Speed of Innovation Diffusion of Water Electrolysis Technologies

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Abstract— **By 2050, the European Green Deal will have "net zero" emissions of greenhouse gases. Many people consider green hydrogen, which is produced by water electrolysis, to be essential for our energy transition to a low carbon future. However, it is more expensive than its rivals in the fossil fuel industry because to a lack of infrastructure, investments, and a convoluted supply chain. The green hydrogen ecosystem needs information on how to strengthen the innovation ecosystem to identify channels for quicker diffusion because more research is being devoted to creating the technology itself. The difficulty of implementing cutting-edge electrolysis technology throughout the green hydrogen supply chain is the main topic of this dissertation. To determine how quickly these innovations will attain market saturation, sixteen case studies were looked at utilising the innovation ecosystem principles and a maturity model. Analyses of important factors that influence diffusion speed of innovations are also conducted. Following validation interviews, results are compared to 12 case studies on the green hydrogen supply chain to give a comprehensive view of the green hydrogen ecosystem. The thesis is broken down into a literature review, case studies on water electrolysis that are instructive, analysis and development of results using the maturity model, and comparison of results from case studies on the green hydrogen supply chain.**

1. Introduction

We are already seeing the repercussions of climate change and addressing them now presents us with uncharted problems. Aiming to achieve carbon neutrality, major international powers are mobilising their finances and resources to combat climate change. The European Union is contributing to the achievement of its long-term objective of becoming carbon neutral by 2050 by implementing an ambitious strategy to reduce greenhouse gases by 55% by 2030.[1]

Our energy shift depends on green hydrogen, or hydrogen produced using renewable energy. Its significance in climate neutrality is asserted by its capacity to substitute hydrogen derived from fossil fuels for industrial uses, revolutionise the transportation industry, which is heavily dependent on emissions, or serve as an energy carrier for renewable sources. Water electrolysis, which uses renewable electricity to split water into oxygen and hydrogen, is seen as essential in any decarbonized energy sector because it creates hydrogen with no carbon emissions. However, green hydrogen is now two to three times more expensive than its fossil fuel rivals because to a lack of infrastructure, investments, and a convoluted supply chain.

Despite the fact that the sector has advanced significantly thanks to strong international regulations supporting green hydrogen, various obstacles prevent its widespread use. Since the hydrogen economy is still in its early stages of development, substantial research and analysis are needed to identify the variables that will help this technology spread more quickly and achieve its intended goals.

The innovation spread of water electrolysis technologies is the main topic of this research. The main objective of this work is to identify crucial criteria for speeding diffusion by estimating the rate at which these technologies will attain market saturation using a maturity model with 16 case studies and comparing it with 12 green hydrogen supply chain case studies.[2] In order to provide a comprehensive analysis and make recommendations for future projects to achieve a higher diffusion rate, this study is divided into finding instructive water electrolysis case studies, analysing and developing outcomes using the maturity model, and comparing with existing outcomes from green hydrogen supply chain case studies.

2. Literature review and Problem definition

2.1. Green hydrogen and climate change

Climate change is an issue already, and not in the future. The consequences of climate change are felt worldwide. Decarbonization is becoming more and more necessary, thus prompt action is required. In industries that are difficult to electrify, such as industry (feedstock to the petrochemical and fertiliser sectors), heavy transportation, heating, and energy storage, green hydrogen is hailed as playing a vital role.[1] Low carbon hydrogen produced using renewable electricity or low carbon power is known as green hydrogen or hydrogen produced from renewable sources. The most established method of creating green hydrogen is water electrolysis, which uses renewable electricity in an electrolyzer.[3] 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 (H_2O) into oxygen (O_2) and hydrogen (H_2) by applying a direct electric current.[3]

