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DETERMINANTS THAT FAVOR GREEN HYDROGEN AND RENEWABLE ENERGY PRODUCTION. A CASE STUDY.

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Abstract

Renewable energies and, more recently, green hydrogen have been presented as alternatives to fossil fuels for energy generation. These two presents themselves as alternatives because they do not generate greenhouse gas emissions and are therefore an option for the energy transition. The current work aims to provide a theoretical framework that brings together a combination of levers or determinants that increase renewable energy and green hydrogen production. These determinants are regulation mechanisms such as policies, laws, or targets; intervention mechanisms in the form of subsidies, tax credits or carbon credits; and investment in research, technology and infrastructure. During the years, academic articles have been written on the effectiveness these mechanisms individually which will be analysed in this paper, and then brought together to form a more holistic framework.

Through the study of three leading countries in the industry, which are China, US and Germany, the effectiveness of these policies is shown. This article therefore provides value by presenting a framework that can be replicated by regulators and policy makers in countries that want to increase their production in this sector.

Key words: green hydrogen, renewable energy, policy, regulation, incentives, investment, and production.

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Acronym glossary

- **CNY:** Chinese Yuan Renminbi
- **CO2:** Carbon Dioxide
- **EU:** European Union
- **FCV**: Fuel Cell Vehicle
- **FIT:** Feed-in-tariff
- **GH:** Green Hydrogen
- **GHG**: Greenhouse gas
- **GO:** Guarantee of Origin
- **GW:** Gigawatt
- **H20:** water molecule
- **IRENA**: International Renewable Energy Agency
- **MW:** Megawatt
- **PPA:** Power Purchase Agreement
- **PTC:** Production Tax Credit
- **PV**: Photovoltaic
- **R&D**: Research and Development
- **RE:** Renewable energy
- **RPS**: Renewable Portfolio Standard
- **TW**: Terawatt
- **UK:** United Kingdom
- **USD**: United States Dollar

1. Introduction and justification

Climate change is in most politician's agenda today, the reason being that climate change is and will affects a country's development. Essentially, climate change refers to the noticeable weather changes that result from a raise in global temperature since the industrial era that have been caused by greenhouse gas (GHG) emissions as a result of human activities (Fawzy et al., 2020). Weather phenomena like floods, droughts or heatwaves are having a negative effect in crops, infrastructure, health, and many other assets that are key to the economic development and the safety of populations all over the world.

While this is happening, economic growth and raising standards of living have been driving energy demand up, in fact, demand for primary energy increases by 1.3% each year globally (Megía et al., 2021). This rise in demand will also mean a rise in GHG emissions unless there is an energy transition from fossil fuels to renewable energy and other electricity generation alternatives such as green hydrogen. This will only exacerbate the climate crisis even more. Therefore, increasing domestic renewable energy production is important for several reasons. First and foremost, renewables do not generate carbon emissions as a byproduct, and therefore by substituting fossil fuels in their countries, they are keeping global warming from carrying on forward. Secondly, fossil fuels are currently a great cause of geographical and political conflict because of the dependence of importing countries have on exporting countries. Hence, why it is in the interest of a country to stimulate their renewable energy and green hydrogen production to reduce this interdepended. Finally, fossil fuels will inevitably fade or take of a very small part of production, which means countries will try to excel in this transition which will in return bring along economic benefits like job creation, innovation, and investment. These reasons all highlight why countries need to begin or accelerate this transition, and also why this research paper is important.

This study is also very policy-making focused. This is relevant because many companies are calling out governments to increase policy making. Pwc, for example, released a journal article mentioning that is key that policy makers coordinate and set clear instruction for the industry (Wilson N., 2021). Similarly, the World Economic Forum and Mckinsey & Company released a join report that proposed a 7-step plant for the energy transition, and two of the initial points mentioned policy design and planned milestones and action (World Economic Forum,2018). The positive thing about policy making is that is has proven effective before, which insures success for this transition. Even Bill Gates mentions the effectiveness of policy making in his book "How to Avoid Climate Change Disaster"; he refers back in time to the Clean Energy Act in America which was published as a result of the crippling air pollution in the 70s, and he argues that it managed to reduce emissions as much as 70% by 1990.

