MSc Program
Sustainable Development
Energy and Materials Track

Support Scheme Design for Green Hydrogen

Thesis Study

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Summary

Hydrogen is the energy carrier of the future as it is considered to be a key enabler towards climate neutrality in several sectors. Unfortunately, green hydrogen production is not yet economically competitive as there are still significant obstacles obstructing full deployment such as high production costs, insufficient infrastructure and no natural market demand. In order to fill these gaps and come closer to the net-zero emissions goal of 2050, policy implementation becomes a necessity as soon as possible. In the past few decades, financial support in the form of support schemes has led to impressive results, especially when it comes to the deployment of renewable energy sources. Following this example, support schemes have the potential to provide the necessary incentives to boost investments on green hydrogen projects and gradually promote green hydrogen production and use. The purpose of this thesis is to shed light on potential support schemes for the promotion of green hydrogen use and production, as well as on their common design elements linked with support payments and overall scheme implementation. It is argued that the similarities of green hydrogen and renewable electricity make it possible for RES-E support schemes to be examined for this purpose. Therefore, the design options of some commonly used RES-E support schemes (Feed-in Tariff, Feed-in Premium, Quota obligations with tradable certificates and Capacity-based Investment Subsidies) alongside with these of a more general support instrument (Carbon contracts for difference) are analyzed through a thorough literature research. In the last part of the study, the support schemes are qualitatively assessed in terms of performance based on a list of suitable criteria (effectiveness, cost efficiency, equity, flexibility, market compatibility and revenue stability). The assessment is then quantitatively processed through the use of SMART method to group the support schemes through different rankings and derive useful conclusions. Feed-in schemes and capacity-based investment subsidies are evaluated to be the most promising options for the support of green hydrogen and thus, it is suggested for future studies to delve more into the design of these support schemes. Also, carbon contracts for difference can also be a promising instrument but call for support scheme synergy in order to achieve positive results. Finally, it is recommended for future studies to address the same research problem through a more quantitative assessment of criteria performance.

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1. Introduction

In December 2019, the European Green Deal was introduced by the European Commission, outlining a set of policy initiatives as a means to achieving the ambitious goal of net-zero greenhouse gas (GHG) emissions until 2050 (European Commission, 2019). Under the Green Deal, green hydrogen is identified as a potent, high-priority area for reaching carbon neutrality within the agreed period of time. Many studies have been conducted, developing different scenarios and setting various decarbonization trajectories in order to project the EU energy system in 2050. The majority of them expects significant decarbonization, meaning more than 80% emission reduction compared to 1990 levels by 2050. The use of hydrogen is a common element of these scenarios, whereas the projection of energy consumption for hydrogen production ranges from 500 TWh to 2700 TWh (Tsiropoulos et al., 2020).

The annual demand for hydrogen in the European Union (EU) is projected to meet a considerable increase in 2030 (Kakoulaki et al., 2020), the achievement of net-zero emissions by 2050 is a major future milestone, so the extended use of green hydrogen would become beneficial. As a clean and flexible energy carrier, green hydrogen can provide an alternative to fossil fuels, assisting decarbonisation of hard-to-abate industries that are unable to adapt to electrification as well as replacing the non-energy use of grey hydrogen in industry (i.e. feedstock).

Many countries are committed towards carbon neutrality but the achievement of a deep decarbonisation demands various actions across every sector of the economy. The truth is that we have barely begun implementing the necessary standards which can eventually lead to the realisation of those highly ambitious goals. Even though hydrogen production from water electrolysis is well-practiced technology, there is no significant green hydrogen production so far (IRENA, 2020). This can be attributed to a diverse set of barriers, such as high production costs, lack of infrastructure (i.e. transportation, distribution) and significant energy losses along the value chain. Dealing with these challenges and most importantly making green hydrogen a more economically feasible energy carrier, capable of contributing towards carbon neutrality, calls for dedicated policy across every stage of technology readiness as well as market integration and market growth(IRENA, 2019).

Over the years, several different forms of policy support have been used for deploying parts of the energy system, from fossil fuels to renewable energy sources (RES). In the case of the latter, more than 1300 support measures were placed in EU countries in the period 2005 – 2015 (Banja et al., 2017). Currently, RES shares in the energy mix are steadily increasing, whereas policy makers gained considerable experience with support scheme design and support schemes became major drivers of investment activities, especially in the electricity sector. Therefore, financial support in the form of support schemes could create the necessary incentives to boost electrolyser capacity and gradually reduce the production costs as the installed capacity grows and the learning process progresses.

Green hydrogen is seen as a technology that can bridge the gap between renewable electricity production and the goal of net-zero by 2050. In order to set the path in which green hydrogen can be used in this way, this study focuses on developing and evaluating different support schemes for promoting green hydrogen use. For the identification of such features, large emphasis is given to existing support schemes, especially to the ones utilized to increase RES shares in the energy mix. Green hydrogen is strongly linked with renewable energy, not only due to the fact that green hydrogen is generated by consuming power generated from renewables but also because it is identified as a potent renewable energy carrier. Thus, these support schemes are analyzed with regard to the extent they can be used or adapted, considering the characteristics of green hydrogen and the barriers currently obstructing its full-scale deployment. In addition, the support schemes are assessed based on a set of criteria (i.e. effectiveness, efficiency, equity, etc.) in order to evaluate their overall performance when it comes to promoting green hydrogen and also draw some key conclusions.

2. Literature review

2.1. Existing literature

Increasing green hydrogen deployment is an ongoing process mandating countries around the world to develop individual strategies with the highest possible ambition. Countries such as Australia, Canada, Chile, Norway as well as the EU have already announced or reported their green hydrogen strategies (IRENA, 2020), whereas other countries are in the process of implementing their strategies (Kovac et al., 2021). Newborough and Cooley (2020) highlight the significance of green hydrogen in the transition towards net-zero and the urgency for policy development to support its adoption. The academic literature dealing with policies to incentivise green hydrogen technologies is relatively scarce, so through this research intends to bridge this significant literature gap.

Due to the focus on the use of hydrogen in the transport sector, a big strand of the scientific literature addresses policies for the transport sector (IRENA, 2020). He et al. (2020) found that a potential policy support to light-duty hydrogen vehicles could in specific occasions result in eliminating fossil fuel imports and ensure maximum revenue, whereas Jones et al. (2020) acknowledges hydrogen vehicles as a strategic option towards sustainability and analyses future policy implications.

In a more related study, Quarton and Samsatli (2021) are analyzing a set of policies supporting emerging technologies like hydrogen, concluded that feed-in tariffs could in some cases be effective for hydrogen uptake and highlighted that careful policy design should be followed when supporting specific energy technologies.

Furthermore, other existing studies are oriented around key characteristics such as the barriers that need to be overcome in order to achieve full deployment (Velazquez and Dodds, 2020; Rabiee et al., 2021) and alternative production pathways (Armijo et al., 2020; Mosca et al., 2020).

2.2. Note on terminology

In the renewable energy literature there are several terms, often used in an equivalent manner, to describe support schemes (i.e. policies, support mechanisms, instruments, etc.). According to Huntington et al. (2017), production-based schemes and capacity-based schemes are two different strategies for the design of a support scheme. In the case of the former, the remuneration takes the form of periodic payments according to the generator’s actual electricity production. Regarding the latter, Riesz et al. (2015) report of capacity remuneration mechanisms, instruments that focus on boosting renewable capacity. In this case, financial support is given in the form of an investment subsidy per unit (i.e. kW) of installed capacity.

In order to facilitate the dialogue for the support schemes, Figure 1 illustrates the different levels of a support scheme within the scope of this study. The first level corresponds to the mechanism of the support scheme and thus, both the previously discussed mechanisms are featured. Then, the second level displays the instrument which is used for the support scheme based on the followed mechanism. The third and final level corresponds to the design elements of the individual instrument. These are design options within the instruments that are used to characterize the remuneration. Some of these options are common for all the instruments, while others are unique and are defined as instrument-specific (Held et al., 2014). Therefore, in this study "support scheme for green hydrogen" refers to a single specific instrument aimed to support green hydrogen use.

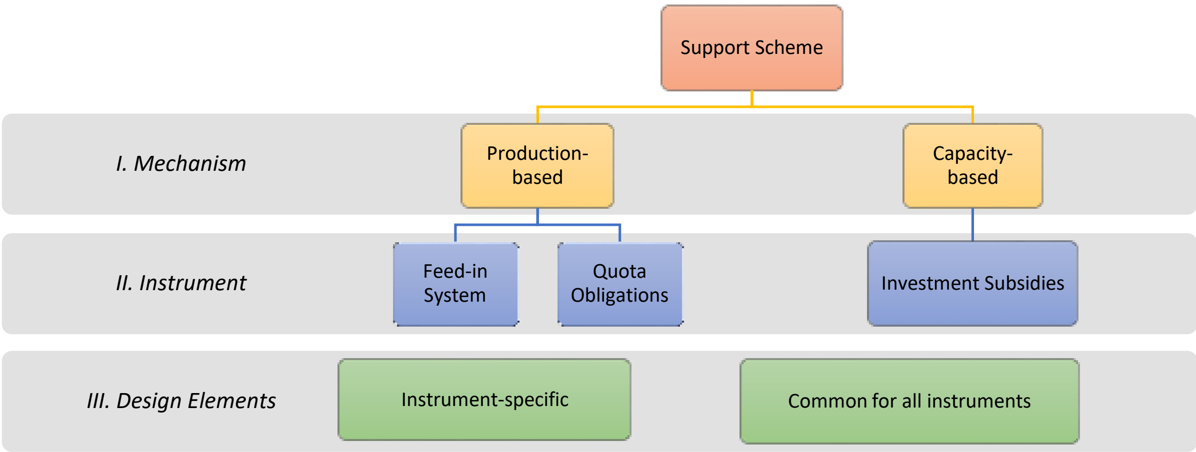

Figure 1: The levels of the support scheme

2.3. Research Goal

In line with the identified literature gap, this research therefore aims to further investigate current approaches in order to develop insights on what kind of support instruments could be utilized for the case of green hydrogen and how these support schemes could look like. An initial emphasis is given to support schemes for RES in order to determine specific instruments, which can provide the basis to design support schemes for green hydrogen. The support schemes for green hydrogen are then evaluated, based on a diverse set of criteria, in order to assess to what extent their purpose could be served. Keeping in mind the overall goal, the following research question is addressed:

"What are potential support schemes for promoting green hydrogen?"

The scope of the study is particularly significant as it can serve as a starting point for policy makers to design effective support schemes, specifically for the promotion of green hydrogen. In order to address the research question in a more adequate manner as well as create a structure for the research methodology, the study is oriented around the following research sub questions:

1. What makes RES-E support schemes applicable for promoting green hydrogen?
2. How can RES-E support schemes be adapted in order to support green hydrogen?
3. What kind of criteria could be used to evaluate different support schemes for green hydrogen?
4. How do the support schemes for green hydrogen perform based on the selected criteria?

Through the first research sub question, the link between renewable energy and green hydrogen is addressed by identifying similarities that make RES-E support suitable for the promotion of green hydrogen, but also differences, the adaptation of whom is necessary to make things work. The second research sub question follows the development of the support schemes for green hydrogen that arise from the adaptation of the support schemes for renewable energy and elaborates on their individual design. The objective of the third sub question is to identify what kind of criteria are appropriate to assess different support schemes. Finally, the fourth research sub question investigates the performance of the support schemes for green hydrogen under the spectrum of the selected criteria through a qualitative assessment. Overall, the first three research sub questions are addressing the designing part of the support schemes for green hydrogen and the necessary tools for their assessment, whereas the fourth and last research sub question serves as an integrating part as a means to draw some key conclusions.

2.4. Relevance

2.4.1. Connection to sustainable development

The International Institute for Sustainable Development (IISD) has defined: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs". These ideals are directly jeopardized by the rapid growth of global climate change and the imminent threat of conventional energy supply shortage, which are direct implications of the unsustainable way of life followed so far. Sustainable energy is now in the epicentre of global attention because of the huge potential not only to deal with such severe problems but also to lead the way towards more sustainable energy systems.

Furthermore, green hydrogen is a significant element of this transition. Through the focus on the design of support schemes for green hydrogen, this research relates closely with sustainable energy and thus, with sustainable development. Simultaneously, Energy and Materials is a multidisciplinary track focusing on the sustainable use of energy and materials. Current energy systems are considered to be unsustainable due to their dependence on finite energy resources as well as being harmful for the environment. This calls for the development of cleaner, more sustainable options, able to contribute towards a more circular economy, such as green hydrogen technology.

2.4.2. Use of research

This research project is conducted under the auspices of the Fraunhofer Institute for Systems and Innovation Research (ISI), which is a pioneer in the field of innovation research covering a diverse spectrum of business fields. The results of this research study can be directly useful for the institution as it can provide the foundations for more in-depth research regarding support schemes for green hydrogen. From a societal point of view, this study could be helpful in case policy making decides to actively support green hydrogen in the short-term. The results of this research can serve as a starting point for the development of several efficient and effective support scheme designs. Last but not least, from a scientific point of view, this research study bridges a huge research gap as there is no precedent case dealing specifically with design options of support schemes for green hydrogen.

