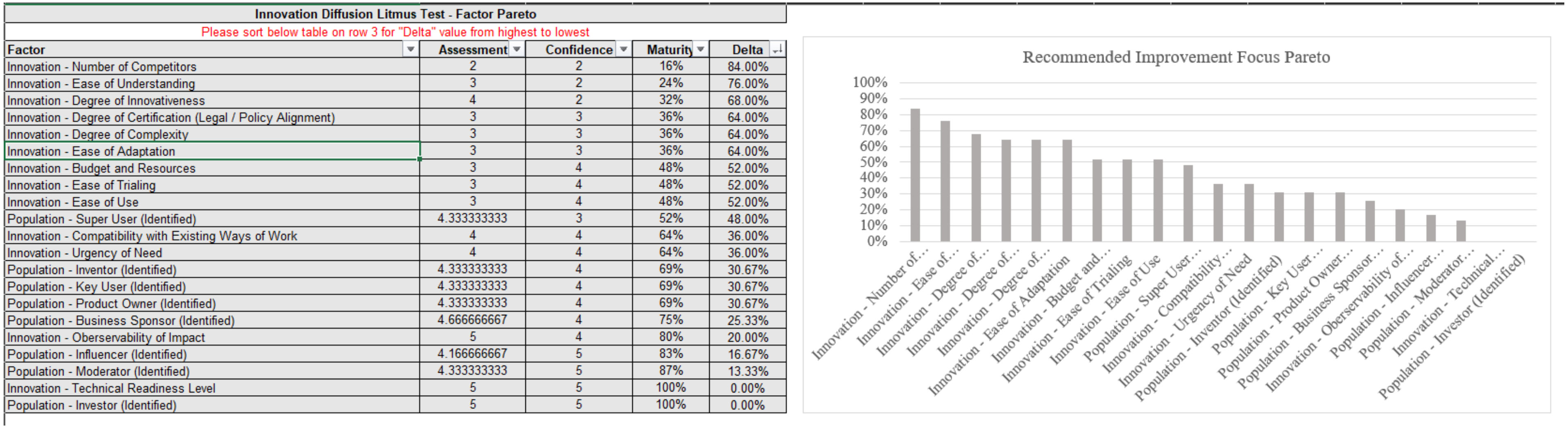
Roles and Participants	Role Type	Name of Individual (Mandatory)	Considers the Diffusion as Urgent	Places Priority on the Diffusion	Is Motivated	Is Domain Competent	Is Collaborative	Engages Voluntarily	Maturity Score	How Confident are you in the Accuracy of your Assessment?
Who is the **KEY USER?**	Core	MPREIS	4	4	5	5	4	4	4.3	4
Who is the **INVENTOR?**	Core	Aragon Hydrogen Foundation, Sunfire Renewables	5	4	4	4	5	4	4.3	4
Who is the **PRODUCT OWNER?**	Core	MPREIS, INYCOM, FEN	4	5	4	5	4	4	4.3	4
Who is the **BUSINESS SPONSOR**?	Core	FCH JU, MPREIS, FEN, INYCOM	5	5	4	4	5	5	4.7	4
Who is the **INVESTOR?**	Accelerator	FCH JU, ARGON	5	5	5	5	5	5	5.0	5
Who is the **INFLUENCER?**	Accelerator	ALL	4	5	4	3	4	5	4.2	5
Who is **SUPER USER**?	Accelerator	Aragon Hydrogen Foundation, FEN	4	4	3	5	5	5	4.3	3
Who is the **MODERATOR / ORCHESTRATOR?**	Accelerator	Diadikasia, FCH JU	4	4	4	4	5	5	4.3	5
		Avg.	4.4	4.5	4.1	4.4	4.6	4.6	4.4	4.3

3.8 0.76346

Transfer formulas / values to forecasting	0.8875	0.85	0.75438
		Maturity Level	0.35353
		Binary scc	0

Ecosystem Mer	**Roles**							
	Orchestrator	**Key User**	**Investor**	**Inventor**	**Product Owner**	**Business Sponsor**	**nfluence**	**Entity Specific Role:**
MPREIS		x			x	x	x	Buying electricity from TIWAG, business plan for hydrogen, buying hydrogen
Hydrogen Foundation				x			x	technicalities and testing of project
INYCOM			x		x	x	x	coverage of H2 demand, participation in power purchase
Diadikasia	x						x	oversees the project
Fen Systems					x	x	x	project development
nfire Renewables				x			x	technicalities and
FCH EU	x		x			x		funding
Total	2	1	2	2	3	4	6	

https://www.demo4grid.eu/



Innovation Diffusion Litmus Test - Factor Pareto

Please sort below table on row 3 for "Delta" value from highest to lowest

Factor	Assessment	Confidence	Maturity	Delta
Innovation - Number of Competitors	2	2	16%	84.00%
Innovation - Ease of Understanding	3	2	24%	76.00%
Innovation - Degree of Innovativeness	4	2	32%	68.00%
Innovation - Degree of Certification (Legal / Policy Alignment)	3	3	36%	64.00%
Innovation - Degree of Complexity	3	3	36%	64.00%
Innovation - Ease of Adaptation	3	3	36%	64.00%
Innovation - Budget and Resources	3	4	48%	52.00%
Innovation - Ease of Trialing	3	4	48%	52.00%
Innovation - Ease of Use	3	4	48%	52.00%
Population - Super User (Identified)	4.333333333	3	52%	48.00%
Innovation - Compatibility with Existing Ways of Work	4	4	64%	36.00%
Innovation - Urgency of Need	4	4	64%	36.00%
Population - Inventor (Identified)	4.333333333	4	69%	30.67%
Population - Key User (Identified)	4.333333333	4	69%	30.67%
Population - Product Owner (Identified)	4.333333333	4	69%	30.67%
Population - Business Sponsor (Identified)	4.666666667	4	75%	25.33%
Innovation - Oberservability of Impact	5	4	80%	20.00%
Population - Influencer (Identified)	4.166666667	5	83%	16.67%
Population - Moderator (Identified)	4.333333333	5	87%	13.33%
Innovation - Technical Readiness Level	5	5	100%	0.00%
Population - Investor (Identified)	5	5	100%	0.00%

Figure A-2 – Sample case (DEMO4GRID)