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

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June 2022

ABSTRACT

The world is facing unprecedented challenges regarding climate change and greenhouse gases emissions; hence the European Union is responding to these issues setting an ambitious yet attainable action plan for a systematic transition towards a carbon-neutral continent by 2050.
Green Hydrogen will be a major player for a sustainable energy transition, representing an energy carrier with numerous uses in transportation, industry, heating, and energy storage, and it is seen by many experts as a viable solution to decarbonize different sectors over time. However, this technology is still in its early stages of development with a lack of infrastructure, investment, and with so many applications, the supply chain becomes more complex and continuous improvements are still needed. The urgent need for a fast shift to a climate neutral economy and the applicability of hydrogen in a large scale, reveal the importance to achieve fast diffusion of this technology and understand the variables influencing its success.
This dissertation focuses on the innovation diffusion of the Green Hydrogen technologies. This was achieved through a maturity model based on Case Studies to understand how these will diffuse in the current market conditions and how fast will each achieve market saturation, followed by validation interviews and final actionable recommendations. The model presented is based on the diffusion of innovations principles developed by E. Rogers (1983), aligned with recent literature review in the field of value networks, innovation ecosystems, sustainable energy, and hydrogen supply chains.
The model's main conclusions suggest that successful hydrogen projects thrive on robust innovation ecosystems, where a web of partners must cooperate with main focus on the technology's variables of compatibility with existing ways of work, adaptability, ese of trialling and technical readiness.

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

1. Introduction

1.1. *Problem background and motivation*

Green Hydrogen (GH) – hydrogen produced from water and renewable sources [1] – and used in fuel cells, both for stationary and mobile applications, constitutes a very promising energy carrier in the context of sustainable development in the global energetic mix. Hydrogen technologies have significant potential to improve energy security and mitigate the effects of climate change, hence creating a path to a clean, sustainable energy system. The concept of GH constitutes a disruptive innovation on how energy is produced, stored, and consumed. Currently, the cost of clean hydrogen is not competitive compared with fossil fuel based hydrogen [2], [3], yet with the development of hydrogen and fuel cell technologies, the increasing fossil fuel prices, and carbon emissions taxation, have resulted in greater competitiveness for hydrogen recently which is expected to improve even more in upcoming years. Several European countries have presented plans to instal hydrogen infrastructures and to accelerate the deployment of the hydrogen economy [4], although much of the required technology is already available to commercialise, the deployment of a hydrogen infrastructure constitutes a challenging task, because of the inherent CAPEX and OPEX, the need to achieve cost-competitive production and diffusing to mass markets. The hydrogen infrastructure and complementary technologies are seen as an important part of the future energy mix, due to their advantages in terms of reducing GHG emissions in various sectors, from transportation, to industry, and the energy sector itself [2]. Given this context, the need to study methodologies for the deployment and design of hydrogen supply chains is increasing [5], enhancing both supply and demand through all its environmental, economic, and social benefits. Both research and projects in the field have been growing at an increasing rate in recent years [7], yet many concepts still remain undeveloped, namely the diffusion process and the variables influencing the adoption of the technological innovations behind GH.
A research-based maturity model for forecasting the speed of innovation diffusion from ideation to market saturation will be developed, with the aim of

understanding and enhancing the acceleration of diffusion in the innovations present in the GH technologies. The following thesis will understand the factors enabling the adoption process, the variables influencing their acceleration and how they actually diffuse with the influence of all stakeholders present in the ecosystem, with the objective of reducing development costs, financial and market uncertainties and to minimize the time needed to reach the critical mass of adoption.