3. Theoretical Background

This chapter provides essential background information for hydrogen and elaborates on some hydrogen types (grey, blue, turquoise and green). Since the focus of this research is primarily on green hydrogen, key characteristics such as production and end-uses as well as known barriers hindering uptake are discussed in depth. Furthermore, this chapter introduces with detail the predominantly utilized support schemes (RES and non-RES related) that are used in the analysis for promoting green hydrogen use. These include feed-in tariff (FIT), feed-in premium (FIP), quota obligations, investments based on capacity and carbon contracts for difference (CCfDs).

3.1. Green Hydrogen

3.1.1. What is hydrogen

Hydrogen is the most abundant element all over the universe as well as one of the lightest elements of the periodic table. At room temperature, hydrogen is a tasteless, odourless and colourless gas. Amongst its other properties, it is non-metallic, non-toxic and highly combustible (Enghag, 2004).Even though it can be found easily in nature, most of the times is bounded together with other elements. In particular, hydrogen can develop quickly bonds with oxygen and carbon forming water, hydrocarbons and other minerals.

As a chemical compound, hydrogen gas (H_2) is scarcely found in the environment and mostly it is generated by extracting it from other compounds. The most common and cost-effective production method is steam methane reforming (SMR), in which methane reacts with pressurized steam in catalytic presence to produce hydrogen as well as carbon monoxide (CO) and a small amount of carbon dioxide (CO_2) (Rödl, 2018). Due to this scarcity, hydrogen is considered as a secondary energy carrier such as electricity and not a primary energy source as coal or natural gas.

In most of the cases hydrogen is produced and used directly on-site in industry. Ammonia production and oil refining are the most significant industrial processes, jointly responsible for more than two-thirds of hydrogen utilization. Methanol production is also an industrial process demanding hydrogen though not in the same scale as ammonia production and oil refining. Moreover, with fuel cell technology hydrogen constitutes a main option for a low-carbon transport sector. Apart from light duty vehicles (fuel cell cars), hydrogen could be suitable for a variety of transport modes with applications such as hydrogen powertrains and fuel cell buses or even ships and aeroplanes (Staffel et al., 2019).

3.1.2. Types of hydrogen

There are multiple production paths for hydrogen, demanding both fossil based and non-fossil based energy sources. In order to facilitate the discussion over the alternative types of hydrogen, a colour code nomenclature has become widely used (IRENA, 2020). Figure 2 illustrates four different types of hydrogen as well as the individual production processes and energy sources. In addition, more types of hydrogen exist depending on the combination of the production method and the type of electricity used during production (i.e. pink hydrogen from water electrolysis with electricity coming from nuclear power production).

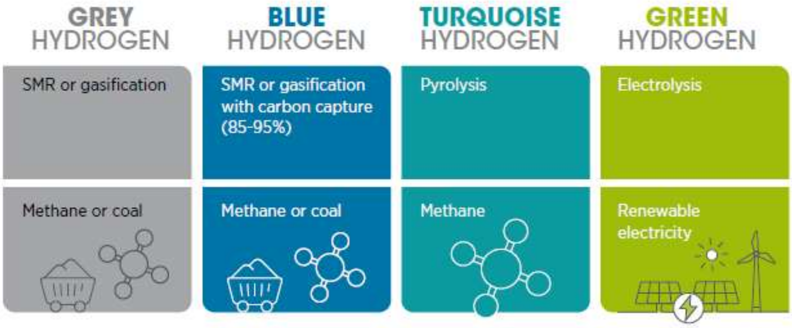

Figure 2: Different types of hydrogen (IRENA, 2020)

i. Grey Hydrogen

Grey hydrogen constitutes the most commercial type of hydrogen as it is produced in large quantities mostly through steam methane reforming but also by coal gasification. Steam methane reforming is used more frequently as it combines low capital cost and an easy-to-control chemical reaction. Both techniques lead to a mixture of hydrogen and carbon monoxide (syngas) and thus, require the latter to be removed. The production of syngas through steam methane reforming is described:

$$CH_4 + H_2O \rightarrow CO + 3H_2 \qquad (1)$$

Then, via the water-gas shift reaction the carbon monoxide reacts with steam to produce carbon dioxide and yield even more hydrogen based on the formula below:

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad (2)$$

In the final step of the process, carbon dioxide and other impurities are removed from the mixture via pressure-swing adsorption, leaving only pure hydrogen. Even though grey hydrogen production is a long established and mature technology, being fossil-based dependent is a decisive limitation from an environmental perspective. Also, it is capacity-limited due to the dependence on the finite fossil fuel reserves. In addition, the CO_2 by-product as well as the CO_2 associated with the syngas production are released in the atmosphere, which significantly contributes to global warming (Newborough & Cooley, 2020).

ii. Blue Hydrogen

Blue hydrogen is a low-carbon version of grey hydrogen. More specifically, the technology of carbon capture, utilization and storage (CCUS) is applied to the traditional production route of steam methane reforming. In this case, the CO_2 by-product is captured with CCUS instead of being released in the atmosphere and as a result hydrogen is significantly decarbonized (Newborough & Cooley, 2020).

Even though blue hydrogen is a cleaner alternative than grey hydrogen, there are still concerns dividing the climate community. From a climate perspective, blue hydrogen still relies on fossil fuels. In addition, the efficiency of CCUS could never reach 100% and thus, blue hydrogen could never become fully decarbonized. Last but not least, blue hydrogen is associated with upstream methane leakage, which creates uncertainty as methane is also a significant climate pollutant (van Renssen, 2020).

iii. Turquoise Hydrogen

Turquoise hydrogen is produced by the pyrolysis of natural gas. Through the process of pyrolysis, natural gas is converted to hydrogen and black coal according to:

$$CH_4 \rightarrow \; 2H_2 + C \qquad (3)$$

This technique demands plasma decomposition, thermal decomposition or catalytic decomposition of methane, which are under research and development stage and thus, turquoise hydrogen is still in pilot stage (Schneider et al., 2020). Unlike the methods of SMR and gasification, no CO_2 generation takes place during hydrogen production. In addition, there is already a market for black carbon, which can be beneficial for by-product utilization and extra revenue. However, it is capacity-limited, since there is still dependence on fossil fuels.

iv. Green Hydrogen

Hydrogen generated through water electrolysis shows great promise as a clean energy source of the future. Electrolysis is a single-step process taking place inside an electrolyzer, where water is dissociated to oxygen and hydrogen in presence of electricity (Kumar & Himabindu, 2019).Simply put, water is pumped into the electrolyzer that uses electricity to split the desired hydrogen gas, while leaving oxygen as benign waste according to the following chemical reaction:

$$H_2O \rightarrow \; H_2 + \frac{1}{2}O_2 \qquad (4)$$

When the electrolyzer is fed with electricity generated by renewable energy, such as solar PV installations, wind turbines, etc., the hydrogen produced is called “green hydrogen”. If the electrolyzer is powered by fossil fuels, then here are still GHG emissions associated with production. Unlike the previous types discussed so far, in this case there is nearly zero release of GHG emissions during production. In addition green hydrogen generation is not capacity-limited. Only the annual solar radiation reaching earth is enough to cover 10000 times the global energy demand (Razi & Dincer, 2020).Figure 3 illustrates the production, conversion and end-uses of green hydrogen across the energy system.

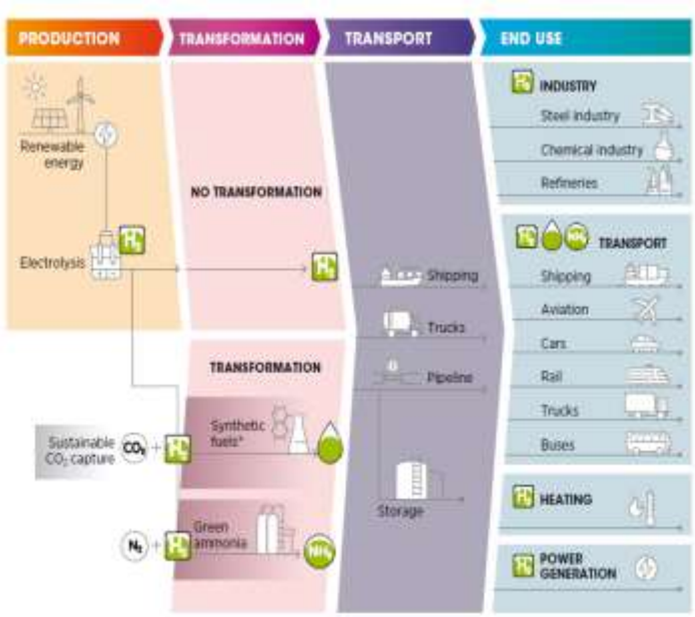

Figure 3: Production, conversion and end-uses of green hydrogen (IRENA, 2020)

Evidently, green hydrogen presents a diversity of potential uses. As an energy carrier, it could facilitate the direction of renewable energy from the power grid into end-use sectors. More specifically, green hydrogen poses as an excellent alternative for fossil fuels successfully assuming their position both as fuels and feedstock and help decarbonizing hard-to-abate sectors, such as industry and transportation (Figure 3). Finally, green hydrogen can deal with the intermittency of renewable energy sources as it can be used for energy storage. The surplus of renewable energy in times of low energy demand could be used to produce and store as hydrogen, which can be afterwards used for power generation or other purposes (van Renssen, 2020).

3.1.3. Barriers for further uptake

Creating hydrogen through water electrolysis powered from renewable energy sources is a new concept in the energy industry and faces barriers obstructing its full deployment and integration in the energy transition. Some barriers are common for all shades of hydrogen, while others exist only for green hydrogen.

As far as the barriers common to each hydrogen type are concerned, they are linked with the lack of dedicated infrastructure. So far, hydrogen production is mostly located closely to the consumption sites and thus, there is no well-developed transport infrastructure able to support hydrogen transmission around the world. In addition, the same applies for storage infrastructure, which is currently not developed to the necessary level that would enable a faster green hydrogen technology commercialization (Pasupathi et al., 2016).

On the other hand, there are barriers faced only by green hydrogen, with high production costs being the most significant. More specifically, the production cost of green hydrogen can be up to 2-3 times the price of grey hydrogen (van Renssen, 2020). Also, green hydrogen is connected with significant energy losses at various value chain stages. Large share of energy is lost during production due to the method's conversion efficiency (~60%). Furthermore, the transformation of green hydrogen to other products as well as the energy used for green hydrogen transportation add significantly to energy loss (Staffell et al., 2019). Higher energy loss results to more renewable energy consumption for green hydrogen production. Moreover, there is no green hydrogen market so far and limited demand. There is limited promotion of green product use, the low GHG-emission attribute of green hydrogen isn't properly valuated and simultaneously, grey hydrogen is widely used because of its low cost.

3.1.4. Production cost

Green hydrogen competes not only with fossil fuels as a burning fuel alternative for the transport sector but also with other types of hydrogen. In order to increase its cost-competitiveness, a good understanding of the parameters determining the production cost is mandatory. Breaking down the production costs (Figure 4), green hydrogen depends on the electrolyzer costs, the load factor of the electrolyzer and mostly the price of the renewable electricity (Newborough & Cooley, 2020).

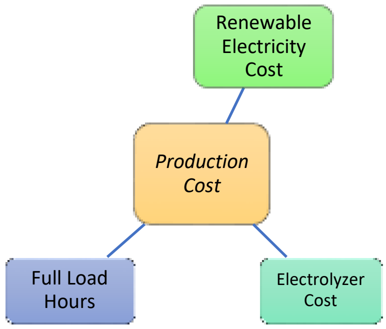

Figure 4: Breakdown of production cost for green hydrogen.

i. Electrolyzer Costs

Until today, there are two types of commercially available electrolyzers: alkaline and polymers electrolyte membrane (PEM).Both types are considered highly expensive, while PEM electrolyzers can be more expensive than their counterpart. In 2020, the investment cost for an alkaline electrolyzer ranged from 750 to 800 USD/kW (IRENA, 2020).Nevertheless, throughout the years, both technologies have realized outstanding cost reductions, which are expected to continue accordingly (Saba et al., 2018).Also, solid oxide electrolyzer cells (SOEC) are considered as a promising electrolyzer alternative yielding high efficiencies but they are still in pre-commercial stage.

ii. Load Factor

When the load factor of the electrolyzer is low, less hydrogen is produced and the investment costs are distributed to fewer units of hydrogen. As the load factor of the facility increases, the investment costs are distributed to more units of hydrogen resulting in smaller contribution to the cost per unit. However, the load hours should be regulated, since the electrolyzer needs to be operating in the optimal zone in order to yield higher efficiencies (Agbossou et al., 2015). In addition, intermediate load hour range (4-5000 h) enables stand-alone operation, which reduces investment costs.

iii. Renewable Electricity Costs

As the load factor increases, green hydrogen production is driven by operational expenditure as renewable electricity becomes the most significant cost component. Over the last years, policy support has been decisive for RES market uptake and capacity increase. Renewable energy generation costs significantly decreased during that time and they are expected to decrease even further (IRENA, 2018).At a specific renewable electricity price, conversion efficiency plays a pivotal role for the determination of the cost as a higher efficiency demands less energy and thus, decreases the cost per unit of green hydrogen. These kind of synergistic benefits alongside with potential electrolyzer cost reduction and higher full load hours shall lead to low-cost and cost-competitive green hydrogen (Newborough & Cooley, 2020). In the short-term, therefore, it is crucial to build electrolyzer capacity and decrease electrolyzer costs as much as possible.