The purpose of this study is to stablish a theoretical framework that states a few factors or levers that help a country enhance their green hydrogen production. That is why my research question is "determinants that increase renewable energy and green hydrogen production". This paper follows a case study structure, which proposes an initial theoretical framework and tests it against a number of countries to them provide further recommendations. To decide which are the levers that form the framework, a thorough scan of the academic literature was made, and the most common and effective policies or actions taken by different countries were collected and brought together to combine them into a framework that had not existed before.

Regarding the justification of why I choose this topic, over the last few years at university, we have studied that economics is about resources, and climate change is about making our earth's resources even scarcer in the long run: our crops, our land, and our cities, all of which are slowly diminishing in their effect. The way I see this work is that by applying microeconomics and macroeconomic concepts, we try and solve the issue of resource scarcity by promoting alternatives like green hydrogen to the current energy sector and adding to the available research of the energy sector, which is one I find particularly interesting.

2. Literature analysis

2.1.Renewable Energy

According to the literature, renewable energy (RE) are sources of energy that are produced with natural means which makes them sustainable in the long run (Sayed et al., 2023). The most common types of renewable energies are solar, wind, geothermal, biomass and hydropower. Solar power harnesses the sun's heat to generate steam, which is then used to power a generator and produce electricity, and similarly, for wind power a wind turbine converts the kinetic energy (motion) of wind into mechanical energy that is used to generate electricity. Geothermal energy captures heat from underground, utilizing it to generate hot water or steam, which in turn drives a turbine to produce electricity. Biomass energy, derived from sources such as wood, agricultural and forestry residues, and municipal waste, and can be converted into various valuable fuels, chemicals, and products. Hydropower utilizes the mechanical energy of flowing water through a penstock to turn a generator and generate electricity, and wave and tidal energy, which are a variation still in the early stages of research, aim to harness the energy from ocean movement (Mohtasham, 2015).

Therefore, renewable energies do not only benefit climate change mitigation, but they also provide energy security, improved energy access, and socioeconomic development (Sen & Ganguly, 2017). This is why RE evolution has been very positive in recent years. In 1990, the world recorded a capacity of 11,8 million terawatt-hour, which then doubled in 2012, and is estimated to reach 40,1 million in 2040. The installed capacity of all technologies has experienced an increase as it is portrayed in Figure 1. And it seems that the outlook carries on with this increasing and positive trend.

	Solar energy capacity (GW)		Wind Energy Capacity (GW)		Biomass Energy production (TWh)	
Year	2005	2015	2005	2015	2005	2015
China	0,14	43,5	1,1	131,1	8	25
United States	0,49	21,7	8,7	72,6	91	375
Spain	0,05	4,7	9,9	22,9	3	13
Australia	0,05	5,9	0,7	4,2	1	3
Germany	2,06	39,2	12,3	44,6	16	37

Figure 1. Evolution of renewable energy in a ten-year gap.
Source: Our World in Data

The reason why regardless of the benefits and their evolution, fossil fuels are still more abundant in use are different ones. In fact, the International Energy Agency (IEA) predicted that fossil fuels will still occupy as much as 55% of energy generation between coal and natural gas in 2040. Throughout the years several barriers have presented themselves to harness RE deployment. The first one is policy and regulatory barriers, because absence of well-defined policies retracts the private sector from engaging. Secondly, there are fiscal and financial barriers, due to lack of investment, lack of lending, and high-risk perception. Thirdly and finally, there are technological barriers, which are mainly due to high capital costs. (Mirza et al., 2009) All of which can be removed or decreased with policy intervention.