1.2. *Hydrogen role in the energy transition*

The decarbonisation of the world's economy will give hydrogen more prominence in the energetic framework. It will hold a special part in hard to electrify sectors, such as industry (feedstock to petrochemical and fertilizer sectors), heavy transportation, heating, and energy storage [2].
Currently a major part of the global hydrogen consumption is dominated by two industries: oil refineries 52% and ammonia production 43%, the remaining consumption lies in other industrial applications [8]. In Europe, ammonia, and oil production account for 50% and 30% respectively, methanol production represents 5% and metal industries around 3% [1]. Most of this consumption derives from fossil fuel based hydrogen, although Iberdrola is currently developing the largest GH project for industrial use in Europe as an off grid hydrogen production to supply an ammonia factory in Spain with an electrolysing capacity of 20 MW [9].
According to the IEA, renewable electricity production increased 45% to 280GW in 2020 and it was the only energy source to increase in this year despite the pandemic effects, it also predicted that the share of RES in the global energy mix to increase in the recent future [10]. By 2022 solar PV production increased 162 GW representing an addition 50% higher than in 2019, while wind energy production increased a record breaking of 114 GW in 2020 a yearly increase of 90% [10]. Bearing in mind the fluctuating nature of RES production compared to the energetic supply and demand, renewable hydrogen has been considered a viable solution as an energy storage method, particularly with large amounts of energy during long durations, through the electricity-hydrogen-electricity cycle (Power-to-Power). The production of hydrogen from RES through electrolysis, storage, and the reconversion into electricity for grid supply, by fuel cells or gas turbines, presents a favourable off-grid application, for instance in isolated areas or as back-up power [2], [11], [12]. However, it does not yet seem viable due to the low full-cycle efficiency currently between 30% to 40% [6]. Another possible pathway lies on supplying hydrogen through the existing natural gas grid, by blending both together to generate hydrogen enriched natural gas (HENG), which is more energetically dense and can be used in buildings or industrial complexes in combined heat and power systems [3], this possibility represents a viable transitioning solution.
Hydrogen can also be distributed to refuelling stations to fuel hydrogen powered vehicles, or fuel cell electric vehicles (FCEV) as a clean energy source, leaving no bi-products other than water. FCEVs are superior in operating range and refuelling time compared to battery electric vehicles (BEV) [13], while their energetic efficiency is significantly lower than that of BEV (electrolysis alone represents an energetic loss of approximately 30% from the useful energetic input). As with common electric vehicles or even traditional ICE cars, a substantial infrastructure is necessary to supply hydrogen-powered vehicles [13]. The FCEV range is wide, while also applicable to cars, and trains, ideally fuel cell technologies are most suited in hard-to-electrify, long-haul, and heavy-duty vehicle markets, such as trucks, buses, maritime shipping, and aircrafts [13]. These represent means of transport where electrifying through batteries or direct electric current is inefficient or even undoable with currently existing technologies, and a different fuelling method is needed to change from fossil fuel based transports and decarbonise each sector [2].

1.3. *Hydrogen Supply Chain / Infrastructure*

The design of a supply chain may vary depending on the desired goal, hence there is no unique HSC, with various energy sources, production processes, means of distribution, storage modes and end applications exist. As a generic simplification, the various pathways involved in the HSC are presented in Figure 1, with a concise picture of the different existent stages. The focus of this

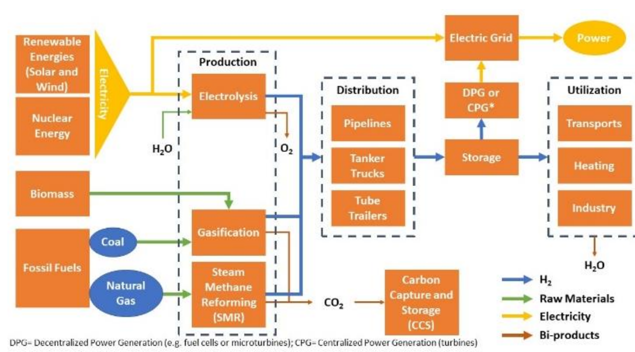

Figure 1 - Pathways involved in the Hydrogen Supply Chain (Adapted from: Hydrogen Supply Chains by Azzaro-Pantel)

dissertation lies in GH production, this means focusing on production through electrolysis via RES, and diffusing this chain to be successful from source to utilization. Nevertheless, other sources and production methods were accounted and are present in Figure 1, as currently these still represent a large percentage of global hydrogen production and their existing supply chain, will serve as a foundation for future developments [2], [14].