3.2. Support Schemes

Our need to mitigate climate change and secure energy supply has led to the implementation of a diverse policy array across Europe, which includes support schemes for electricity generated from renewable energy sources (RES-E) and measures that help decarbonizing European industry and simultaneously preserving its competitiveness.

In this analysis five different support schemes are introduced. These are the feed-in tariff (FIT), the feed-in premium (FIP), quota obligations, capacity-based investment subsidies and carbon contracts for difference (CCfD). The focus here is primarily on RES-E support schemes (i.e. FIT, FIP, Quota and Investment Subsidies) due to their success throughout time to boost renewable deployment, but also in schemes of a broader spectrum (i.e. CCfD). The aforementioned support instruments were chosen because they are commonly used across the globe to support innovative projects as well as because they represent different categories, i.e. feed-in system, quota system, subsidies and contracts for difference.

According to Held and Ragwitz (2014) support schemes can be differentiated according to three characteristics:

- Support for the provision of final energy (Production-based) or support for installed capacity (Capacity-based).
- Price-driven schemes, for which the government sets the price and the volume develops according to the cost-potential curve of the country or volume-driven schemes, in which the volume is predetermined and the price follows based on individual resource conditions and technology costs.
- Overall or partial remuneration

Table 1 illustrates the main characteristics for the support schemes used in this research.

Table 1: Main characteristics of the studied support schemes.

Support Schemes	***Characteristics***
Feed-in Tariff	Production-based, Price-driven, Total remuneration
Feed-in Premium	Production-based, Price-driven, Partial remuneration
Quota Obligations	Production-based, Volume-driven, Partial remuneration
Capacity-based Investment Subsidy	Capacity-based, Volume-driven, Total remuneration
CCfD	Production- based, Price-driven, Partial remuneration

3.2.1. Feed-in Tariff (FIT)

A feed-in tariff is a policy aiming to boost energy supply by supporting the development of new renewable energy projects. A FIT scheme offers a long-term agreement, under which the supply side receives a periodic and fixed support payment per unit of generated renewable electricity, totally independent with the electricity market value (Couture et al., 2010). As a result, the total income of the renewable electricity producers is formulated by the constant support flows for producing renewable electricity as they have no electricity market income.

Generally, FIT schemes have created a significant renewable energy deployment, placing the countries that utilized them in the forefront of renewable energy industry. A significant advantage of the feed-in tariff schemes is the high effectiveness of support which can be attributed to the constant income flows (Held & Ragwitz, 2014). FITs typically lead to low revenue risks, low electricity market exposure and thus, they are not capable to create a liberalized electricity market (Couture et al., 2010).

Couture and Gagnon (2010) identify three pivotal elements contributing to the success of a FIT scheme:

(i) Guaranteed access to the grid
(ii) Stable and long-term power purchase agreements
(iii) Calculation of prices should be based on the levelised costs of electricity (LCOE)

Consequently, solar photovoltaic (PV) technologies are priced higher than wind energy due to the former's higher electricity cost. The level of the feed-in tariff is often set by administrative procedures or through auctioning mechanisms. In case of the former, the calculation is sometimes based not only on the LCOE but also on potential benefits from RES use (Held & Ragwitz, 2014). Last but not least, FIT schemes can also be used as regulation instruments because of the government's ability to direct the market based on the prices agreed in the FIT contracts (Abolhosseini & Heshmati, 2014).

3.2.2. Feed-in Premium (FIP)

The feed-in premium is one of the most common instrument for renewable energy support and a variation of the feed-in tariff. Similarly to the FIT, a FIP scheme dictates a constant payment, called premium, on top of the electricity market price. The premium is also technology dependent meaning that the payment changes for different technologies (Schallenberg J., 2017). This case though presents a fundamental difference with the FIT; RES-E producers are obliged to sell the produced electricity directly at the electricity market and receive the premium (in some cases) on top of the market price (Held & Ragwitz, 2014).

For the determination of the premium, there are several different options including fixed premium and sliding (also known as floating) premium. As it can be clearly seen in Figure 5 the fixed premium is a fixed payment on top of the electricity price, while sliding premium is calculated on a fixed temporal basis as the difference between the technology-specific electricity market price and the predefined tariff level (strike price). A significant feature of the fixed feed-in premium is the fact that support is still given even when the electricity price is above the strike price, which does not apply in the case of the sliding premium (Harmsen R., 2020).

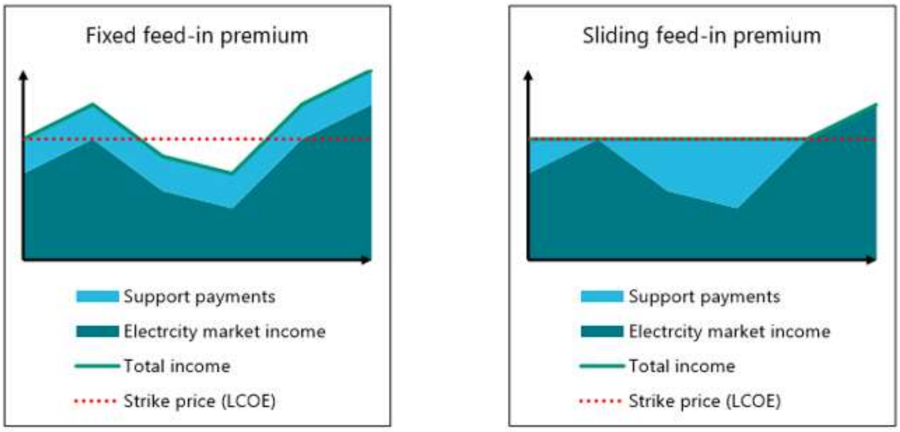

Figure 5: Fixed feed-in premium (left), Sliding feed-in premium (right) (Harmsen R., 2020)

Feed-in premium schemes incentivize RES-E producers to respond to the price signals of the electricity market, for example generate electricity when the demand is high and/or generation from other sources is low. Also, in case of new projects, investors are encouraged to consider expected load patterns in regards to the engineering of the individual projects, which is not always the case for FITs (e.g. orientation of PV, site, wind turbine type etc.). Through this way, FIP assists significantly in the market integration of RES, matching efficiently electricity supply with demand.

3.2.3. Quota Obligations

Quota obligations is a volume-based instrument that aims to support renewable energy production by increasing renewable electricity demand and supply. This is achieved by obliging consumers or producers to consume or generate a minimum amount of RES-E, while the price is determined by the electricity market (Schallenberg J., 2017). The obligation scheme is mostly imposed on the consumer side and usually it involves a penalty in case of non-compliance to meet the obligations.

Quota schemes typically include two different concepts, the quota and the tradable green certificates (TGC). The former corresponds to the percentage of renewable electricity which is mandatory to be supplied, while the latter is the physical certificate per unit of renewable electricity that practically guarantees the unit's renewable origin. RES-E producers receive certificates for the green final energy they generated, which afterwards they can sell to the actors mandated to meet the quota obligations. In order to verify their compliance, the actors retire or hand over the required number of certificates on a temporal basis to the monitoring authority. Just like any other commodity, TGCs can be traded, banked and consumed. The sale of a certificate can be detached from the sale of the electricity unit and thus, this creates an additional revenue on top of the electricity market earnings (Van der Linden et al., 2005). Figure 6illustrates the flow chart of a typical obligation scheme.

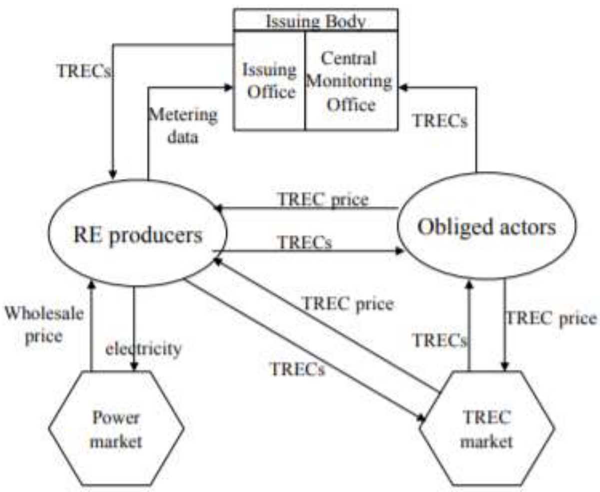

Figure 6: Schematic overview of a typical obligations system (Van der Linden et al., 2005).

In regards to the design of the quota obligation with TGC, a significant first step is the determination of the target, which often is a specific RES-share in final consumption. Furthermore, quota obligation schemes are typically designed in a technology-neutral form, resulting in the same level of support for every renewable technology (Held & Ragwitz, 2014).

3.2.4. Capacity-based Investment Subsidy

An investment subsidy is a direct subsidy created by the government for businesses in order to encourage further investments in innovative, capital-intensive technologies. RES-E investment subsidies has been used from several EU member states in order to incentivize the take-up of less mature renewable energy technologies. Investment subsidies also were applied for mature renewable technologies with high investment costs. This type of investment support can also be used as a complementary measure alongside with other instruments such as FITs or FIPs (Held & Ragwitz, 2014).

The primary aim of a capacity-based investment subsidy is to bridge the gap between the upfront investment cost and the expected market earnings in present value (upon subtracting the costs for operation), in order to make the project look more attractive to potential investors. The payments are either given based on the expected installed capacity or expected project cost. Both alternatives are relatively similar, since they are taking into account the expected performance and not the final power generation (Huntington et al., 2017).

3.2.5. Carbon Contracts for Difference (CCfD)

The industrial decarbonization is not an easy task and certainly requires investments in innovative low-carbon technologies. In many industries, these technologies are already known and ready for deployment from a technological perspective. However, because of increased investment and operational costs as well as the presence of high revenue risks compared to conventional alternatives, these technologies are not yet ready for commercial deployment. For this reason, governments that are aiming for emission abatement can assist in this significant transformation by setting a higher level in carbon pricing. Carbon contracts for Difference (CCfDs) is an alternative that can deal with risks sharing the burden between governments and private entities, while significantly contributing towards industrial decarbonization.

Carbon contracts for difference are a project-based financial instrument, strongly linked with the EU Emissions Trading System (ETS). With CCfDs, the cost differential between the incremental costs of production with an innovative, low carbon technology and the respective conventional, emission-intensive technology are compensated (Agora, 2021). The mechanism for a CCfD is illustrated below in Figure 7. When the mitigation costs of the innovative technology (CCfD strike price) are higher than the effective carbon price, the company receives the difference as a compensation. However, if the carbon price overcomes the CCfD level price, then the company is mandated to give the additional earnings back to the government. Through this mechanism, the CCfDs are used as a hedging instrument since they decrease the carbon price risk and, simultaneously give space for long-term financial planning (CFM, 2021).

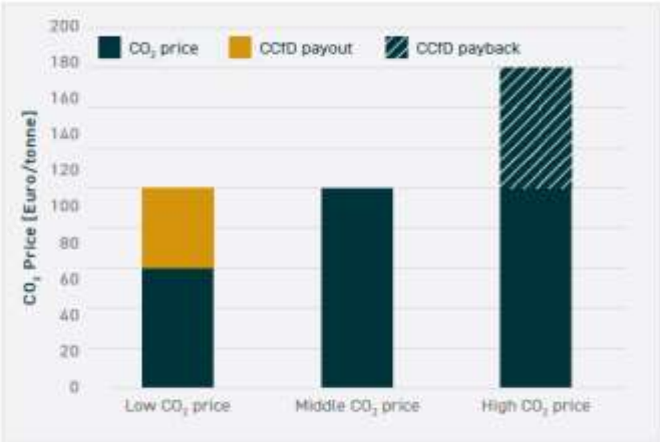

Figure 7: The CCfD mechanism (Richstein, 2017)

4. Research Methodology

This chapter describes the methodological framework and planned analyses of the study. Initially, section 3.1 provides an overview of the research design that serves as a base to address the main research question. The approach of the study is purely qualitative, so the research methods to be employed are literature research and theoretical analysis. Section 2.2 elaborates more on both the selected analyses.