New discoveries and development are being done in the field of renewables, but these are experiencing even lower acceptance due to the early stage where they are at. Topics like smart grid integration (Ahmad et al., 2022), robotics engineering (Iqbal et al., 2019) or energy storage (Das et al., 2022), are all examples of new trends and developments related to the energy sector by the academic literature that are considered upcoming. Similarly, green hydrogen is another topic that is recently receiving more attention because of its ability to decarbonize relevant sectors such a heating, or transport. However, as much as 99% of the hydrogen produced nowadays uses fossil fuels as feedstock which does not make it "green". Which is why there needs to be more academic papers like this one to ensure production increases.

2.2.Green hydrogen

Hydrogen is the most abundant element in nature, but it is rarely found alone. To separate it from other elements, a wide range of technologies are available. Consequently, hydrogen production could be divided into the following three categories, depending on the technology used to obtain it: grey, blue and green. Grey hydrogen is usually produced by a method called steam methane reforming, using fossil fuels such as coal, natural gas, or oil as feedstock. Blue hydrogen is generated using the same methods as grey hydrogen, except that carbon capture and storage technologies are used to ensure that it is a low-carbon process. Finally, green hydrogen (GH) is usually produced by electrolysis, a method that uses renewable energy to power the process and produces no or low carbon emissions (Hermesmann & Müller, 2022). It is the latter type that will be discussed throughout this article.

Though this electrolysis method, a water molecule (H2O) is split into oxygen and what we know call green hydrogen. The issue with this method is that it is not cost effective and therefore the price of this energy is more expensive (find a source that speaks about why it is expensive) The hydrogen that is obtained can then be burned to obtain heat, it can be transformed into electricity, and it can also store energy due to its properties (Oliveira, Beswick & Yan, 2021). These functions are what make it suitable to decarbonize many industries. Some industries that are currently being mentioned are the automotive or shipping industry, but green hydrogen could also be used for other purposes like construction or heating.

Countries around the world are trying to exploit green hydrogen to decarbonise their economies. For now, China is the largest producer of green hydrogen, with local policies even more ambitious than national ones. The European Union and the United States are rapidly catching up and have also drawn up clear roadmaps for the coming years.

Many countries are also taking initiatives to import or produce their own GH. Already in 2020, the EU adopted a hydrogen strategy for a climate-neutral Europe that included an investment agenda and a series of actions to clarify the framework for the coming decades. In addition, in May 2020 the European Commission also published a new document called REPowerEU, which has since given rise to two different major projects: IPCEIHy2Tech and IPCEI HyUSe. These two projects contain more than 40 sub-projects to be carried out by more than 35 companies and 15 member states, to combine a total of 20Mtn GH by 2030. But countries are also acting individually, and some are further ahead than others. In the following we will look at what factors ensure a head start or success in these projects and what other factors are driving the development of GHG projects in the EU.

2.3.Theoretical framework

With an appropriate understanding of what renewable sources and green hydrogen are and their applications it is now easier to understand why countries are racing to produce the most energy via these sources. The following framework has four pillars with different subsections that explain why some countries might have an advantage over others in this race. Understanding that these factors foster the production of renewable energy and green hydrogen might help countries increase their production. After understanding the following framework, several cases of different countries will be studied where we will understand the impact of each pillar. The four determinants are the following.

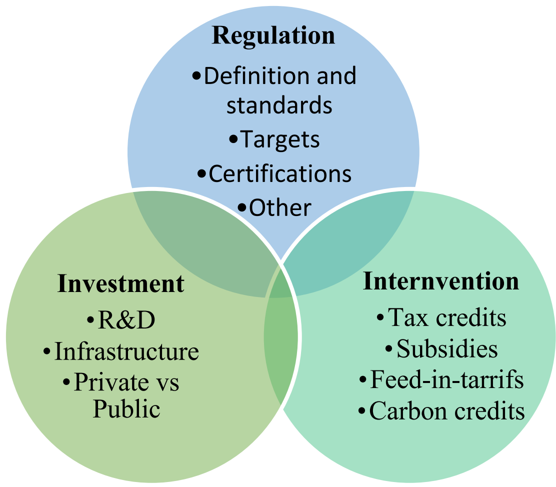

Figure 2. Theoretical framework to enable renewable and green hydrogen production.
Source: Own elaboration