1.4. *Problem Definition*

The primary challenge present on developing an efficient hydrogen infrastructure is overcoming the issue of who develops first, this is particularly problematic for the vehicle sector where the private consumer is dispersed and high in volume of individuals to reach. On one hand, the vehicle manufactures are reluctant in investing on fuel cell technologies and vehicles, with a lack of refueling infrastructure since the consumer will not buy a vehicle if there is no close location to refuel it. Conversely, energy and gas companies will not invest on hydrogen production, and distribution through refueling stations while vehicles are not commercially available, as the return on investment would take too long to achieve [13]. Finally, the end user is awaiting the development and maturity of these two complementary technologies when deciding to invest and use an FCEV.

On other sectors of applicability, such as industrial, energetic storage and grid balancing, where the number of players involved in the ecosystem of diffusion and the complexity of the network are lower, there are less constraints for the diffusion to mass consumption. Nevertheless, it is possible to interpret the need to understand what can be done in the EU as a holistic view. The different infrastructure levels presented are currently inexistent as a global supply chain, hence they will generate different innovations, in different fields (e.g., production through electrolysis, distribution through pipeline, use via FCEV, etc.)[8], with different stakeholders, that need to be implemented and developed. The degree to which each one of the members influences the upcoming level needs to be understood and the key uncertainty factors of diffusion in the referred innovations need to be assessed.

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

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

2. State of Art

2.1. *Diffusion of Innovations*

The study of the diffusion of innovations was first introduced by Gabriel Tarde (1903), a French sociologist, providing original concepts in his book The Laws of Imitation [16] about opinion leadership, the S-curve of diffusion, and the role of socioeconomic status in interpersonal diffusion. Schumpeter (1939) broadened these studies and classified the phases of technological change in three levels, invention, innovation, and diffusion [17]. Based on Tarde’s work, Everett M. Rogers, a pioneer in diffusion research, developed what has been the foundation of research in the field of innovation since the mid-twentieth century. Everett Rogers (1983) with his book Diffusion of Innovations [18], which has been regarded as a pivotal theory when it comes to understanding how technological innovations become diffused, and potentially adopted by individuals and/or organizations. Rogers defines diffusion as the process by which an innovation is communicated through certain communication channels over time among members of a social system, this process connects the four main elements of the theory: innovations, communication channels, time and, social systems, these elements are identifiable in every diffusion research study. The concept of innovation has been ever-evolving throughout the years, tough the most common definitions are based on the ideas of newness of change and a degree of usefulness or accomplishment in something new.

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

The members of a social system may differ among them as individuals, informal groups, organizations, and/or subsystems.

2.2. *Value Networks and Innovation Webs*

The existence of inter-organizational relationships and collaboration, enable the dissemination of information and products, a vital role for the diffusion of innovations, mainly happening through value networks [19], [20]. Value network analysis in an important process in the diffusion of innovations since it allows to understand the members present and assets that are exchanged. The theoretical foundations of value networks derive from the exchange theory and living systems theory [21] and from Rogers previously described Social Systems. A value network is a set of connections between organizations and/or individuals interacting with each other to benefit all parties involved. It allows members to exchange both tangible and intangible assets, as well as sharing information. The benefit that a value network provides comes from the way a business or individual applies the resources, influence, and insight of others to whom they are connected [22]. Allee provides studies on the value network analysis of tangible and intangible transactions, mainly focusing on integrating intangible assets, such as knowledge, favours, and benefits that go beyond the actual service or product [22]. Generally, a tangible transaction incurs in parallel intangible transactions and initiates a unique chain of relationships, interactions, and exchange of resources in value conversion networks.
value networks related with innovations systems [23]. This concept was initially proposed by Moore [24], he suggested that a company can be considered part of a business ecosystem, in which organizations coevolve capabilities around a new innovation. However, the concept was specially adopted after the article of Ron Adner [25] where he provides the most commonly used definition of innovation ecosystems as "the collaborative arrangements through which firms combine their individual offerings, into coherent, customer-facing solution". A review on innovations ecosystem has shown that emphasis is put on collaboration/complements and actors, as the main components, indicating also the importance of the artifact (i.e. product or technology). Nevertheless, Moore emphasizes equally on the elements of collaboration and competition, as ways for companies to co-evolve new rounds of innovations.
Innovation Webs are specific forms of value networks [26], these represent the basis for how innovations spread throughout all the stakeholders (Figure 2). Aligned with the theory of the innovation-development process by Rogers, an idea is diffused through the different innovation web archetypes: (1) Research, (2) Socialization, (3) Market Validation and (4) Commercialization. Each archetype forms a pattern of roles and interactions which involve, Buyer, Commercializer, Funder, Innovator, Marketeer, Product Packager, User and Web weaver. On the innovation web perspective, what influences the speed of value creation from ideation to market saturation comes from a combination of concepts reaching from value network analysis, process analysis [27], complex adaptive systems and social and network analysis.