4.1. Methodological framework

In order to realize the research goal and properly address the main research question, the study consists of a succession of three stages. Each of the first two steps addresses the corresponding sub research question. The third and final step integrates the findings of the previous steps in order to address the remaining two research questions. The key conclusions drew from the integration step provide the means to successfully fulfil the research objective. Figure 8 illustrates the schematic overview of the research design leading to the answer of the main research question: “What are potential support schemes for promoting green hydrogen use?”

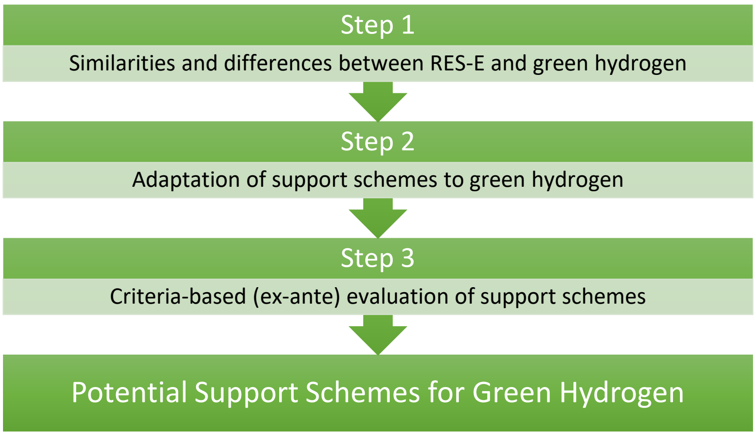

Figure 8: Schematic overview of the research design

First Step

In the first step of the research the focus falls on the comparison of green hydrogen and renewable electricity in order to indicate whether RES-E support schemes could be used for increasing green hydrogen production and use. There are apparent similarities between the two energy carriers that make it possible for RES-E support schemes to be utilized for green hydrogen purposes. Also, there are some key differences which make it necessary for the RES-E support schemes to be adapted. Through this step the first sub question “What makes RES-E support schemes applicable for promoting green hydrogen?” is answered.

Second Step

In chapter 3, a number of support schemes was introduced. While the majority of them are commonly used for RES deployment, there is also a support scheme that is not. Having determined that RES-E support schemes can indeed be helpful for the promotion of green hydrogen, this step focuses on their design. Therefore, this step focuses on the most crucial design elements that need to be taken into consideration for the development of support schemes aiming to promote green hydrogen. These elements are mostly connected with the payments as well as the general implementation of the support schemes. Upon conducting this theoretical analysis, several support schemes for green hydrogen are developed. Through this procedure, the sub question "How can RES-E support schemes be adapted in order to support green hydrogen?" is answered.

Third Step

After the adaptation of the support schemes, a literature review is conducted in order to identify some common criteria (i.e. effectiveness, efficiency, equity, flexibility, market integration and revenue stability) for support scheme evaluation and answer the third sub question "What kind of criteria could be used to evaluate different support schemes for green hydrogen?"

The final step includes the integration of the results from the previous steps. This is realized through a criteria-based evaluation, in which the support schemes for green hydrogen are evaluated based on the selected criteria in order to assess their overall performance. This method answers the sub question "How do the support schemes for green hydrogen perform based on the selected criteria?" and consequently, draws significant conclusions in order to determine the most appropriate support schemes for promoting the use of green hydrogen.

4.2. Planned analyses

The planned analyses for addressing the questions of this study are literature review and criteria-based (ex-ante) evaluation. Literature review is used to address the first three sub questions, while the criteria-based evaluation is employed for answering the fourth sub question.

Literature Review

Literature review constitutes an important research method for this research. All the necessary elements for the development and evaluation of the support schemes for green hydrogen are collected through this research method. More specifically, literature review is mostly important for the identification of specific design options needed for the adaptation of the support schemes to green hydrogen. Furthermore, it is used for the selection of appropriate criteria that can be used for the evaluation of different support schemes for green hydrogen.

Criteria-based (ex-ante) Evaluation

Ex- ante evaluation is commonly used to provide strategic information for a group of options. In this case, the evaluation is employed in the last step of the research, integrating the results of the previous steps and performing an evaluation of the developed support schemes for green hydrogen based on a set of criteria. In order to evaluate the overall performance of the support schemes the Simple Multi Attribute Ranking Technique (SMART) is utilized. Initially, the support schemes are analyzed qualitatively based on their criteria performance and in comparison with each other. In a later stage, the overall performance of each alternative is calculated based on the SMART method. Through this simple, fast and easily applicable method the support schemes are grouped and discussed based on the ranking of their overall performances.

5. Comparison of Green Hydrogen and Renewable Electricity

The development of a hydrogen system produced by using the multi-energy complementary of renewable technologies, much like renewable electricity, has the favourable characteristics of being green, sustainable and low-carbon, which are placing it in the centre of global research attention. This chapter aims to analyze the similarities and differences related to support schemes between renewable electricity and green hydrogen. Through this comparison, the goal is to indicate the similarities making the RES-E support schemes applicable for green hydrogen as well as the principle differences, the adaptation of which is necessary to design support schemes appropriate for promoting green hydrogen.

The strict climate agenda towards the mitigation of climate change and the creation of circular systems is driving change in the energy sector. Renewable electricity and green hydrogen are commodities fairly considered as crucial elements of the process towards net-zero. The effective deployment of green hydrogen demands a significant amount of excess renewable energy, which is yet not available. Hence, electrolyzers operate on low full load hours, driving up the costs per unit. Evidently, green hydrogen costs are two to three times higher than its fossil based counterpart (grey hydrogen). The same applied for renewable electricity before the policy implementation that eventually drove down costs.

Green hydrogen finds application across several sectors, such as industry, buildings, mobility and the power generation sector. Although such green, innovative technology is still in nascent stage, there is a great potential for market competitiveness. Even though grey hydrogen is at the moment the dominating form of hydrogen in terms of utilization, renewable hydrogen's versatility and lower environmental impacts will make the difference, especially as the cost efficiency gap between these two alternatives starts to bridge. Blue hydrogen could also be a potential substitute, already being a cost efficient alternative to grey hydrogen. However, the fossil-based origin of blue hydrogen is an important factor decreasing its value, especially in light of the grand net-zero goal by 2050. Thus, the focus now should fall into finding more cost-effective production pathways for green hydrogen. The market competitiveness of renewable energy was also highly potent and nowadays it has reached fairly significant levels as hydropower, onshore wind, biomass and geothermal can, where good resources and structures exist, provide electricity as competitively as their fossil-based counterparts.

Arguably, renewable electricity and green hydrogen are two secondary energy carriers with several similar properties. When breaking down the supply chain of renewable electricity and the supply chain of green hydrogen this can be easily identified as many similarities can be observed. For renewable electricity, the process from raw materials to final product can be described by five distinct phases including energy source procurement, production, transmission, distribution and demand (Engelken). Similarly, the design of the supply chain of a hydrogen system includes the energy source, production, transport, storage and distribution for end-use (De-Leon, 2014). In the case of green hydrogen the energy source should be renewable, just like the procurement phase of renewable electricity.

Besides the apparent similarities, the analysis of the individual phases can bring in the surface some key differences between renewable electricity and green hydrogen. These are closely connected with storage, transport/distribution and demand. Apart from these, the lack of infrastructure for green hydrogen production, storage and distribution as well as the market difference of these two commodities are also significant factors.

Storage

Unlike the versatility and flexibility that green hydrogen presents, the transient nature of some renewables question their reliability due to their associate intermittency. As wind and solar technologies keep penetrating the energy mix, the intermittency issue will keep getting more persistent. This stems from the fact that excess renewable electricity cannot be directly stored. On the other hand, hydrogen can be stored and this makes it a promising chemical energy storage technology. Green hydrogen appears to be a good fit as it has high energy density, storage duration ranging from days to months as well as negligible environmental impact. (Sterner & Stadler, 2017).

A major part of renewable electricity production is characterized by a large degree of intermittency driven by the natural variability of climate factors such as air temperature, wind velocity, solar radiation, precipitation, evaporation, and river runoff. Renewable electricity prices are following this erratic behaviour, they drop in case of excess renewable energy and vice versa. As green hydrogen originates from renewables, it is logical for the same dependences to be present. However, the fact that hydrogen can be stored and easily transformed is an attribute missing from renewable electricity. Therefore, it might be much more possible to better control the green hydrogen prices due time.

The ability of long-term storage can be exploited in case of daily or seasonal variation due to the intermittent nature of renewable energy sources. In case of excess renewable electricity, green hydrogen can be produced and stored. So, in times with high variation that increase the cost of producing green hydrogen, the reserves can be used. Also, countries with characteristics preventing the penetration of renewable electricity (e.g. low solar radiation or low wind velocity) can still receive green hydrogen as it can stored and transported. The energy sector has gained valuable experience of transporting gases for long distances over the course of time.

Demand

Unlike the never-ending electricity demand, the demand for green hydrogen is still in infancy. Even though there are great promises and national plans still there is lack of clarity regarding the actual future demand. The recognition for the green value of hydrogen is still little and the real demand exists mostly for products made using green hydrogen (e.g. green steel or green ammonia). Once electrolyzer capacity as well as renewable energy capacities increases, higher amount of green hydrogen can be produced. Support schemes are the crucial tools to not only assist in increasing the demand for green hydrogen but also bridging the price gap between green hydrogen and its counterpart, blue and grey.

Infrastructure

Electricity infrastructure provides a substrate for modern life through the network of wires, towers, dams, and turbines that literally powers our economic and social practices. Due to its importance to everyday life, electricity infrastructure is constantly evolving as new technologies and business models promoting economic development and improving reliability are inserted into the grid. Renewable electricity runs through this same electricity infrastructure. However, there is not such a ready, organised infrastructure system for green hydrogen

Transport-Distribution

Hydrogen is highly volatile and lighter than air, making the transportation and storage tricky. Thus a major challenge in the near term is to locate green hydrogen production close to demand site. Over time, however, as demand for green hydrogen rises, the cost advantages of producing large volumes of hydrogen, from major sources of renewable energy, will drive further growth of international markets for hydrogen.

Long-distance transportation networks must be developed, most likely using ships. For shorter distances, large amounts can be sent through pipelines, while a combination of trains and trucks can deliver smaller amounts. Hydrogen is highly flammable and explosive, escapes easily, and has a relatively low density. Transporting it in one of its higher-density forms is preferable but requires compression, liquefaction, or conversion. The most economical way to transport green hydrogen across distances of up to a few thousand kilometres is through pipelines, opening up a further opportunity in pipeline construction and repurposing.

Market Difference

Over the last three decades, the electricity market has evolved greatly and managed to supply consumers with reliable electricity at the least possible cost. The same doesn't apply yet for green hydrogen, as the global green hydrogen market was only $0.17 billion in 2019 (Mohite & Danekar, 2021). However, there great prospects for a more strong, mature market in the future. According to a report from Mohite et al. (2021), green hydrogen market size almost doubled in 2020 (i.e. $0.3 billion), while it is projected to reach nearly $10 billion by 2028.

At present, the nascent market for green hydrogen is both highly complex and highly fragmented, but it holds real promise. Governmental support and private investments are beginning to flow into the sector, and large companies, small and midsize enterprises, as well as start-ups are rapidly entering the field. Yet uncertainties—about the market, the right business models, the best technologies, and ongoing government support—remain high.

Navigating the market will take a great deal of expertise and a consistent, carefully considered strategy.

The uncertainty over the green hydrogen market is of great significance in this analysis. This is credited to the fact that it can directly influence the choice of policy support packages, as some instruments serve different purposes and can be more suitable for promoting green hydrogen under the current market (status quo), while others can be more suitable to use within the framework of a more mature market.

Considering all the above, it is undisputed that green hydrogen shares many similarities with renewable electricity, which indicate that the utilization of RES-E support schemes for promoting green hydrogen has a significant potential. Nonetheless, there are some significant differences that differentiate these two energy carriers and need to be taken into consideration during the support scheme design. Table 2 below, contains the overview of this chapter.

Table 2: Similarities and differences for green hydrogen and renewable electricity

Similarities	**Differences**
Commodities produced and sold	Infrastructure
Energy Carriers	Market Maturity
Applicable in several sectors	Storage
Capacity boost mandatory	Transport/Distribution
Similar Supply Chain	Demand

6. Design of Support Schemes for Green Hydrogen

In this chapter the instruments for bridging the gap between green hydrogen and its fossil counterparts are discussed. More specifically, the primary focus of this part is shifted on the most common design elements connected with the payment as well as the general support scheme implementation. The design options of feed-in schemes, quota obligations with tradable certificates, capacity-based investment subsidies and carbon contracts for difference are analyzed.

6.1. Feed-in Scheme Design

In order to incentivize investment in a highly capital intensive technology as green hydrogen is, here, the feed-in system is proposed as a support scheme encourage green hydrogen production and use. The following sections provide an overview of the basic feed-in payment and implementation options.