2.3.1. Regulation

Regulation is an important component of energy production (Yu, 2010). Although it may not seem so, due to the fact that we may relate green hydrogen production with scientific and engineering fields and legislation to more academic ones, this factor is indeed critical. Breaking regulatory barriers and harmonizing standards is crucial for the development of green energy. Regulation and legislation, which in this case we will use interchangeably, provide clarity for many actors that are involved in the production process of GH and are indeed enablers of energy deployment (Apolonia et al., 2021).

Firstly, it provides clarity to developers. Companies, which are usually the ones who develop these significant projects, will more likely pursue them if there is enough information and laws about it, and if its clear. If they understand the concepts, the limits, what they gain, the help they will receive from the state or the benefits they can reap in the future, it is more probable that they will go forward with it. Similarly, investors are another actor that benefits from clear and abundant regulation. It is much more likely that they will invest in a project if they know that the project is related to something to which countries are giving importance, and if it's a project that is going to be relevant and profitable in the following years. A recent study about green energy deployment in Iran mentions that a legal and regulatory framework is crucial for the reasons just mentioned. (Hassan et al., 2023)

Whether you are an investor, or a developer, the less uncertain a project is, the more clarity there is surrounding that topic, and the more legislation there is, the higher the chances of going forward with it. Now, there are various instruments that governments can include into regulation to increase the deployment of green energy production. We will now discuss several of them.

2.3.1.1. Definition and standards

Many definitions have been given to green hydrogen, a commonly accepted definition by the literature could be "hydrogen that is produced from renewable energy". However, the green energy sector is evolving rapidly, there are different definitions given to GH, and there are many new concepts that are appearing constantly that need defining and understanding. Providing clear definitions is imperative because it provides clarity and security for all stakeholders. In addition to definitions, sustainable standards have also shown to support energy development (Fortuński, 2008). Similarly, a study from 2012 affirms that if the government want to shift private capital funds towards a sector, definition (and standards) help accelerate this shift (Inderst G. et al, 2012).

2.3.1.2. Targets

We have before mentioned the importance of defining and setting standards for green energy production, but setting future targets is equally important (Parris & Kates, 2003). By the end of 2012, more than one hundred and thirty countries have introduced renewable energy targets (WWF,2013). Some well-known targets today are a reduction in emissions of 55% for

2030 and a production of 10Mt of national green hydrogen by the same year as stated in the Fit for 55 Package.

There is literature that explains why countries are implementing targets and incorporating them in the legislation. A report published by IRENA in 2015 illustrates how targets are key in different stages of the policy making process. At the very start, targets generate debate, provide awareness of the topic, and help policy formulation. Later, targets guide and motivate stakeholders to take action, as well as push political engagement. Finally, targets signal market growth in the sector for investors, and allow for evaluation of progress (Kieffer G & Couture, 2015).

2.3.1.3. Certification

Another instrument the government can incorporate into regulation, is the use of certification schemes. Certification schemes are tracking documents that allow producers to certify the origin of the energy produced. Many types of these certification documents are being used currently, such as Guarantee of Origin (GO's), Renewable Energy Certificates (RECs) or International Renewable Energy Certificates (IRECs). The use of these certifications is key to increase green hydrogen production because it generates trust and veracity around the renewable energy sector. These certifications also serve as a signal for investment.