3. Methodology

3.1. *Bass Diffusion Model*

The Bass Diffusion Model [28] is used as the theoretical foundation of the methodology used in the maturity model, this method allows to mathematically model the Diffusion of Innovations theory [18] and outline the major ideas of the theory as they apply to the timing of adoption. It is extensively used as one of the methods to assess the diffusion of ideas specially in technological innovations for forecasting purposes [17]. It assumes the traditional S-shaped curve of adoption (Figure 3), from a mixture of internal interactions with peers from the social system for instance word of mouth, and external influences. The Bass model aggregates the adopter categories defined by Rogers in two main classes, the innovators and the imitators, that unlike the previous are influenced in timing of adoption by pressures from the surrounding social systems and not by the urge to innovate.
Therefore, in mathematical terms of the model formulation, two coefficients are calculated to measure the degree to which external and internal influences impact the rate of adoption, the coefficient of innovation (p) and the coefficient of imitation (q). As time progresses the number of new innovators adopting the idea decreases while the number of imitators starts to increase until it reaches a peak. The model can be simply expressed through the following mathematical form:

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

The equation represents the growth of adopters N throughout time t, it contains two distinct sections, the first one $\left(p + \left(\frac{q}{M}\right) \times N\right)$ represents the diffusion effects and the last one $(M - N)$ represents the saturation effects, where M is the size of the total potential market and N is the cumulative number of adopters at instant t.
Bass initially applied the model to study the growth of sales in certain consumer durables back in the 1960s, the real values throughout the years were proven to be in a respectable agreement with the predicted ones, similarly more recent studies supported this evidence [29].

3.2. *Litmus Test*

A mathematical tool was developed, the Innovation Diffusion Litmus Test [30] created by Dr. Oliver Schwabe, to understand how fast a technological innovation diffuses from ideation to market saturation, identifying what variables are present and their interdependence in the present ecosystem. The test is aligned with previous literature in Diffusion of Innovations, Value Networks and is based on the formulation of the Bass Diffusion Model [28]. A survey and research tool were used to provide a high-level assessment of the underlying innovation web model created by Dr. Oliver Schwabe [31], [32]. The test performs as a simple set of core questions applied to an Excel (R) based maturity model to understand the level of maturity of the innovation web present in the idea's environment.

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

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

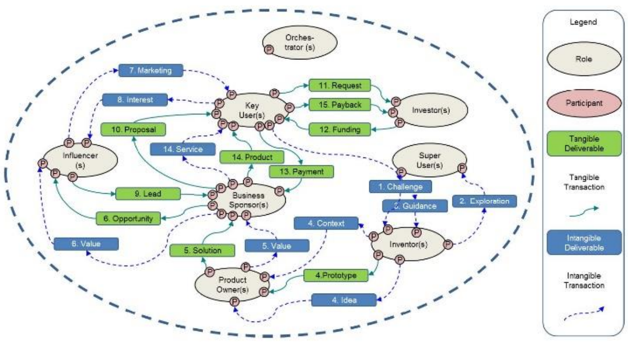

Figure 2 - Value Network of Innovation Diffusion to Late Adopters [Schwabe et al. 2020]