6.1.1. Dependence on market prices

A significant feed-in payment element is the choice on whether the feed-in scheme depends on the market prices or not. As introduced in Chapter 3, the feed–in tariff scheme is independent of the market price and constant over a pre-determined period of time. On the contrary, in a feed-in premium scheme the payment is closely linked with the market as it is determined by simply adding a premium price on the spot market price. For green hydrogen, the two options could be adjusted as described below.

i. Feed-in Tariff Scheme

The support is given to the independent green hydrogen producer as a fixed payment per unit (i.e. kg or tonne) of produced green hydrogen. More specifically, the hydrogen generated by renewable electricity is directly sold to the hydrogen market in the pre-determined strike price. Therefore, the producer is obliged to provide the green hydrogen at this specific pre-determined price no matter the green hydrogen market status and thus, the income is a direct function of the quantity of the green hydrogen that is produced.

Under the feed-in tariff scheme, the payment is independent of the market prices and constant over a fixed time frame. Through these reliable, long-term income streams a stable and attractive investment environment is created. Consequently, investors are encouraged to invest on green hydrogen projects, being offered long-term, stable income streams which provide a revenue stability and an attractive return of investment.

ii. Fixed Premium Scheme

In this case, the financial support is provided to the independent green hydrogen producer as a form of a fixed premium on top of the green hydrogen market price. More specifically, the producer sells directly to the green hydrogen market, while also receiving a fixed, periodic payment. The support payment is once again totally independent to the market price and remains unchanged according to the duration of the contract.

Under the fixed premium scheme, the revenue of the producer is determined by the earnings from selling green hydrogen to the corresponding market price alongside with the fixed premium received from the support scheme.

6.1.2. Strike price determination

The determination of the strike price level is a very crucial design element for developing a cost efficient and effective support scheme. On the one hand, the determination of an appropriate strike price helps to avoid overcompensation, which can lead to a very costly support scheme. On the other hand, the strike price clearly determines the level of support as well as it influences the attractiveness of the green hydrogen investment. There are two common approaches used to set the overall payment to producers. The first one entails to base the strike price on the levelised costs of generation alongside with a targeted return. The second approach is a category on its own, the design of auction schemes to set payment levels.

a. The levelised costs approach

A common approach for the determination of the strike price level includes the levelised cost approach. According to Klessmann et al. (2013), the levelised cost approach is described as the present value of the overall costs of a plant across its lifetime, converted into yearly payments. So this calculation corresponds to the economic assessment of the project over its lifetime. The levelised costs are calculated through a net present value - cash flow model which includes a combination of economic and technical variables. However, the sophistication level as well as the sensitivity of the analysis can result into variations across different models. Generally, the norm for feed-in systems is to design support schemes providing attractive return of investment rather than excessive. Consequently, there is a characterisation of typical projects that assume some general prices, which not only increases the transparency of the scheme but also assumes responsibility from a societal point of view (Held et al., 2014).

b. Auction Schemes

An auction is not a support scheme itself, but it can be easily combined with other supporting instruments, especially feed-in tariffs and feed-in premiums. In an auction, the strike price of the feed-in scheme is determined through a very competitive procedure as described in Figure 9 (Klessmann, 2014).

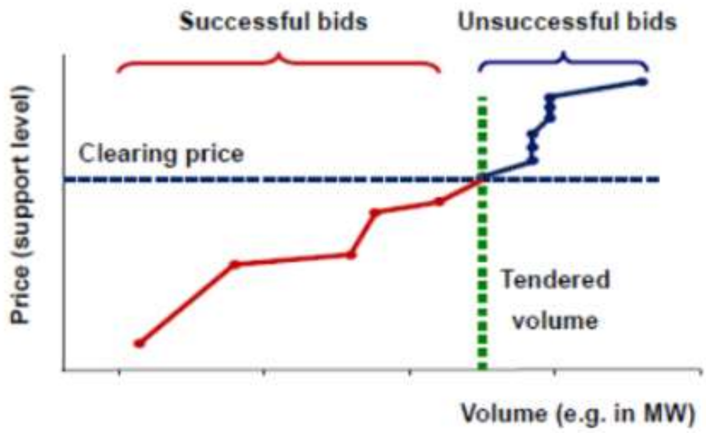

Figure 9: Auction procedure (Klessmann, 2014).

When designing an auction, the regulatory body usually indicates the desired capacity of the technology-specific project to be auctioned (Becker et al., 2013). During the auction, the interested parties perform their bids (usually in the form of euro per product unit). The bidder with the best offer or the lowest bid wins the auction and is allocated the project in this specific strike price for a pre-determined time period.

Auctions are a different way to establish feed-in prices, one that appeals to the market directly rather than through third-party analysis. This approach is when an auction (separate from the policy itself) is used to inform feed-in price setting for projects of various kinds. A big advantage of the auctions is that they can be significantly cost-efficient since the lowest bid usually (depending the auction type) wins the project. This advantage can be extremely beneficial in the case of green hydrogen as it entails that the bidders do their own research, set their own strike price and ultimately make a bid. Through this way, not only the winning bid is most cost efficient bid but also gets the strike price that deemed appropriate for the feasibility of the project, thus decreasing the risks of over- or under-compensation.

6.1.3. Contract duration

The duration of the contract can be short (e.g. 5-10 years) or long (e.g. 20-25 years). As previously discussed in Chapter 2, long-term contracts have been very effective for renewable technologies and this could also be the case for green hydrogen as longer contract duration offers long-term financing which is highly important for capital-intensive projects. On the counterpart, short-term agreements can be more flexible, as they can be adjusted after a short while, under new market conditions and thus, becoming more custom to the project avoiding over or under-pricing.

6.2. Quota Obligation with Tradable Certificates Scheme

The implementation of quota for green hydrogen would lead to the creation of reliable demand in several sectors such as transport, industry and buildings. This in turn would be a great stimulus for further green hydrogen growth as well as for technological learning.

Following this logic, the quota enforces a specific share of green hydrogen on general hydrogen demand. Therefore, the quota can be imposed on the demand side, however the obligation for compliance falls on the supply side. Non- compliance to the quota is treated with a financial penalty.

Tradable certificates can be used to ease this burden and facilitate the obliged market participants to verify compliance. They are commonly used, especially in the renewable electricity sector, and contain in detail the generation characteristics of the unit. In this case, the certificates for green hydrogen can verify the renewable origin of the produced hydrogen as well as other attributes such as the production site, age of the plant, plant capacity etc. In addition, the production side is incentivized to produce green hydrogen and receive tradable certificates, which after being sold offer an additional revenue. The generated hydrogen and the certificates are traded on different markets – the certificate market and the hydrogen market.

The basis of the tradable certificates can be described in the following steps:

- Step 1: The tradable (green hydrogen) certificate is issued to the producer from the issuing party per unit of produced green hydrogen.
- Step 2: The producer can sell the certificates separately from the green hydrogen and create an additional revenue.
- Step 3: The green hydrogen supplier buys the green hydrogen certificate in order to cancel it and ultimately comply with the quota.

6.2.1. Setting the quota level

By definition a quota is a government-imposed restriction imposed on a variety of traded commodities. Within the international trade framework, quotas are used for the regulation of trade between countries. In any case the quota level is determined by regulatory bodies, usually governments. Quota obligations for green hydrogen can be used as an instrument to regulate the percentage of green hydrogen within the hydrogen market. Therefore, the quota level is closely linked with the country's long-term goals, the level of commitment to green hydrogen deployment as well as the desirable result to be achieved. Given the immaturity of green hydrogen market and the absolutism o the quota obligations it would make more sense to initially set low quota levels. A successful implementation of quota obligations will lead to a minimum share of penalties, increased green hydrogen share in the hydrogen market and a stronger and more mature green hydrogen market. Once these levels are achieved, then there should be a consideration of higher quota levels.

6.2.2. Banding coefficient

A significant design element is the determination of the banding coefficient, i.e. the number of green certificates issued per unit of production. Banding coefficients vary greatly among different technologies. For example, under a Romanian scheme, solar PV installation were awarded six certificates per MWh, while small hydro projects were eligible for three certificates per MWh (Pislaru, 2014). However, technology-specific banding coefficients can also vary by nation and time, as they are subject adjustments as a result of the evolution of investment costs, market prices etc. Once a banding factor is assigned for a project, it is fixed and unable to change. Evidently, for the region of Flanders, which has implemented a quota system paired with certificate trading, banding coefficients are communicated by the Flemish Energy Agency annually. In contrast to the Romanian scheme, in this case, solar PV installation were awarded with one certificate per MWh.

6.2.3. Penalty Level and Certificate Price

In order to ensure a demand for certificates there must be a penalty mechanism in place when not meeting the legally required number of certificates each year. In other words, the cost of failing to meet the legal obligation to purchase certificates must be higher than the market price for certificates. Most countries have an administratively set rule on how to determine the level of penalty. It is usually either set annually or as a fixed price level. Similar to a tendering scheme, the level of penalty needs to be well designed to exercise the right amount of pressure to ensure compliance.

Wholesale prices for certificates intended for compliance vary greatly by nation and through time as it depends on specific policies as well as the supply-demand dynamics. Maximum certificate prices can be introduced to limit the maximum burden imposed on the end consumers. In case the price overrides this level consumers would reasonably choose to pay the penalty instead of buying more certificates. Also, a minimum price can be set, as a means to ensure that producers have revenues from the certificate market even in case of high production, thus high certificate supply that pushes down certificate prices.

Correspondingly, one could argue that also a minimum certificate price should be set, as to ensure the “green” producers a minimum revenue from the green certificate market even in times with very high production (and thereby high supply of certificates, potentially pushing the price down to a level under the minimum price)

6.3. Capacity-based Investment Subsidy

Capacity remuneration schemes are implemented or more specifically their implementation is widely discussed across the EU. Within the energy sector, these mechanisms are designed to generate revenues in order to remunerate the fixed costs of a plant.

As discussed in the second chapter of this thesis, capacity-based investment subsidies are intended to return the difference between the upfront investment costs of a plant and the present value of the projected market income. The operation costs are subtracted from the expected market earnings, as the aim of the scheme is to make the project look attractive and profitable for the potential investors. For a green hydrogen project, the support will be given on the basis of final performance, therefore based on the overall installed electrolyzer capacity (in MW). Here, the focus falls on the design elements connected with the format of the remuneration.

6.3.1. Estimation of the market-based earnings

The most significant part of this subsidy is the selection of the method, through which the calculation of the market-based earnings of a project will be performed as well as the determination of the operating costs to be subtracted. These can be determined based on two different methods, either an ex-ante forecast of projected market earnings for a given plant over its lifetime or ex-post by focusing on market results.

The ex-ante method constitutes a straightforward approach, as an ex-ante projection of market prices is developed through which future market revenues for a given plant over time can be determined. When it comes to forecasting renewable electricity prices, calculations can become error-prone due to the intermittency of the renewable energy sources. This, in turn, creates great risks of under- or over-estimating the investments. Actual market revenues turning out to overpass the projected amount, the support scheme becomes more expensive, more funding than necessary is used and the RES-E investors enjoy windfall profits. On the counterpart, if future market revenues prove to become lower than expected, then the side obtaining the support faces the danger of not being able to recover their costs.

The ex-post method uses a benchmark plant, a reference facility that could serve as an efficient, good-structured and well-managed model. As part of the analysis, the market income of the reference plant is calculated, thus enabling the determination of the support level that allows the plant to break even. This approach not only offers more certainty to the investors, but also encourages competitiveness among the competitors. Support payments are the same for all units, so the plant that outperforms the rest earns higher revenues in return. Reference plants need to be constantly updated due to the highly evolving conditions of the market. Last but not least, it is important to identify the silver lining between the amount of benchmarks to be used and the overall transparency of the process.

6.3.2. The timeline of the support

Support payments can also be realized ex-ante or ex-post taking into account observed market income of the benchmark. In case of the latter, if actual market prices fail to meet the expectations, then the ex-post capacity incentive can be adjusted to make sure that the plant breaks even. This ensures investors that fixed costs shall be recovered, but demands a high capital of initial investment. Capacity-based support can be awarded as a one-time payment or with form of periodic payments due time, each one presenting a unique advantage. When it comes to one-time payments they are simpler, as they involve a single transaction and with less administrative work for both ends. On the counterpart, periodic payments can be more flexible offering the opportunity of further adjustment.

6.3.3. Performance regulation

A potential disadvantage of capacity-based schemes, which is often a source of consistent criticism, is the lack of motivation towards effective – focused on maximum output – design, which eventually leads to lesser generation per unit of installed capacity (Harmsen, 2020). The market remuneration prospect plays a significant part, as high potential market income is a great incentive towards optimized, efficient installations.

This applies mostly to low-cost projects, able to recover the investment through the support. However, the uncertainty over the green hydrogen market as well as the high remuneration levels needed for the support may be decisive towards similar behaviours. In this case, mechanisms to avoid such risks are deemed necessary.