2.2. Diffusion of innovations

Innovations, which are defined as "a sequence of significant improvements in company operations that will increase firm performance," are crucial for any progressive environment.[4] The Diffusion of Innovation hypothesis, created by E.M. Rogers in 1962, explains how a concept or a product spread within a social system.[5] Adoption of a concept is not instantaneous; rather, it is a process, and some people are more open to innovation than others. Adoption of a concept depends on its impression as creative. Understanding that target segment's characteristics and needs is essential to implementing innovation for that group. This concept is based on the premise that products are "reinvented" or evolved to better match their target audiences, with an emphasis on the innovation of the product or idea rather than a change in an individual. The acceptance of innovations is influenced by five main elements, according to the Diffusion of Innovation hypothesis. These include compatibility, simplicity, trialability, and observability as relative advantages. Even if these are important aspects, other elements including the social system's structure, channels of communication, and decisions on innovation should also be taken into account when evaluating adoption.[5] A successful diffusion also takes time into account, with time playing a critical role in determining the speed of innovation diffusion and whether or not to embrace it. In accordance with their level of adoption resistance, the theory also suggests several population segments. Based on their propensity to adopt or reject innovations, the general public is divided into innovators, early adopters, early majority, late majority, and laggards.[5] Each group has a distinct "personality," with communication style, socioeconomic standing, and personality traits having the greatest bearing. To be adopted, an innovation must fulfil the needs of the target audience. Our analysis of water electrolysis systems is based on this theory.

Although research on the diffusion of hydrogen systems has been conducted in the past, the majority of that research has concentrated on hydrogen fuel cells for use in automobiles. In an investigation by Trencher, impediments to the adoption of fuel cell electric cars (FCEV) in California, USA, were discovered through interviews.[6] The study demonstrates the importance of stakeholder involvement and the necessity of methods including regulation, market and consumer incentives, and public-private collaboration. Another study by Hacking and Pearson uses interviews and event history analysis to examine fuel cell innovation in the UK.[7] The importance of legislation for the widespread deployment of fuel cell electric vehicles is one topic that both studies emphasise (FCEV).

With the EU's energy roadmaps becoming more inclusive, it is safe to state that green hydrogen plays a crucial part in the majority of its plans for the energy transition. Because the importance of green hydrogen for the energy transition is increasing quickly, more attention needs to be paid to strengthening the innovation ecosystem in order to identify new avenues for faster diffusion.

2.3. Problem statement

Overcoming the cost barrier is the main obstacle to creating an effective hydrogen infrastructure. Green hydrogen is currently an expensive alternative due to its high production and shipping costs as well as the growing demand for renewable energy. Even fuels based on hydrogen, such synthetic aviation fuels, are thought to cost eight times as much as traditional fuels. The development of specialised infrastructure and the cost problem go hand in hand. There have been advancements made in technology to enable more infrastructure development, such as mixing hydrogen into natural gas pipelines, however there is still a significant deficiency when compared to natural gas pipelines. Another problem is the 30- 35% energy loss that occurs during electrolysis.[8] Lack of goals and incentives also hinder the development of this technology, hence reducing downstream demand.

However, the majority of the difficulties raised are a result of green hydrogen's fast growth in popularity worldwide. It is conceivable to read the requirement to understand what can be done in the EU as a comprehensive strategy to influence a smooth, energetic transition in the numerous downstream uses to the defined aims in such a short period of time. The EU's objectives for reaching climate neutrality by 2050 are startlingly obvious, as are the investments made in knowledge, money, materials, and resources, with a planned strategy to develop hydrogen economies toward widespread use and adoption. With a long road ahead in terms of infrastructure, cost savings, supply and demand factors, and scientific and technological advancements, the hydrogen economy is still in its early stages. With the EU's energy roadmaps becoming more inclusive, it is safe to state that green hydrogen plays a crucial part in the majority of its plans for the energy transition. Because the importance of green hydrogen for the energy transition is increasing quickly, there needs to be a greater emphasis on enhancing the innovation ecosystem in order to identify new avenues for faster diffusion. It is important to comprehend how much each member affects the next level and to evaluate the major diffusion uncertainty elements in the mentioned innovations.[9]

The dissertation will be focused on understanding how the technology has evolved from an innovation standpoint over time, in particular how it can find success in the EU and meet the goals set for hydrogen technologies. To do this, it will evaluate various cases of water electrolysis using the maturity model to understand how quickly diffusion and adoption happen, what factors influence them, and what steps should be taken to facilitate the deployment. In order to identify the missing components required for the overall acceleration of these technologies, a holistic perspective of the complete green hydrogen ecosystem will be provided by the integrated assessment and case studies of the green hydrogen supply chain.