The web narrative used consists in a series of relations and exchanges between the stakeholders as displayed in Figure 2. The Innovation Web begins when the Inventor(s) receives an intangible challenge from the Key User(s). Inventor(s) investigate the matter with Super User(s) and develop the possible solution for the problem as a tangible prototype that is presented to the Product Owner(s). The Product Owner(s) take the prototype and transform it into a potential tangible solution with the clarification of the ways it can generate value to the consumer. Afterwards, the solution and possible value creation is shared with the Business Sponsor, who reshapes the solution into a tangible opportunity and presents it to the Influencer(s). The Influencer(s) commercialize the solution and provide value proposition back to the Key User(s), to create an intangible expression of interest, which the Influencer(s) convert in a tangible asset passed through to the Business Sponsor(s). The Business Sponsor(s) provide a tangible commercial proposal for selling the solution to the Key User(s), after receiving the proposal, they request funding from the Investor(s), and ideally it is provided that is used as payment for the tangible solution to the Business Sponsor(s). After receiving the required payment, the Business Sponsor(s) provide the developed solution and needed intangible services back to the Key User(s). Key User(s) eventually use the product to solve the problem/need initially announced and then provide the feedback and assets, necessary for relevant changes in return of the funding from the Investor(s) [31].

An important factor to consider is the shift from a linear and modular perspective to considering the whole ecosystem as a living and continuous interchange of tangible and intangible assets between the many stakeholders present in the diffusion process. Precisely, the idea presented in the Litmus Test is as a "virus" spreading as quickly as possible through the living ecosystem of the innovation web.

Moreover, it is considered that the "success", or market saturation, of the diffusion of an innovation is the sustained use of the idea or product by the late majority of adopters, accordingly, aiming for 84% of adoption in the total market share to achieve sustainable use and enough value created for continued stakeholder investment [18], [31].

The Litmus Test is designed with a semi-structured interview assessing the factors that influence the diffusion of the idea, as well as the degree of commitment that all the roles and participants present in the generic diffusion of the innovation web, while at the same time, intaking the level of confidence for each factor assessed.

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

The amount of new adopters over time ($s_a(t)$) is determined using the two coefficients of innovation (p) and imitation (q), Total market size (m) and the Cumulative number of adopters (S(t)) (Schwabe et al. 2020), through the following equations adapted from the Bass Diffusion base equation:

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

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

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

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.

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

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

This thesis is organized by the theoretical foundations and inherent methodological steps to complete, as well as the practical applicability of the Litmus Test model to the different cases researched. The main goal is for an innovation to achieve rapid diffusion to late adopters, its success depends on reaching 84% adoption of the potential target market, specified to GH technologies.

4. Results and discussion

4.1. *Results Analysis*

The results obtained from the Litmus Test applied to the 12 cases are displayed on Table 1, with the innovation maturity, population maturity, overall maturity, level of adherence to the schedule forecast compared to the initially expected and the confidence level of the inputs in the model for each case. The overall Case Study results displayed on Table 1, also show the first case which is the Reference Model as developed by E. Rogers, where the diffusion throughout the innovation web is ideal.

Regarding the overall results of the Case Studies present on Table 1, it is possible to observe high values for the Idea Maturity with the totality of the cases located on the highest level of Maturity, level 5, showing a high level of maturity on the technological innovation component, with the lowest percentage at 86%. The case studies assessed represent a holistic view of the GH value chain thus, considering the technology as a whole, it is possible to interpret an elevated level of idea maturity in hydrogen projects, whereas concerning the population perspective there are lower values of maturity in the generality of the projects. Concerning the population maturity, the majority of the portfolio appeared on Level 4 with only 2, NorthH2 and REFHYNE indicating Level 5 maturity. The average for the 12 case studies was 87% on the idea maturity and 79% on the population maturity, this comparison can