A possible course of action would be the introduction of minimum performance requirements to the agreement of the support, penalizing non-conformance. These can take the form of minimum standards for system design, overall efficiency or full load hours of operation. The realisation of such measures demands continuous performance monitoring. This definitely sets a minimum barrier for acceptable design that ensures higher production, but also creates more administrative costs.

6.4. Carbon Contracts for Difference (CCfDs)

As previously discussed, CCfDs reimburse the cost differential between the incremental costs of production with an innovative, low carbon technology and the respective conventional, emission-intensive technology. In exchange for this significant insurance, given the high volatility of carbon prices, the investors are subjected to payments when the carbon price overcomes the CCfD level price. Through this agreement, companies have a considerable financial incentive to make innovative, climate-friendly investments.

A common element of innovative technologies used for carbon mitigation purposes within the industrial sector is the high investment costs. Often, the operation costs can be even higher, as in the case of green hydrogen. Under other funding schemes there is a great risk, in case of low carbon prices, the operation of the plant not being worthwhile, which eventually may jeopardize the investment. The notion of this prospect can contribute negatively towards the realization of any innovative, green project.

Implementing CCfDs for the promotion of green hydrogen projects offers a great advantage, the reduction of financing costs. Through CCfD agreements, investors are receiving stabilized revenue streams, independent to the high volatility of carbon prices, which enables them to secure loans, resulting in cutting financing costs. Generally, the stabilization of the revenue stream gives the necessary confidence to the creditors that their debts will be eventually repaid. In addition, CCfDs can be combined with traditional investment grants, which can in turn further decrease financing costs.

6.4.1. Design elements

When it comes to the realization of a CCfD agreement, several different design elements can be taken into consideration and be carefully addressed. Several of them are influencing the financing conditions of the project, while others are linked with the practical implementation. Options directly associated with the financing perspective include the exact remuneration level (i.e. reference contract price) as well as the exit-options of the contract. The way in which the CCfD is awarded as well as the contract duration and the combination with other policies are very important of the overall framework. Most importantly though, since the company receiving support from the government is taking an advantage from its competitors, CCfDs are technically state-aids and therefore should follow the EU State Aid rules.

6.4.2. Award process

Regardless of geographic scope, commercialisation contracts should be allocated via a competitive process. This would involve bids from individual low-carbon projects. The core of a project's bid should be the strike price, or the guaranteed carbon price the project asks for in order to proceed with commercial operation. The central component of allocation should be an auctioning system: the lower the strike price, the more attractive the bid. Auctions work as a mechanism because of the information asymmetry between industry and policymakers. Industry better understands the true costs of decarbonisation and their preferences could be revealed through auctioning.

6.4.3. Duration of the CCfD

Certain industrial sectors such as green hydrogen have very long investment cycles. Given the high technological and financial risk that is intrinsic to projects introducing new process technologies at such a massive scale, it is particularly important to allow CCfDs to cover the entire period of the investment. Ideally, in this timeframe, reliable political framework conditions enabling internationally competitive production of green hydrogen will be introduced, allowing green hydrogen to become economically viable and operate without any CCfD support. However, should this not happen, the capability of extending the support of the instrument should exist.

6.4.4. Geographical scope

A very decisive design element is the determination of the party that issues the contract. It could be national governments or the European Union alongside with its institutions. The discussion of whether a CCfD should be implemented at a national or international level can be very debatable. On one hand, the European approach could serve providing a total transparency as it would prevent distortions between different companies and ensure that every party is treated equally. Also, it could serve well to avoid the considerations on whether the CCfDs should be considered state aids. Furthermore, a European approach could also create incentives for project implementation in developing countries. On the other side of the coin, a national approach might be easier to coordinate the support given from a CCfD through national support systems. In addition, it would be very challenging to make Member States to renounce their plans and competences over such an important decarbonization policy. Considering all the above, it would be more practical to acknowledge that CCfDs shall be awarded on a national basis. This, however, subjects them under the State Aid rules, which ultimately entails a specific harmonization level between the Member States.

6.5. Overview

In the sections 6.1 to 6.4, five different support scheme designs were discussed as well as their basic design elements, which need to be taken into consideration when it comes to promoting green hydrogen. The present section summarizes the most important data of this chapter and are illustrated in Table 3 below.

Table 3: Support schemes for green hydrogen overview

Support Schemes	***Design Elements***	***Income***
Feed-in Tariff	Strike price determination, Duration of support	Payment per unit of generated hydrogen
Feed-in Premium		Payment on top of the hydrogen price
Quota with Tradable Certificates	Determination of quota level, Banding Coefficient, Penalty level, Certificate price	Income from hydrogen and certificate price
Capacity-based Investment Subsidy	Estimation of market-based earnings, Timeline of support, Performance regulation	Income from hydrogen price and capacity premium
Carbon contracts for Difference	Remuneration level, Exit options, Contract duration, Alignment with EU State Aid rules	Income from hydrogen price and per tonne of avoided CO_2 (can be negative)

7. Multi-criteria (Ex-ante) Evaluation of Support Schemes

The evaluation of various policy instruments have received an extra attention during the last years due to their usefulness to provide assistance to governments in the identification and optimization of the instruments dynamics in a more effective manner. Energy policy making is one of the most significant issues for countries and it can be evaluated by using multi-criteria decision making (MCDM) methods. The energy decision and policy-making problems include selecting among energy alternatives, evaluating energy supply technologies, determining energy policy and energy planning. There is a wide range of studies about energy decision-making problems in the literature and different types of energy alternatives are considered in these studies. The MCDM methods are used as effective tools to facilitate the decision making process to conduct qualitative and quantitative evaluations through the use of criteria, which reflect not only their preferences but also these of the involved stakeholders. The purpose of this chapter is to evaluate the support schemes promoting green hydrogen through a qualitative analysis in order to identify strengths and weaknesses as well as to indicate the overall individual performance.

Konidari & Mavrakis (2007), present in their paper an integrated multi-criteria analysis for the quantitative evaluation of instruments used for climate change mitigation policies. The elements of the analysis include a set of criteria and sub-criteria that in total describe the overall performance of the different chosen instrument, an Analytical Hierarchy Process (AHP) for the determination of the weight coefficient as well as a Simple Multi-Attribute Ranking Technique (SMART) in order to assign grades for all the evaluated instruments under each specific sub-criterion. The proposed evaluation tool is characterized as simple, flexible, reliable and convenient for the analysis of the performance of different climate change evaluation policies. Indeed the evaluation tool is simple and flexible as it demands minimum assistance from the decision making process and the individual instrument performance can be easily assessed due to the properties of the SMART procedure. Considering all the above and the fact that the promotion of green hydrogen could also be part of the climate change mitigation agenda, an adaptation of the tool proposed by Konidari and Mavrakis will be used for the assessment of the different instrument aiming the promotion of green hydrogen.

More specifically, the multi-criteria evaluation of support schemes for green hydrogen consists of four distinct steps. The evaluation’s first step includes the creation of the criteria list. Then, the second step corresponds to the determination of the weight coefficient of each criterion. Third step discusses the assumptions taken for the realization of the analysis. In the fourth step, the grading of the support schemes under each criterion is performed, followed by the illustration of the final results over the support schemes’ overall performance.

7.1. Criteria List

In practice, criteria are the measurable dimensions of an objective. Different policy alternatives or support schemes are compared using criteria on how close they can come to goal realization. The evaluation criteria are a critically important input for a multi-criteria analysis procedure. In this study, critical criteria for policy assessment are identified on the basis of past evaluation and contemporary literature. The aspiration is to indicate essential criteria and identify those frequently used for energy policies and often connected with overall policy performance. The criteria list is created by reviewing the criteria applied in several sources of the scientific community such as Ericksson (2006), Konidari and Mavrakis (2007), Aldy et al. (2003), Held and Ragwitz (2014), Sorrel (2001), Kraft and Furlong (2010) as well as Ortiz and Leal (2020). Table 4 contains some general information about these studies, such as the used sets of criteria as well as the type of evaluated policies. Moreover, all the criteria are independent, meaning there is no connection between them when it comes to the total score. Thus, the individual contribution of a criterion is autonomous.

Table 4: Literature review on common criteria used for policy evaluation

Source	***Criteria List***	***Policy Type***
Sorrel (2001)	Effectiveness, static efficiency, dynamic efficiency, equity, transparency, political acceptability	EU-ETS, national climate policy instruments
Aldy et al. (2003)	Cost efficiency, Effectiveness, Flexibility, Equity, Environmental Outcomes	Global climate policy architectures
Ericksson (2006)	Competitiveness, Cost efficiency, Effectiveness, Flexibility, Side-effects	Scheme on energy efficiency in industry
Konidari & Mavrakis (2007)	Static & Dynamic Cost efficiency, Effectiveness, Equity, Flexibility, Administrative Feasibility, Financial Feasibiliy	Climate change mitigation policy instruments
Held & Ragwitz (2014)	Effectiveness, Static efficiency, Dynamic efficiency, Market Compatibility, Distributional Effects	Renewable energy policy assessment
Kraft & Furlong (2015)	Effectiveness, Efficiency, Equity, Liberty, Political Feasibility, Social Acceptability, Technical Feasibility, Administrative Feasibility	Evaluative criteria for policy proposals
Ortiz & Leal (2020)	Effectiveness, Efficiency, Equity, Economic Competitiveness, Affordability, Accessibility, Impact on climate change	Energy policy concerns, objectives and indicators

Overall, for the purposes of this thesis study, five criteria are chosen to be adopted as necessary for the assessment of the different support schemes for the promotion of green hydrogen. The criteria are general, can be used for policy assessment in any country, however individual prioritization can vary.

i. Effectiveness

Effectiveness is the likelihood of achieving objectives and goals or their demonstrated achievement. Identification and development of proper indicators is mandatory for the assessment of effectiveness of schemes and policies in general. The literature on evaluating policy effectiveness is concerned with evaluating the results energy policies have delivered. Much of the literature associated with effectiveness has a developed national context, often with a particular focus on the European Union (EU) where there has been an appetite for comparing policy approaches across nations within the context of successive directives and targets, for example Jenner et al. (2013), Li et al. (2017) as well as Mazzanti and Zoboli (2008). The simplest indicators measure installed capacity or electricity output and growth rates thereof, either in absolute or percentage terms. These measures have the potential to provide a simple proxy for effectiveness, with minimal data requirements. Measuring energy output offers advantages over measuring capacity growth, since the latter is not able to capture the productivity of the installations. It is true however that simple measures can be substantially limited as they cannot be related with technical or economic potential or even broader policy goals. More sophisticated approaches assess deployment against a country's overall potential, measured over a period of time. This introduces more complexity. Quantitative data such as estimates of resources and technical and economic constraints are needed for the calculation. Overall it is limited by the capacity to estimate uncertain projections of future events as well as to link policies and anticipated outcomes in causal relationship. For all these reasons the literature considers effectiveness alongside other measures, which can better describe the overall performance of a policy instrument.

ii. Cost efficiency

Cost efficiency or Efficiency entails an assessment of achieving goals and providing benefits in relation to costs. This can either mean largest benefit for a given cost or a least cost for a given benefit. Generally, cost efficiency encourages the evaluation of costs and benefits of programs as well as the development of alternatives to change them or substitute them. The literature on cost efficiency is principally focused upon evaluating whether policy, in simple financial terms, has been economically efficient. It serves as a way of justifying governmental action on the basis of economic concepts. Cost efficiency is often discriminated to static and dynamic efficiency. More specifically, static efficiency shows the ability of an instrument to realize the overall goal by maintaining the financial burden in acceptable and affordable limits for all the entities taking part. The principle for this financial burden is to be always as minimum as possible (Konidari and Mavrakis, 2007). Literature is also focusing to dynamic efficiency, the potential of an instrument for innovation and competition to reduce costs. Unlike static efficiency, dynamic efficiency focuses on the evaluation of costs towards goal realization in the long-term and indicates whether an instrument drives down the cost of less mature technologies (Held & Ragwitz, 2014). However, such a discrimination is beyond the scope of this study as the criterion is used in its generic form, including both its counterparts.

iii. Equity

Equity refers to justice or fairness in the distribution of the costs, benefits and risks across the subgroups within a policy. In terms of a support scheme, the equity criterion is predominantly concerned with distribution of instrument impacts and more importantly ensuring equal distribution rights among every entity towards the realization of the instrument's goal (Konidari and Mavrakis, 2007). Much like cost efficiency, equity consists also from two counterparts. On one hand, process equity, refers to open and fair decision-making processes and procedures to all participants. On the other hand, outcomes equity is often referred as social justice and refers to the fair distribution of societal goods. Besides distributional impacts, equity may be interpreted based on the potential for stakeholders to participate in policy development. Such participation can not only improve the perceived equity of a policy, but can also reduce implementation costs, by allowing potential difficulties to be identified and mitigated. The evaluation of equity for energy policies varies considerably among the examined sources and can be decisive in whether a policy is judged to be equitable. This obviously presents difficulties for the development of internationally applicable short-hand indicators. For the purpose of evaluating renewable energy deployment on a national basis, evaluations should reflect the concept of equity as understood by the instrument's stakeholders and the local drivers for energy deployment. Therefore, equity is likely to be central to any support scheme consideration as it invariably raises in every area where decisions turn on who wins and who loses as a final outcome of a new scheme or the modification of an existing one.