3. RESEARCH DESIGN AND METHODOLOGY

3.1. RESEARCH DESIGN

The maturity model based on the Diffusion of Innovation theory is quantitatively modelled using the Bass diffusion theory.[5], [10] This approach, which is frequently used to assess how technical ideas spread, makes the assumption that adoption is the result of both innovation and imitation. Positive word of mouth encourages creativity through influences and imitation.[11] 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.[12] 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.[12]

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

The equation represents the growth of adopters N throughout time t. The equation can be broken down to two sections, the first one$\left(p + \left(\frac{q}{M}\right) \times N\right)$,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.[12]

Through measure the rate of dissemination of technical innovation from the ideation stage to its market saturation, a mathematical technique called the Innovation Diffusion Litmus Test is used. The test is built on the Bass diffusion theory and is based on research on value networks and the spread of innovations.[10] The assessment uses a maturity model built on Microsoft Excel and a collection of questions to determine the level of maturity of an innovation ecosystem. The responsibilities that various ecosystem participants play as they trade concrete and intangible deliverables are crucial test components. The aim put out in the Litmus test is to spread the invention as rapidly as feasible by thinking of the innovation web/ecosystem as a living entity.[2] When 84% of the market, or the late majority, has adopted an innovation, it is said to have reached market saturation and can continue to benefit its stakeholders.[12]

The Litmus test is a collection of semi-structured interviews that evaluates the variables driving diffusion while taking into account the level of commitment from the various roles and ecosystem stakeholders. The Likert scale is used to rank the factors, with 0 representing not at all and 5 representing extremely high. The criteria taken into account for innovation include degree of inventiveness, technological readiness level, budget and resources, number of competitors, degree of complexity, compatibility with existing technologies, ease of understanding, simplicity of use, and ease of adoption.[12] Population-level aspects take into account how people behave in the innovation network, paying particular attention to urgency, priority, motivation, expertise, collaboration, and whether or not people are actively participating. By incorporating a user-provided confidence score during evaluation, the test also takes subjectivity into account. The major outcomes of the study approach in evaluating the innovation and population's maturity level as well as the overall maturity of the project are determined if adoption in each stage occurs after 84% of the stage's population has adopted it.

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.[12] 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.[12] The amount of new adopters over time (sa(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:[12]

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

$$p = m \times s_r(t) \quad (3)$$

$$q = p \times s_r(t) \quad (4)$$

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. [2]

Finding pertinent case studies is a critical component of data retrieval since it helps us evaluate how quickly these examples are being adopted and how mature they are overall. The cases being examined involve useful ideas that are at various phases of development, from ideation to full commercialization. The technology utilised to manufacture hydrogen and the intended application of the hydrogen are what define and support each scenario. The cases were selected from the database of IEA hydrogen initiatives and the list of funded projects maintained by the Fuel Cells and Joint Hydrogen Undertaking (FCH JU).[13] The cases were taken into account with the practicality of locating relevant information to make informed decisions. Only instances with sufficient details on the project's scope, size, electrolyser type, stakeholders and their contributions, project timeline, and results were taken into consideration. Establishing and identifying the ecosystem and stakeholder present to implement these applications is a crucial element. These data sets are then further organised and specified to offer the necessary details regarding the hydrogen production technology applied in the project as well as the state of the ecosystem of project partners (businesses, research institutions, and governmental bodies). The case studies under consideration along with web URL for this dissertation are in the Table 1.