A document by the International Renewable Energy Agency IRENA provides information about the two most popular approaches regarding certification, which are book and claim model and mass balancing. The first method allows customers of that energy to "claim" or keep the energy that has been stored or "booked" by producers. The second method, mass balancing, requires a physical connection to transport the energy from the producer to the consumer. The report also mentions that both methods promote and facilitate the consumption, as well as the production of green hydrogen.

2.3.1.4. Other regulatory mechanisms to increase production

There are a couple of other less popular instruments, whose objective is not directly to increase green hydrogen production but may indirectly help this happen. The first one is PPAs, which are long term contracts between electricity producers and electricity consumers, which in this case are GH producers, that allow for them to sell electricity at a fixed price. This instrument is usually required by financial entities to evaluate different projects and provide stability for GH producers which consequently results in confidence to increase their production capacity. This instrument was in fact evaluated as one of the main drives of wind energy deployment (Kandpal & Dhingra, 2021), and the theory suggest that it will result in the same for GH. Furthermore, PPA quality in a project is seen as important criteria for investment decisions, which will then in turn affect green hydrogen production (Baumli & Jamasb, 2020).

The second instrument is Renewable Portfolio Standards (RPS). The way RPS work is by setting a target share of RE that must be delivered by producers (Xin-gang & Yu-qiao, 2021). This is effective because it drives production up by force. Studies indicate that these programs increase renewable energy generation for each year that a state retains this policy (Carley, 2009). This policy, although less widespread, it already being implemented by some countries.

2.3.2. Intervention

Many neoliberal economists are of the opinion that markets self-regulate. However, over the past century it has become increasingly clear that market intervention is key to develop infant industries and sectors. The case for renewable energies is no different, and government intervention needs to take action to increase hydrogen production. Whether it is incentivizing or punitive instruments that are being used, interventionist measures reduce the cost for producers, consumers, and lectures those who are using polluting alternatives.

The literature backs the theory. A 2022 study about institutional and socio-technical determinants of renewable energy production determined that there is a positive relation between public intervention and promoting renewable energies (Marra & Colantonio, 2022). Similarly, another study about renewable energy penetration suggests that economic incentives are key for the development of RE technologies (Painuly, 2001). Other institutions like the European Investment Bank, are also acknowledging that public intervention is needed to overcome the high costs of production that are popular in today's hydrogen ecosystem. It is clear that there is demand for intervention instruments in the sector, and there are a number or instruments that can be employed, which we will discuss below.

2.3.2.1. Tax Credits

Tax credits are reductions in the tax liabilities that producers might have incurred during the process of production clean energy, based on the amount of electricity produced. This definition refers to production tax credits (PTC), which are the ones we will discuss in this section, but there are other types like Investment Tax Credits, or Fuel Tax Credits. These tax credits are usually subject to a few conditions like date of construction of the project or number of Megawatts. Now, the theory suggests that if this is implemented correctly, it will lead to lower cost of production (Piper et al.,2023), which will lead to a reduction in the price of renewable energy, including clean hydrogen, if it is passes to the consumer, and therefore makes RE a viable alternative to conventional fossil fuels. The practice, as stated in a study by the National Renewable Energy Laboratory (NREL), affirms that federal tax credits have a measurable impact on future RE deployment.

Several countries are currently using tax credits. Italy, Spain, Poland, or Belgium are examples that are implementing tax incentives in a number of renewable energies (Goryunova, 2017). The US is also a leading country when it comes to tax credits. In the last decade, a renewable energy PTC that covers until 1.3cent/kWh was incorporated in the U.S tax code. Similarly, more recently the have passed different laws in the US Inflation Reduction Act (IRA) that allow producers to choose from a 30% investment credit tax in the cost of the production facility, and a hydrogen PTC that would pay producers up to 3$ per kg of H2 produced.