iv. Flexibility

This defines the characteristic of an instrument to be adaptable along the process and provide all entities with a set of options and measures that can be implemented in order to achieve the most favourable result. The design should contain flexible mechanisms that can be adapted in any potential market condition. Changes can be plain, for instance the need to control support costs more effectively, or even more fundamental such as the change from one instrument to another. The flexibility criterion can be extremely useful for capital intensive projects with market uncertainty such as the promotion of green hydrogen. Since it is difficult to predict exactly the future market state, even though there are some indications, it is very important for instruments to have the opportunity to be redefined along the way.

v. Market Compatibility

Even though the compatibility with market principles is not a frequently used criterion, still is one of great importance. Under this criterion, the support schemes are analyzed to determine whether they encourage the integration of green hydrogen in the hydrogen market. This will become even more important within the next few years in light of the expected rising share of green hydrogen in the market. Therefore, the extent of how much can a particular support scheme promote market integration is definitely a very helpful tool to assess its overall performance.

vi. Revenue Stability

The stability of revenues is also a very important criterion, especially when it comes to the economic perspective of a support scheme. Stability is always a key investment goal and a necessary element of to attract potential investors, as it creates a secure investing environment. Increasing revenue stability is associated with lower revenue risks and thus, lower weighted average cost of capital. Considering the market uncertainty of green hydrogen due to the market immaturity, revenue stability is an important criterion for the assessment of the support schemes aiming to its promotion. Also, the stability of the income stream is an important factor as it closely linked with the overall support scheme efficiency (Rathmann et al., 2011).

Figure 10 below depicts the evaluation criteria that were chosen to carry out the multi-criteria analysis for the determination of the overall performance of the support schemes for the promotion of green hydrogen.

Figure 10: Evaluation criteria for multi-criteria analysis

7.2. Determination of weight coefficient

Weight assignment to criteria is a pivotal step in every multi-criteria decision making process, even though it often poses a great challenge towards the realization of the analysis (Pamučar et al., 2018). Even a minor alteration of weight coefficients can significantly change the final outcome. Applying weights to criteria requires attention as it can be a source of subjectivity. A criterion weight may be defined as a value which specifies its importance relative to other considered criteria and indicate the concern of the decision-maker about the criterion importance. The weights may be obtained directly from the decision-maker, stakeholders or may be developed by applying appropriate methods. There is a large variety of different weighting methods, direct or indirect, such as the ranking method, the entropy method, the mean weight, the standard deviation etc. According to Odu (2019), the weight assigning methods can be classified in three distinct categories including subjective, objective and integrated weighing methods, as illustrated in Figure 11.

The subjective weighting method is focused on the opinion of experts. Under normal circumstances, a set of question is presented to the experts in order to acquire their subjective response. In most of the cases, experts express their opinion over the importance of the criteria, either through the representation of an interval scale (e.g. 1-10) or through ratios (e.g. criterion A is two times more important than criterion B). On one hand this kind of approach can be more accurate, since the product of this method corresponds to the collective expert thought, however it can be significantly time consuming, especially in light of contradicting views among the experts. Fixed point allocation, point allocation, direct rating, ranking and ratio weighting are common subjective weighting methods (Zandari et al., 2015). The objective weight determination negates the involvement of decision makers as each criterion is weighted through mathematical models.

Objective weight methods present the computation efficiency advantage, especially there is a significant amount of criteria making the analysis more complex. Common objective weighting methods are including mean weight, standard deviation, entropy method, statistical variance procedure and criteria importance through inter-criteria correlation.

The integrated weight determination approach contains methods that are built from the combination of subjective and objective weighting. Multiplication synthesis, additive synthesis and optimal weighting based on sum of squares are common integrated practices (Odu, 2019).

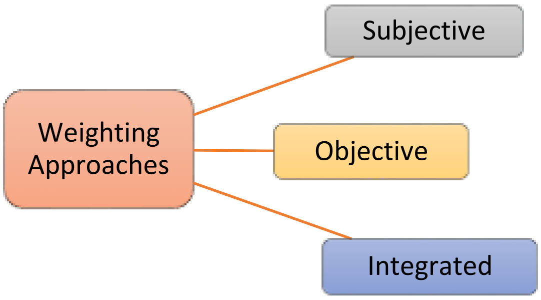

Figure 11: Approaches for the determination of weight coefficient

In the context of the present study, multidisciplinary approach is absolutely necessary for the support scheme assessment. Therefore, it would be logical to suggest that a group of experts representing various disciplines can increase objectivity of the inputs in multi-criteria assessment and consequently, the validity of the results. The opinions of experts are needed as an input in many policy areas in which objective data is unavailable and subjective judgements play a significant role. Considering all the above as well as the fact that there is no actual information from decision makers or no sufficient information to reach to a solid decision, for the purposes of this thesis an objective method will be deployed. When the aforementioned conditions are present, the mean weight method is frequently adopted (Jahan et al., 2012). Mean weight portraits a simple way for weigh determination as it equally distributes weights among the selected criteria. Consequently, the multi-criteria analysis is based on the assumption that each criterion is equally important (Table 5).

Table 5: Weight coefficients

Criteria	***Weight (%)***
Effectiveness	16.7
Cost efficiency	16.7
Equity	16.7
Flexibility	16.7
Market Compatibility	16.7
Revenue Stability	16.7

7.3. Evaluation

7.3.1. Effectiveness

Chapter 6 introduced a set of support schemes aiming to promote green hydrogen. Effectiveness is the criterion that indicates the likelihood of the support schemes realizing this goal. Feed-in systems are the most popular support schemes, being implemented widely across the globe. A good reason for this outcome is the fact that they turned out to be highly effective when it comes to goal realization, as they create favourable investment environments due to the stable income flows. This is why feed-in schemes are associated with low risk premiums, especially FITs. Highly effective can also be quota obligations as they are practically designed to enforce compliance towards objective realization. However, there have been cases of target over-fulfilment or short-fall as described by Wood and Dow (2011). For this reason, the impact of quota obligations in terms of effectiveness is assumed to high. Even though capacity-based schemes are designed to boost capacity, this doesn't necessarily mean that they are highly effective. The support has no connection with the performance and this can sometimes lead to the creation of inefficient sites. Last but not least, carbon contracts for difference can be a very effective tool for incentivizing the production through innovative, carbon-free and thus, more expensive production methods. Since the mitigation costs are reimbursed, it creates value for producers to implement new technologies. However, a CCfD that compensates only for the difference with the carbon price would fail to provide sufficient incentives for high-risk investment in low-carbon technologies since they would remain exposed to international competition not subject to any carbon constraints.

7.3.2. Cost Efficiency

The support scheme of feed-in tariffs (FITs), bears a high risk of an increase in support costs. If FITs are available without a quantitative target for a specific technology, the expansion of new installations maybe higher than expected, thus strongly increasing the costs of support and simultaneously decreasing cost efficiency. So, cost and volume control mechanisms are important to maintain the required cost efficiency of FITs and in the same time provide certainty to investors. In comparison to FITs, FIPs enable producers to participate in the market and thus, regulate better supply and demand and possibly avoid any overcompensation. However, the degree of cost efficiency depends on the whether the premiums are fixed or floating. With floating premium the risk of overcompensation is more or less avoided, whereas this doesn't apply to fixed premiums. Introducing auction schemes as an addition to feed-in schemes could potentially increase cost efficiency significantly (Mahalingam et al., 2014). Quota obligations systems generally present a higher cost efficiency in comparison to feed-in schemes. However, they tend to provide inadequate support for cost-intensive technologies, which can be adjusted by the utilization of technology-banding systems that ultimately decrease overall cost efficiency. Capacity-based subsidies have the potential to present high levels of cost efficiency but it depends highly on their design. The accuracy of the method to determine the future market earnings is pivotal as it entails a risk of overcompensation, which can make the support more expensive than anticipated. So, for the purposes of the assessment a mid-level of impact is assumed, even though potentially it could be higher. The same is assumed for carbon contracts for difference, as they are also dependent on the volatile nature of the carbon prices which also creates a level of uncertainty.

7.3.3. Equity

Feed-in systems are widely used in the energy sector, especially for the promotion of renewable energy, presenting a high level of equity. Social equity issues are material nonetheless in the context of feed-in schemes as they frequently involve very large private and public spending commitments (Grover and Daniels, 2017). On the other side, quota obligations have a lower level of equity, as they are most commonly supporting the more competitive technologies. Capacity-based schemes and carbon contracts for difference can both be very equitable as both promote equal distribution of costs and benefits, which can be adjusted along the way. Both support schemes are significant in terms of promoting alternative, low-carbon technologies and in the same time maintaining high levels of process and social equity.

7.3.4. Flexibility

As it was previously discussed, support schemes should be able to adapt to the change of market conditions regardless the extent of the change. All the support schemes that were introduced in this thesis can be reformed when necessary but not to the same extent. There is large experience with the design and implementation of feed-in schemes, especially with feed-in tariffs, which has enabled designs with flexible mechanisms while simultaneously ensuring stability. The same however does not apply for quota schemes as they are comparably inflexible due to the fact that long term targets are mandatory for keeping certificate prices in a stable state as well as because quota systems don’t behave well when being with other support schemes in parallel (Ragwitz and Held, 2014). If for instance, an FIT is implemented alongside with a quota obligation is highly likely that the certificate prices will be affected as the amount of available certificates changes while the amount of certificates needed to reach the target stays the same. On the contrary, capacity-based schemes contain mechanisms that offer great flexibility such as the option of periodic payments as well as the possibility to redefine or update support payments. In addition, they can easily coexist with other support schemes such as feed-in schemes. As already mentioned in the previous chapter, the same applies for CCfDs, as they create great opportunities for synergy with other instruments. However, they don’t offer the same level of flexibility as capacity-based schemes do as they are highly dependent on carbon prices.

7.3.5. Market Compatibility

In general, feed-in tariffs perform the least best when it comes to the application of the market principles because neither operational decisions nor investment decisions are affected by market signals. The response to market signals gradually increases for feed-in premium options as there is higher market compatibility with the basic principles of liberized markets. More specifically, the production side is responsible for balancing the production and selling directly on market. Therefore, feed-in premiums offer the possibility of a better market exposure. The impact of a feed-in premium scheme on market compatibility varies on the type of premium (sliding or fixed). Quota obligation schemes and capacity-based subsidies behave extremely well when it comes to compatibility with market principles leading to reduced market distortion and large market exposure (Harmsen, 2020). Therefore, both support schemes appear to have a high performance when it comes to their impact to the market. Also, this high level of compatibility with market principles makes absolute sense for both support schemes as their design encourages response to market signals. Capacity-based subsidies are designed to boost the technological capacity by providing a stable revenue but in the same time income is dependent on the market price. Same applies for the quota obligation systems with tradable certificates, which provide a financial incentive through the certificate market but in the same time income is once again dependent on the market price. Last but not least, when it comes to Carbon Contracts for Difference, mid impact is assumed.

7.3.6. Revenue Stability

The more stable the income from a support scheme is, the lower the risk premium. However, this is also connected with the market integration, because increasing market exposure results to decreasing revenue stability and thus, increased revenue risk. Consequently, FITs provide a very high level of income stability due to the fixed amount for each unit produced as well as the significantly low response to market signals. Therefore, FIPs have a higher revenue risk since they offer higher market integration. Again, the performance level varies with the type of FIP, so medium level is assumed for revenue stability. Given the very high market integration of quota schemes, they provide the least revenue stability. This stems from the fact that certificate prices are not fixed and can potentially attain significantly low prices. Even though capacity-based subsidies present also very high market integration, a medium revenue stability is assumed as they are very flexible and can be designed to offer stable, periodic income. When it comes to CCfDs, the level of impact is medium to low considering that the carbon prices are significantly to turn important breakthrough technologies such as green hydrogen to economically viable. However, in this case mid level of impact is assumed, as they can be more flexible than quota schemes.

Overall, the support schemes are assessed qualitatively based on their criteria evaluation ranging from a very high to low impact. The results of the assessment are shown in Table 6.