Table 1 - Wider Case Studies Results

Case	Context (Detailed assessment results available in the assessment tool)	Idea Maturity	Population Maturity	Overall Maturity	Schedule Forecast	Assessment Confidence
1	**Reference Model:** Perfect innovation diffusion curve based on the research method	5 (100%)	5 (100%)	5 (100%)	100%	100%
2	**H2 FUTURE:** Generation of Green Hydrogen with the purpose of supplying a steel production plant in Austria	5 (86%)	4 (72%)	67%	260%	58%
3	**NorthH2:** Large-scale Green Hydrogen production resourcing to offshore wind power in the Netherlands	5 (90%)	5 (90%)	77%	180%	72%
4	**BIG Hit:** Production of Green Hydrogen in isolated territories in the Scottish islands	5 (88%)	4 (78%)	64%	260%	61%
5	**H2 REF:** Develop cost effective and reliable FCEV refueling systems	5 (85%)	4 (84%)	64%	260%	56%
6	**Hy STOC:** Supply and transportation using liquid organic hydrogen carriers (LOHC), to a commercially operated HRS	5 (86%)	4 (80%)	60%	260%	53%
7	**HPem2Gas:** Develop, validate, and demonstrate robust, flexible, and rapid response PEM electrolysis	5 (84%)	4 (72%)	56%	280%	53%
8	**H2ME:** Deploy the firstEuropean netwok of HRS and implement a significant fleet of FCEVs	5 (87%)	4 (76%)	76%	180%	86%
9	**H2HAUL:** Develop hydrogen mobility in heavy duty and long haul transport by implementing fuel cell electric trucks	5 (88%)	4 (83%)	72%	180%	71%
10	**Neptune:** develop solutions at materials, stack, and system levels of PEM eletrolysers	5 (88%)	4 (80%)	66%	200%	63%
11	**HySTories:** adress main technical feasibility for underground storage of pure hydr hydrogen in aquifers or depleted fields.	5 (89%)	4 (76%)	65%	260%	62%
12	**REFHYNE:** install and operate world's largest PEMWE for industrial use (10MW) produced onsite and apply directly in the oil refining process	5 (88%)	5 (90%)	76%	180%	72%
13	**ELY4OFF:** implement a fully integrated off-grid production pf GH through efficient and cost-efective PEMWE	5 (86%)	4 (72%)	61%	260%	61%

prove the idea that the hydrogen technologies necessary to develop the industry, are slightly ahead compared with the maturity of the innovation ecosystem needed to diffuse these projects. The lower value of the overall Population Maturities shows the need to focus on the ecosystem present on hydrogen projects and at the same time that the ideas behind the cases are already mature

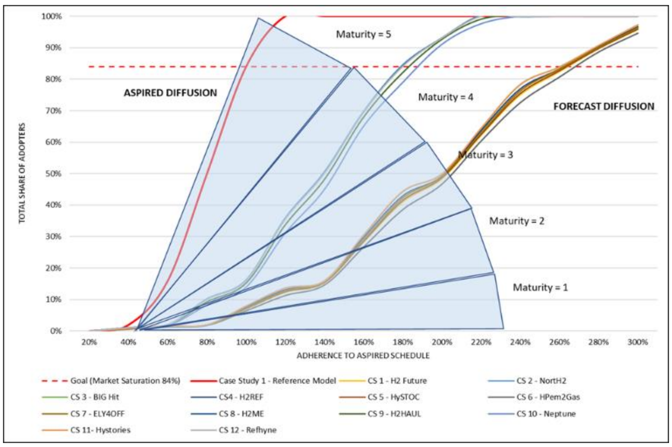

Figure 3 - Cumulative Share of Adopters for the Reference Model and the 12 Case Studies

enough to be commercialized and adopted at large scale, currently lacking only the financial, market and technologic incentives, necessary to engage on a stronger network of stakeholders.

The Schedule Forecast stands for the time needed to reach 84% share of total adopters compared to the initially aspired schedule, this factor illustrates essentially how fast the innovation will reach mass adoption compared to the ideal reference model. There are four cases (NortH2, H2ME, H2HAUL and REFHYNE) showing lower Schedule Forecast at 180% which accordingly also display the highest Overall Maturity. On the other hand, the highest Forecast Schedule was 280% where the diffusion occurred the slowest and lead to the lowest Overall Maturity of the portfolio, the HPEM2Gas. The remaining cases showed a low adherence to schedule at 260%, with the exception of Neptune that had a schedule forecast at 200%.

The Confidence level introduced in the assessment of the Litmus Test negatively influences the overall maturity of the projects, in the majority of the cases, it is affected by the availability of information, uncertainties on the knowledge about the subject assessed and on the innovation factors studied.