TABLE I

No.	Case Study	URL
1	The Anione Project (2020)	https://anione.eu/
2	The Channel Project (2020)	https://www.sintef.no/projectweb/channel-fch/
3	DEMOGRID (2017)	https://www.demo4grid.eu/
4	ELY4OFF (2016)	http://ely4off.eu
5	Haeolus Project (2018)	https://www.haeolus.eu/
6	H2FUTURE (2017)	https://www.h2future-project.eu/technology
7	Glomfjord Hydrogen AS (2020)	https://www.glomfjordhydrogen.no/ac/glomfjord-hydrogen-as
8	EFarm (2019)	https://www.h2v.eu/analysis/best-practices/efarm
9	HyDeploy (2017)	https://hydeploy.co.uk
10	Methycentre (2019)	https://methycentre.eu/
11	SALCOS (2015)	https://salcos.salzgitter-ag.com/en/salcos.html#c141547
12	HyBridge (2023)	https://www.hybridge.net/index-2.html
13	GrInHy 2.0 (2019)	https://www.green-industrial-hydrogen.com/
14	GAMER (2018)	https://www.sintef.no/projectweb/gamer/
15	PrometH2 (2020)	http://promet-h2.eu/
16	HyBalance (2015)	https://hybalance.eu/

A preliminary review of more than 100 projects led to the selection of 16 case studies as the minimal number of combinations of the four casual factors to be taken into account for the analysis.[14] Understanding the product and the technology underlying it, locating the ecosystem's members, and giving them jobs that were sufficiently relevant were all part of the selection process. In order to gather data for the maturity scores and diffusion forecast, the case studies were also exposed to a questionnaire about the project's goals and the roles played by the ecosystem's participants. The case study collection gains some variation with projects at different stages of development and with diverse timelines. In order to cover a range, the instances were chosen using a variety of water electrolysis technologies and final applications for the green hydrogen they produced. Due to the EU's active development of a hydrogen economy and the fact that knowing the diffusion hurdles in this region would enable the provision of qualitative solutions, all instances were chosen to be located on the European continent.

3.2 Dissertation Methodology

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

- 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).
- Model development – Customize and adapt the maturity model with the questionnaires in the project and run the Litmus Test for each Case Study.
- Model Testing and Validation – Validation interviews of the results with experts in the area to assess the robustness of the model and outputs. Additionally, test variations of the inputs to understand which variables have more influence in the speed of diffusion and what changes should be made. In this sense, two experts in the field of hydrogen and innovation and strategy building were interviewed.

  The interviewees were previously given a questionnaire describing the general results, 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.
- 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.[2]

4. RESULTS

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. The terms a, b, c, d, e and f refer to case study from Table 1, idea maturity, population maturity, overall maturity, scheduled forecast and assessment confidence respectively with case study 0 being the reference model.

TABLE II

a	b (%)	c (%)	d (%)	e (%)	f (%)
0	100	100	100	100	100
1	62	35	52	300	63
2	51	53	52	280	76
3	48	76	59	280	76
4	48	76	59	280	72
5	52	73	60	280	76
6	53	67	59	280	73
7	49	34	44	300	61
8	43	50	46	300	60
9	44	67	53	280	70
10	46	60	52	280	67
11	46	60	52	300	67
12	49	49	49	300	64
13	50	72	59	280	73
14	51	70	59	280	73
15	53	77	63	260	77
16	52	80	63	200	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. 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) as shown in Fig. 1.

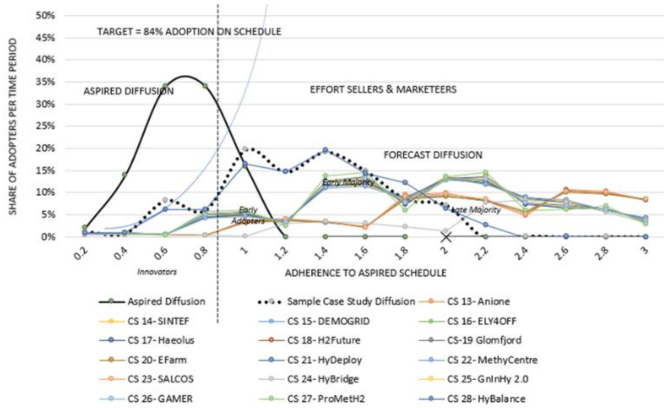

Fig. 1 Share of Adopters per Time Schedule for the Reference Model and the 16 Case Studies.