2.3.2.2. Subsidies

Capital expenditure, electricity costs and electrolysis costs are the three main components that explain why the GH production process is so expensive (Bartlett & Krupnick, 2020). Once again, to make clean hydrogen an economically feasible alternative to fossil fuels, governments can use another intervention mechanism, subsidies. Subsidies are financial payment from the government to help lower the price for consumers or lower the costs for producers. This was, you are either increasing demand and creating a market, or alleviating some of the investments of the producers. These differ from tax credits because they are a direct form of financial support, while the previous instrument is an example of indirect financial support. However, both policies are effective and necessary. In fact, not only are subsidies necessary, but without subsidies alternatives like grey hydrogen, for example, remain matchless, as expressed in a recent study about GH marketability in Denmark (Panah et al., 2022). Wind and solar energies where much more expensive electricity alternatives until subsidized, and the same evolution needs to occur with green hydrogen.

However, subsidies need to be implemented well, and efficiently, because there are other drawbacks against them compared to tax credits, like the fact that they increase government deficit or that they may create market inefficiencies. For subsidies to work as they are intended to, they should be transparent, they should target specific goals, and they should have a phase out time stablished (IEA,2010). By having transparent subsidies, you foster public trust and investor confidence. By stablishing clear objectives like reducing costs, cutting emissions projects, or increasing production capacity, you increase the chances of a targeted and effective result. Finally, having a phase out period is relevant so that producers don't become reliant on the financial aid, and to ensure these subsidies do not become a long-term expense for the government.

2.3.2.3. Feed-in Tariffs

While on the topic of subsidies, it would be interesting to highlight the use of a specific subsidy that has gradually gained relevance in the energy sector throughout the years: feed-in tariffs (FIT). FITs are schemes that reward energy suppliers with a fixed price for their energy generation. In countries like the UK this has proven hugely successful (Cherrington et al., 2013). Additionally, studies mention that FITs contributed as much as 75% to PV and 45% to wind deployment (NREL, 2010). Not only do developers benefit from this, but also investors. A study in 2009 suggested that FITs reduce investment risk and that they are the preferer policy for venture capitalists in general (Bürer & Wüstenhagen, 2009). However, this long-term payment is not given to any producer, but it is usually subject to different criteria or requirements like capacity (MWh) or type of energy generator (Solar, Wind, etc.)

2.3.2.4. Carbon Credits

Carbon Credits or Carbon Offsets are instruments that do not specifically focus on RE deployment, but in reducing emissions. This option is worth mentioning because it is a very popular financial incentive used in the energy sector. They are defined as tradable permits that measure the right to emit 1mT of CO2 (in the case of credits) or the ability to reduce CO2 from the atmosphere (in the case of offsets). These instruments work because governments around the world have set quotas or limitations on the amount GHG emissions companies can produce. If a company exceeds this quota, they must buy a carbon credit, on the contrary, if a company goes bellow this quota, they can sell their carbon credits (Gupta,2011). This way companies that exceed their GHG emissions are paying for their pollution, and companies that do the opposite are being rewarded. This advantage of this process is that it incentivizes companies to produce lower or no CO2 emissions.

The former is not the only advantage of this tool. Because Carbon Credits are tradable, they can be exchanged between companies, but also between countries, both developed and developing. This exchange creates a market and signals once again to investors and developers the importance of discovering new alternatives of carbon capture and renewable energy projects. Creating a "Green Hydrogen Credit market" is actually one of the goals and a consequence of a study by Dong and Yang, which introduces the first framework of a "Green Hydrogen Credit (HC)" (Zhang et al., 2021). In the study the HC represents the net savings of CO2 per ton of hydrogen, and it works for the same purpose that regular carbon credits do, but it would also incentivize green hydrogen projects.

2.3.3. Investment

The two previous policy initiatives help generate demand, create a market, or even lower the cost of production, but to make green hydrogen a competitive reality and economically viable you need financial investment. There are studies that point out that high costs and lack of funding are one of the main barriers that are preventing GH from developing (IRENA,2020). A recent study even suggest that this might be the most important barrier (Eh et al., 2022). The reason being that financial support is critical in all steps of the value chain of GH, and even before. It is needed for research, technology, construction, commercialization, and many other purposes. In this section we will therefore delve deeper on how financial aid can be used in the different parts of the process, what are the two areas where investment is usually directed at, and what actors can be responsible for it.