A covariate analysis of each case then assesses the Overall Maturity weighing the idea, the population, and the assessment confidence, the highest overall maturity stands on the NortH2 (77%) on Level 4, with a robust diffusion of the innovation and the lowest maturity lies on the HPEM2GAS (56%) at Level 3, where the population and idea maturities are relatively lower and highly influenced by the degree of confidence on the assessment. The weighted average of the Overall Maturity on all Case Studies is 66% at Level 4, which shows a relatively high rate of diffusion for the hydrogen projects studied but where quotation is required, and improvements are still needed mainly.

The cumulative share of adopters throughout time is represented on Figure 3 as function of the percentage of the original aspired schedule, the Case Study 1 is the previously described S-Curve 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 presented in Figure 3, is an easier way of interpretation of the results where the closer the curve of each case is to the reference, the faster the speed of diffusion. It shows the distinct forecasts of diffusion for the 12 Case Studies, with two distinct patterns can be observed, where 5 cases (NortH2, Refhyne, H2ME, H2HAUL, and Neptune) acquire a larger share of adopters earlier on ensuing an earlier arrival to the mass adoption of the network and higher maturity for these cases, the second pattern shows a lower diffusion curve for the 7 remaining cases (BIG HIT, ELY4OFF, HyStories, HPEM2GAS, H2 Future, H2REF and HySToc) where the maturity levels end up with lower diffusion rates. The patterns present on the diffusion forecast support the different maturity levels previously observed and can be explained by the case's dimension and applicability, as well as the development and engagement of the ecosystem present on the project.

Table 2 - Comparison of factor maturity between NortH2 and HPem2Gas

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

To better understand how the different factors influence the diffusion of the portfolio, an in depth analysis was put together. This analysis is drawn on Table 2 with all the factors studied and a comparison of two CS, the one with highest overall maturity and the one with lowest. The case with highest overall maturity was NortH2 at 77%, and the lowest maturity was at the HPem2Gas at 56%, demonstrating the ones that presented fastest and slowest diffusion respectively. With the aim of understanding which factors influence the success and speed of diffusion of the project, the table presents the average factor maturity for each case, the standard deviation analysis, and the delta between all the factors.

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

The delta between each factor indicates the difference between all the factors from both cases, and the highest deltas (displayed in yellow on Table 2) demonstrate the variables that influence the more negatively the diffusion of the lowest maturity, HPem2Gas, while simultaneously positively influencing the maturity of the NorthH2 case results. These factors are the Observability of impact, the Ease of Trialling, and the Compatibility with existing Ways of Work, the main variables to focus on, when improving the overall maturity of the portfolio studied, considering that enhancing the performance of these three factors will eventually bring higher maturity levels to the lowest maturity cases, therefore enhancing the speed with which an innovation is adopted and diffused in the GH technologies studied.

4.2. *Results Validation*

The results previously presented were then submitted to validation by field experts. In this sense, five hydrogen experts were interviewed in three different online sessions. The validation interviews concluded that the forecast diffusion patterns represent a robust view of the project's history with further specific and personal experience recommendations, furthermore the factors influencing more negatively the diffusion were validated as relevant conclusions of the influences on the GH diffusion to achieve market saturation.

4.3. *Results Discussion*

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

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

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

In the course of the different interviews, it was possible to notice a certain consensus and agreement between the interviewees on their position concerning the three factors presented as critical to achieve faster diffusion, further complemented with personal perspectives of what factors could be emphasized as recommendations or as critical fields for successful hydrogen projects. In the interviews the low degree of acquaintance of the model by the experts was a challenge, since it was an open discussion, it often fell to a more personal outlook or the ideas of their work rather than the focus on the diffusion factors and