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. 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.

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. Fig. 2 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.

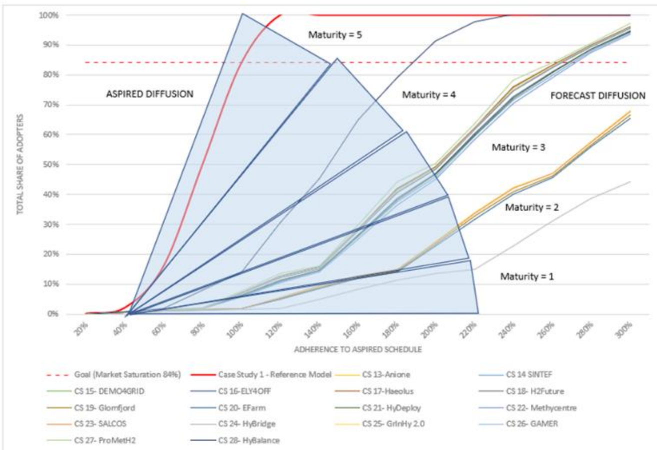

Fig. 2 Cumulative Share of Adopters for the Reference Model and the 16 Case Studies.

4.1 WATER ELECTROLYSIS CASE STUDIES

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. 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. 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.

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.[14] 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.[15] 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.[16]

4.2 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.[2] 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. 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.[2]

4.3 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.

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.[17] The Commission has also set up Hydrogen Public Funding Compass to guide stakeholders to find public funding sources for their hydrogen projects.[18]

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.[19]

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.

TABLE III

	Water Electrolysis	**Green Hydrogen Supply Chain**
Factors with the highest maturity	Population -Moderator	Population- Investor
	Innovation- Urgency of need	Innovation- Number of competitors
	Population- Investor	Innovation- Degree of Innovativeness
Factors with the lowest maturity	Innovation- Number of competitors	Innovation- Degree of certification
	Innovation- Degree of certification	Innovation- Degree of complexity
	Innovation- Ease of trialling	Innovation- Compatible with existing ways of work

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 III shows the top and bottom three maturity scores of factors affecting diffusion of both case studies.

4.4. Result validation

Field specialists were then asked to validate the results that had previously been given. In this regard, interviews with two experts, one in the field of hydrogen and the other in innovations and strategy development, were conducted. In addition, the factors influencing the diffusion more negatively were validated as pertinent conclusions of the influences on the diffusion of green hydrogen to achieve market saturation, according to the validation interviews. The forecast diffusion patterns represent a robust view of the project's history with additional specific and personal experience recommendations.

5. Conclusion

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 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

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.

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6. References

[1] IEA, 'The Future of Hydrogen', 2019.

[2] L. Correia, O. Schwabe, and N. Almeida, 'Speed of Innovation Diffusion in Green Hydrogen Technologies', in *15th WCEAM Proceedings*, Cham, 2022, pp. 101–111. doi: 10.1007/978-3-030-96794-9_10.

[3] C. Azzaro-Pantel, 'Preface Hydrogen Supply Chains: Design, Deployment, and Operation', in *Hydrogen Supply Chains*, C. Azzaro-Pantel, Ed. Academic Press, 2018, pp. xix–xxiv. doi: 10.1016/B978-0-12-811197-0.10000-4.

[4] H. Tohidi and M. M. Jabbari, 'The important of Innovation and its Crucial Role in Growth, Survival and Success of Organizations', *Procedia Technol.*, vol. 1, pp. 535–538, Jan. 2012, doi: 10.1016/j.protcy.2012.02.116.

[5] E. M. Rogers, *Diffusion of innovations*, 3rd ed. New York : London: Free Press ; Collier Macmillan, 1983.