Table 6: Results of the qualitative criteria-based assessment

Scheme/Criteria	*Effectiveness*	*Cost Efficiency*	*Equity*	*Flexibility*	*Market Compatibility*	*Revenue Stability*
Feed-in Tariff	Very High	Low	High	High	Low	Very High
Feed-in Premium	High	High	High	High	High	Mid
Quota with Tradable Certificates	Mid	High	Mid	Low	Very High	Low
Capacity-based Investment Subsidy	Mid	Mid	Very High	Very High	Very High	Mid
Carbon Contracts for Difference	Mid	Mid	Very High	High	Mid	Mid

7.4. Simple Multi-Attribute Rating Technique

SMART is based on a linear additive model, which means that a performance score for all individual alternatives can be calculated as the sum of the relative performance of each alternative on each identified evaluation criterion multiplied by the relative importance of that specific criterion. In this case, the technique therefore consists of three distinct elements: A set of support schemes, a set of criteria that the support schemes are to be evaluated on and the relative importance of these criteria.

The weighting of SMART uses a scale of 0 to 1, thus simplifying the calculations as well as the evaluation of the different support schemes. The model applied in this analysis follows the formula below:

$$u_i = \sum_{j=1}^{5} (w_j s_{i,j}), \qquad i = 1,2, \dots ,5 \quad (5)$$

Where:

$$u_i: overall\ score\ of\ support\ scheme\ i$$

$$w_j: normalized\ weighting\ value\ of\ criterion\ j$$

$$s_{i,j}: score\ of\ support\ scheme\ i\ under\ criterion\ j$$

7.4.1. Normalization

The first step of the calculation requires the normalization of the weighting coefficients in order to calculate the normalized weighting value of each criterion (Table 7). Since all the criteria are weighted equally then the normalized weighting values are also equal.

Table 7: Normalized weighting values

j	***Criteria***	***Normalized Weight (w_j)***
1	Effectiveness	0.2
2	Cost efficiency	
3	Equity	
4	Flexibility	
5	Market Compatibility	
6	Revenue Stability	

7.4.2. Assignment of parameter values

In the second step of the rating technique takes place the assignment of parameter values. During the evaluation part, the performance of each support scheme was discussed under the spectrum of each criterion. Qualitative impact levels concerning the impact of each support scheme on each criterion were categorized either with low, medium, high or very high impact. The parameter values are grouped and illustrated in Table 8 below.

Table 8: Group of parameter values

Impact	***Parameter Value (v)***
Low	1
Medium	2
High	3
Very High	4

Therefore, the parameters of Table 4 are exchanged with their respective parameter values and the result is illustrated in Table 9 below.

Table 9: Parameter values of support schemes for each criterion.

Scheme/Criteria	Effectiveness	Cost Efficiency	Equity	Flexibility	Market Compatibility	Revenue Stability
Feed-in Tariff	4	1	3	3	1	4
Feed-in Premium	3	3	3	3	3	2
Quota with Tradable Certificates	3	3	2	1	4	1
Capacity-based Investment Subsidy	3	2	4	4	4	2
Carbon contracts for Difference	2	2	4	3	2	2

7.4.3. Determination of individual scores

The most crucial part of the rating process is the determination of the individual scores or more specifically, the score of a support scheme i under a criterion j ($s_{i,j}$). The calculation is based on the following equation:

$$s_{i,j} = \frac{v_{i,j} - v_{min}}{v_{max} - v_{min}} \quad (6)$$

Where:

$$v_{i,j}: parameter\ value\ of\ support\ scheme\ i\ under\ criterion\ j$$

$$v_{max}: maximum\ parameter\ value$$

$$v_{min}: minimum\ parameter\ value$$

7.4.4. Final Calculation

After the determination of the individual scores comes the final step, which is the calculation of the overall support scheme scores. As mentioned previously, the overall score of a support scheme (u_i) is determined through the utilization of equation 5, whereas the values are within the range of 0 to 1. Table 10 illustrates the final results of SMART, which contain the individual criteria-based scores of each support scheme as well as their overall rankings.

Table 10: Overall performance results based on SMART.

Scheme/Criteria	***Effectiveness***	***Cost Efficiency***	***Equity***	***Flexibility***	***Market Compatibility***	***Revenue Stability***	***Total***
Feed-in Tariff	1	0	0.67	0.67	0	1	**0.56**
Feed-in Premium	0.67	0.67	0.67	0.67	0.67	0.33	**0.61**
Quota with Tradable Certificates	0.67	0.67	0.33	0	1	0	**0.44**
Capacity-based Investment Subsidy	0.67	0.33	1	1	1	0.33	**0.72**
Carbon Contracts for Difference	0.33	0.33	1	0.67	0.33	0.33	**0.50**

In general, the studied support schemes present good rankings when it comes to their overall performance, as 80% of them receives a ranking of 0.5 or more. In addition, all the final rankings are close as they fall in the range of 0.44 to 0.72. Capacity-based investment subsidies receive the highest ranking (0.72), performing significantly well under most of the criteria. With high effectiveness and very high levels of flexibility, equity and market compatibility they pose as an exceptional candidate for boosting green hydrogen capacity as well as encouraging green hydrogen production and use. The feed-in systems receive the second highest rankings, both of them proving to perform similarly well. In this case the criterion that makes the difference in the final ranking is the market compatibility. Feed-in tariffs are not encouraging at all market exposure, whereas feed-in premiums do. Interestingly, CCfDs present great results among the majority of the criteria however, they are unable to provide the necessary incentives for green hydrogen technology resulting in a lower effectiveness compared to the other support schemes. Consequently, CCfDs would be unable on their own to lead to the desirable result, but they could be very beneficial when introduced in synergy with other support schemes. Finally, quota obligations with tradable certificates receive the lowest ranking from all the alternatives (0.44). However, they present high effectiveness and their design pretty much leads to increased green hydrogen shares in the hydrogen market. On the other side they present very low levels of flexibility and revenue stability, which apparently are the criteria that make the difference in the final ranking. If these areas can be enforced in the future, quota obligations with tradable certificates could have a significantly better overall performance.

8. Conclusions

In the past, the combination of cooperation, coordination and effective design has been utilized for the support of different elements in the energy sector. This approach has already proved that it can lead to the generation of efficient and effective support schemes that enable a constant and step-by-step market integration and thus, it can most probably be the most feasible approach to be followed in the near future for green hydrogen. This type of hydrogen is the focus of this thesis as it is considered to be the bridge between renewable energy generation and the highly desired net-zero carbon goal of 2050. Considering all the above, this thesis research is oriented around the following primary research question:

"What are potential support schemes for promoting green hydrogen?"

Support schemes for green hydrogen are in the same early stage that green hydrogen market is and thus, the answer to this question proves to be far from straightforward. This is why support schemes for renewable energy were used as a benchmark for this research, as well as the fact that they generated and still generating great results in terms of renewable energy development. Initially, the similarities between green hydrogen and renewable electricity making possible RES-E support schemes to be utilized in this research are explored. Besides these profound similarities there are, nonetheless, some significant differences that not only differentiate the two energy carriers from each other but also highlight that need to be taken into consideration during the designing part. Moreover, the design of five different support schemes was investigated by analysing each individual remuneration scheme (how the remuneration could work in the case of green hydrogen) and the most important design elements that can be taken into consideration for each alternative. Finally, the overall performance of the support scheme for green hydrogen was evaluated through a multi-criteria analysis. Effectiveness, cost efficiency, equity, flexibility, market compatibility and revenue stability are used to assess each individual support scheme performance.

Based on the results of the theoretical analysis (Chapter 4,5) well as these generated by the ex-ante evaluation (Chapter 6) the following conclusions are extracted, the combination of which sufficiently provides an answer to the research question of the thesis research.

- RES-E support schemes can be used for the support of green hydrogen and have the potential to make it an economically viable solution in the future. The similarities between green hydrogen and renewable energy make it possible for RES-E support schemes to be used for the promotion of green hydrogen. In the same time, the effectiveness that they have presented over the years promises that upon implementation they could result in a gradual green hydrogen uptake in the near future.

- Based on the evaluation, feed-in schemes and capacity-based subsidies are the most appropriate options for the support of green hydrogen. All the support schemes were evaluated qualitatively on their individual performance from the perspective of each criterion, ultimately receiving the highest ranking. Capacity-based subsidies seem to be the most appropriate support scheme for the promotion of green hydrogen as it automatically leads to the boost of green hydrogen capacity, while giving high levels of flexibility as well as allowing producers to respond to market signals. However, in order to ensure as high effectiveness as possible, capacity-based subsidies should be introduced alongside with appropriate performance regulations.

- The status of the green hydrogen market influences significantly whether feed-in tariffs or feed-in premiums needs to be implemented. Market integration is the criterion that makes the difference in the overall grading of the two examined feed-in systems, since under the other criteria both schemes have pretty much similar performance. Under the present market state, boosting electrolyzer capacity and creating a place for green hydrogen in the market is of highest priority than increasing market exposure and thus, feed-in tariffs that create safe and attractive investment environment make more sense to be implemented. However, in the coming years, where the market for green hydrogen is projected to be more mature and well-developed, feed-in premiums would be a more efficient way of support as they definitely present higher market compatibility, encouraging the production side to respond market signals – adjust supply and demand.

- CCfDs constitute a significant instrument but call for support scheme synergy. CCfDs for green hydrogen projects have the potential to fill a crucially important gap in the current policy framework to promote green hydrogen use and also decarbonise energy intensive industries. However, it must be stressed that CCfDs are not a panacea to achieve these results on their own as there is a significant lack of effectiveness. Other policies will be needed to help ensure that they can be as effective and cost efficient as possible. Other policies will also be needed to tackle parts that CCfDs do not fully address. In addition, CCfDs that compensate only the difference with the carbon would be unable to sufficiently create incentives in high-risk, low-carbon technologies as they would still be exposed to international competition not subject to any relevant constraints. Consequently, the appropriate strike price of a CCfD should cover the full cost-difference of the transformation, i.e. the difference between production costs of green hydrogen and production costs of the conventional alternative, as well as operational costs and additional investment costs.

9. Discussion

The present study provides an insight in the design and overall performance of five different support schemes for green hydrogen. The instruments were assessed qualitatively based on their criteria performance as well as in comparison to each other. The qualitative scale ranges from very high to low and based on these inputs SMART generates the final results and completes the evaluation of the support schemes. The evaluation of the support scheme alternatives that were studied concludes that feed-in systems and capacity-based subsidies constitute promising support schemes for green hydrogen and therefore, it is suggested for future studies to focus more on the design part of these particular support schemes and especially how can they be better adapted for the needs of green hydrogen.

In some cases the categorisation of the support schemes in the qualitative scale was difficult to be realized and for this reason assumptions were made. This served the overall purpose to identify appropriate support schemes for the promotion of green hydrogen. However, this means that the results are not panacea and therefore, they tend to become indicative. The precision could become significantly better if the individual performances are quantitatively calculated. In this case this would have been impossible as there was no access to this kind of data. Due time, as the support scheme implementation will start to increase, it will be easier to collect these kind of data and conduct quantitative analyses. Considering these facts, it is proposed that future studies should address the same research problem based on quantitative assessment of criteria performance.

A larger list of criteria could have been used in order to raise the sensitivity of the analysis. When it comes to the Simple Multi Attribute Ranking Technique, the increasing number of criteria results in higher accuracy for the results. In the same time, as the number of criteria increases so does the complexity of the method. Accuracy and complexity alongside with sensitivity and consistency are some of the drawbacks of this method. Scale ranges are not adequately addressed and the method is not consistent due to its subjective nature. On the other side, the technique is immensely simple and present very high levels of applicability.

The use of different weight assignment among the list of criteria could have provided greater insights as some criteria have greater impact than other in terms of the performance of a support scheme. Generally, cost efficiency and effectiveness are considered as the most important criteria as they are always present when it comes to policy or support scheme assessment. Evidently, all of the references illustrated in Table 4 contain these two criteria. Therefore, in case of a larger scale, quantitative study, a more advanced weighting assessment would be proposed. For instance, expert opinion could be utilized. Even though this can be very time-consuming, it gives the advantages of high accuracy and transparency, provided experts have no connections with the project stakeholders.

Furthermore, this thesis research is not taking into consideration the geographical perspective, which is a crucial element for the support scheme implementation. For example, in countries with a low renewable share in the energy mix, there would be no sense to support electrolyzer capacity. Therefore, this limitation harms the sensitivity of the analysis and for this reason it is proposed that future studies should focus on specific geographical locations. This however won't be an issue for quantitative analyses as the data will be connected with a specific location.

The constantly increasing focus on green hydrogen has led to significant geopolitical developments across the globe. A great number of countries are examining how to use green hydrogen in order to decarbonise hard-to-abate industries within their individual strategies to reach net zero by 2050 and deal with climate change. Similarly with renewable electricity, which also presented great potential and several end-uses, green hydrogen could also obtain great geopolitical significance. Within the framework of the much anticipated low-carbon future, the technological knowledge will be of great geopolitical importance. Green hydrogen has caught the attention of both the private and public sector. Strategies are being developed in national and international level through national strategies and international agreements respectively. In regards to the private sector, oil companies most likely will try to bridge the gap that is unavoidably going to occur through the energy transition. Consequently, as the technology matures and the knowledge is getting distributed, this might create significant changes in the import-export landscape, which should be taken into consideration in case of future studies.

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