their perceived understanding of what could be done to improve the innovation. This was already expected as an open discussion, but in a future validation I recommend explaining thoroughly the model, the cases, and the results obtained in depth, for the interviewees to know the importance of the ecosystem and the different factors.
Subsequently, a variety of factors were highlighted during the discussions as relevant to consider on the recommendations for GH projects. As initially mentioned, the infrastructure availability, specifically the lack of it is one of the major factors delaying the diffusion of the hydrogen technologies. this was mentioned frequently by the interviewees as present in the factors of Technical Readiness Level, the Compatibility with Existing Ways of Work, Ease of Use, and Ease of Adaptation.
Aligned with the infrastructure issue, the question of geography was discussed since distinct locations present different accessibilities or even different levels of development to the GH technologies. This variable was highlighted particularly when considering the global value chain of the aviation industry, although it also relates to other applications and industries. Indeed, this factor was not highly considered in the model as the Case Studies represent developments inside the EU where the GH value chain is being developed jointly as a whole and, Europe is one of the global regions more invested in developing this technology, which does not directly translate to the desire of other developing countries.
Another factor emphasized was the political and regulatory perception, in the sense that an enabling legal and political framework engages with the GH technological and industrial development as a driver for successful projects. This factor was particularly pointed as important not only in the innovation's characteristics, where the Degree of Certification is assessed in fact with a low factor maturity, rather than with its presence on the innovation's ecosystem as an entity, performing a key role on the diffusion of the GH in countries where the technology is still undeveloped.
The significance of the cost was also mentioned as critical for the development of the technology, in particular the costs of the prototypes, the projects CAPEX and OPEX, the costs of raw materials and complementary technologies. These variables heavily influence the decision making and strategic view of stakeholders on the development and implementation of GH technologies, as excessive costs drive down the incentives from these entities of investing in riskier projects and innovations, therefore investing in safer projects and more traditional technologies. Henceforth, the previous statements suggest the need to focus on the population's factor of the Investor, the Business Sponsor, and on the innovation's Budget and Resources factor.
The presented results support recommendations for stakeholders implementing the technology, with a specific application for policy makers on where to act while reaching for faster diffusion, governmental entities as the current players showing the most interest in the GH. Additionally, these variables are recommended for businesses establishing and developing the GH technologies on their operations, namely energetic companies, industrial players or even vehicle producers.

5. Conclusion and Future Work

The proposed work focuses on the impact that different factors have in the diffusion process of the GH technologies. The population/ecosystem proved to be an enabling element of diffusion, by empowering the innovation webs present, while maintaining focus on the technological attributes, the cases tend to achieve higher speed of diffusion, reach the late adopters faster, and lastly accomplish market saturation sooner.
The main findings from this dissertation, lie on the importance of 3 main factors highlighted and validated as key ones driving down diffusion in the portfolio of cases assessed, the Observability of Impact of results attained from implementing GH projects, the Ease of Trialling as the possibility to which an individual or entity is able to experiment the outcome of the technology, and the Compatibility with Existing Ways of Work as the connection with traditional methods of applying the similar or complementary technology, and its connection to different end uses. These are the variables to consider as recommendations that require more investment from the stakeholders implementing future projects.
Furthermore, there are other factors slowing down diffusion that must be accounted for, the Degree of Certification of the technology, the Degree of Complexity of implementing in a certain environment or location, and the presence of the Super User in the population component that must be enhanced. On the other hand, it is also important to note the factors accelerating the diffusion such as the Degree of Innovativeness, the Number of Competitors, the presence of the Moderator and Investor, and these variables must receive relevance by the stakeholders as major drivers to achieve faster diffusion in new ventures.
When applied to the cases of interest the research method in combination with the assessments of the selected change factors lead to an initially accepted robust validation of the diffusion theory selected. Although monitoring of the cases studies is an ongoing process, that requires further research focused specifically on the diffusion of the assessed projects to continuously refine the approach to the GH technologies. The limitations of this study reside precisely on the holistic view considered during the dissertation, more specifically on the difficulties to present concrete recommendations in particular levels of the Supply Chain or specific value chains, where there can research developed separately for each case,

technology, or location. Bearing in mind the previous, the recommendations for potential future research lie in the development of the Litmus Test to specific parts of the HSC with the focus on delivering specialized recommendations to a certain value chain and then proceeding to interlink the different assessments to achieve the structured view from the bottom to the top of the value chain. Additionally, the need to examine further factors such as value network intent and value network / ecosystem performance.

Additionally, the geographical variable needs to be considered in alignment to the TRL in different locations with distinct availability and compatibility to the hydrogen technologies. The importance of the Regulator and Policy makers on different industries of hydrogen use are also emphasized as important to consider in future research as part of the ecosystem members to be addressed.

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