The benefits of investment seem to be clear and well accepted, and that is reflected in the investment trends for the past couple of decades. Global investments since 2004 until today have experiences an upward trend. (Figure 3).

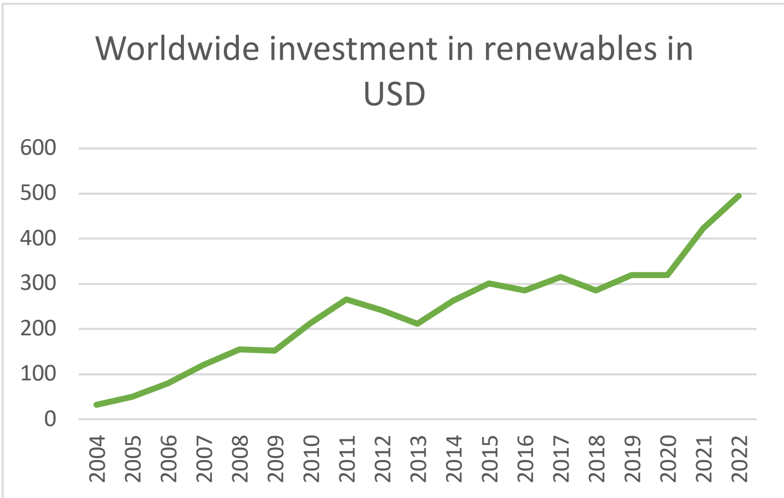

Figure 3. Worldwide investment in renewables.
Source: *Statista*.

2.3.3.1. Research and Development

The first section where investment can be directed is Research and Development (R&D) which coincides with the earlier stages in the green hydrogen generation process. Investing in research and development is in fact seen as a strong determinant for increased hydrogen production (Ampah et al., 2022). R&D is regarded as a necessary part of the transition to net-zero because it is the seed of the whole process, and the literatures backs this (Lee & Kim, 2021). There are different approaches and different actors, but it generally includes research entities like universities, research facilities, NGO's, governments, or private companies carrying out research, testing prototypes, analyzing, and collecting data which then leads to new discoveries. This process leads to innovation and advances in technology, which are key to improve the current production process and develop new ones, as well as increased efficiency and lower costs in the long term (Prokopenko et al., 2023). From 2004 to 2015, global government R&D in renewable energy increased 1,9$bn to 5,1$bn and corporate R&D 3,2$bn to 6,6$bn (Zeng et al., 2017).

Within the field of renewable energy there are many areas that need further R&D like, nanomaterials for efficiency, smart grids, marine and hydrokinetic energy, microbial fuel cells, and many other cutting-edge technologies. Similarly, in the green hydrogen sector there are different technologies also in need of further development. An example might be alkaline or PEM electrolysis stacks, which are components of the electrolyzing process, as stated by a 2021 IRENA report. This obvious need for new technologies has materialized itself in literature, where papers with keywords "hydrogen production and storage" have seen a soaring trend, with just 10 papers in 1990 and more than 680 papers in 2021 (Lebrouhi et al., 2022).

2.3.3.2. Infrastructure

In the same way that R&D is crucial for earlier stages of the clean energy production process, infrastructure plays an important role later in stages like storage, distribution, or transport. Nevertheless, investing in infrastructure is equally as important. In storage, for example, we find physical storage like tanks (for amounts up to a few MWh), and material storage like salt caverns (for higher amounts of hydrogen). The case is that physical storage infrastructure is fairly mature, but long-term material storage infrastructure for amounts like 100 GWh of GH is not and needs high levels of investment (Deloitte, 2023). For distribution and transportation, structure like pipelines, tube trailers or trucks are needed, and investing in this will accelerate the transition and will make large scale production and commercialization plausible.