[6] G. Trencher, 'Strategies to accelerate the production and diffusion of fuel cell electric vehicles: Experiences from California', *Energy Rep.*, vol. 6, pp. 2503–2519, Nov. 2020, doi: 10.1016/j.egyr.2020.09.008.

[7] N. Hacking, P. Pearson, and M. Eames, 'Mapping innovation and diffusion of hydrogen fuel cell technologies: Evidence from the UK's hydrogen fuel cell technological innovation system, 1954–2012', *Int. J. Hydrog. Energy*, 2019, doi: 10.1016/j.ijhydene.2019.09.137.

[8] IRENA, 'Green hydrogen: A guide to policy making', 2020.

[9] P. E. Meyer and J. J. Winebrake, 'Modeling technology diffusion of complementary goods: The case of hydrogen vehicles and refueling infrastructure', *Technovation*, vol. 29, no. 2, pp. 77–91, Feb. 2009, doi: 10.1016/j.technovation.2008.05.004.

[10] F. M. Bass, 'A New Product Growth for Model Consumer Durables', *Manag. Sci.*, vol. 50, no. 12, pp. 1825–1832, 2004.

[11] B. Boucher, 'The Bass diffusion model for communication technology globally and the economic factors that influence it', Thesis, Stellenbosch : Stellenbosch University, 2019. Accessed: Oct. 21, 2022. [Online]. Available: https://scholar.sun.ac.za:443/handle/10019.1/106166

[12] O. Schwabe, 'Open European Network for Enterprise Innovation in High Value Manufacturing (ENTOV-HVM)', *ResearchGate*, 2019. https://www.researchgate.net/project/Open-European-Network-for-Enterprise-Innovation-in-High-Value-Manufacturing-ENTOV-HVM (accessed Oct. 21, 2022).

[13] IEA, 'Hydrogen Projects Database', *IEA*, 2022. https://www.iea.org/data-and-statistics/data-product/hydrogen-projects-database (accessed Oct. 24, 2022).

[14] J. Freymann, K. Hauptmeier, and A. Kamolz, 'Assessment of hydrogen certification standards and requirements'. Sunfire, 2020. [Online]. Available: https://www.green-industrial-hydrogen.com/fileadmin/user_upload/D4.2_Assessment_of_hydrogen_certification_standards_and_requirements.pdf

[15] European Union Agency for the Cooperation of Energy Regulators, 'Transporting Pure Hydrogen by Repurposing Existing Gas Infrastructure: Overview of studies and reflections on the conditions for repurposing', 2021. Accessed: Jun. 16, 2022. [Online]. Available: https://acer.europa.eu/Official_documents/Acts_of_the_Agency/Publication/Transporting%20Pure%20Hydrogen%20by%20Repurposing%20Existing%20Gas%20Infrastructure_Overview%20of%20studies.pdf

[16] D. Mahajan, K. Tan, T. Venkatesh, P. Kileti, and C. R. Clayton, 'Hydrogen Blending in Gas Pipeline Networks—A Review', *Energies*, vol. 15, no. 10, Art. no. 10, Jan. 2022, doi: 10.3390/en15103582.

[17] Reuters, 'EU gives green light for $5.2 bln in state aid for hydrogen development', *Reuters*, Sep. 21, 2022. Accessed: Oct. 21, 2022. [Online]. Available: https://www.reuters.com/business/energy/eu-gives-green-light-52-bln-state-aid-hydrogen-development-2022-09-21/

[18] European Commission, 'Hydrogen Public Funding Compass', 2022. https://single-market-economy.ec.europa.eu/industry/strategy/hydrogen/funding-guide_en (accessed Oct. 21, 2022).

[19] IRENA, 'DECARBONISING END-USE SECTORS: GREEN HYDROGEN CERTIFICATION', 2022. Accessed: Jun. 16, 2022. [Online]. Available: https://irena.org/-/media/Files/IRENA/Agency/Publication/2022/Mar/IRENA_Green_Hydrogen_Certification_Brief_2022.pdf