More specifically, GH can be used to decarbonize different sectors, and each sector needs viable infrastructure to do so. In the case of the transport sector, hydrogen fueling infrastructure to support the development on Fuel Cell Vehicles (FCVs) is currently one of the biggest challenges (Stephens-Romero et al., 2010). Similarly, for the heating sector, it is believed that in the future GH can be used to heat our homes, power are day-to-day appliances, and replace gas networks. But for this to happen, once again, heating systems and infrastructure need to be updated and made “hydrogen-ready”.

2.3.3.3. Public vs Private Investment

The two areas where financial investment can be poured into to improve production have already been discussed, what is now important to review, is who are the actors responsible of making this investment and what is their role.

The first actor we can mention is the government. Public Investment results from government expenditure being used in numerous ways. This money is generally used to support many of the instruments discussed above like subsidies, feed in tariffs or grants for R&D.

The second type of investment is private Investment, which in this sector can be subdivided into three dominant categories: corporate investment, venture capital (VC) and project finance. Corporate investment refers to each company investing their capital into the transition of their own company. This can be done by making their value chain “greener”, redefining their objectives, or even changing the product they offer to ensure it is more sustainable. VC is slightly different and is usually a firm which invests in pre-mature companies that are in early stages, which is the case for many companies that are developing new technologies in the energy sector (look for examples). Finally, project finance refers to institutions like banks, or even private investors placing their money in different companies or projects. Private Investment differs from public investment because the owner of the funds is looking to obtain a return, and may therefore invest in more researched way, arguing therefore that this type of investment is more efficient. The reality is that both parties are necessary, and in many cases these two works together in what are called Public-Private-Partnerships.

Now that all three determinants; legislation, intervention, and investment, have been explained, as well as some mechanisms to deploy them, there is better understanding on how they work and their efficiency. Having done that, it is now possible to analyze how leading countries in the renewable and green hydrogen industry are employing these instruments. We will do this by analyzing three case studies bellow: China, the US and Germany.

3. Methodology

Having stablished a theoretical framework with four levers to propel renewable energy production, more specifically green hydrogen deployment, three real cases of countries will now be examined following this framework. Each lever is evaluated individually to show how they contribute to the country's success in GH production.

The countries analyzed bellow are China, USA and Germany, and there will be specific numbers and actions provided for each of them. The reason these three countries were chosen is because they are large countries that are leading in both renewable and green hydrogen production. While these three countries have different sizes, cultural traditions, or political systems, there are some factors that do indeed make them comparable. Firstly, they are large and influential economies. Secondly, they heavily industrialized and have important manufacturing industries which allow them to be heavy exporters. And thirdly, they are all committed to turning their respective countries into more sustainable economies and using renewable energy deployment to lead this transition.

3.1. Case study 1 – China

China is certainty one of the runner ups in the race for a sustainable economy and a transition to GH. This is understandable considering they must mitigate the damage made these past decades. China's economy grew 224% from 2004 to 2015 and, due to this rapid economic growth, and the increase in energy demand by an enriched population, China was classified as the world's largest GHG emitter in 2019 with 12.7 billion tons of CO_2 (European Parliament, 2022). In addition, the country's economy is heavily based on the manufacturing industry, which is one of the most polluting industries in today's economy.

Although they lead in harmful emissions, they compensate by being the world's leader in renewable energy in many aspects too. China's numbers of manufacturing installations and installed capacity are impressive. In 2013 PV capacity reached 13GW, and just two years later, it was more than twice that amount. Similarly for wind capacity, in 2014 they broke a record by contributing 20GW in a year which then contributed to a total capacity of 96GW (Sokolowski. M. 2016). This data shows that the renewable industry in China is leading and will not stop growing any time soon. An IRENA report predicts a 16% increase in renewables by 2030, and a 30% of the country's electricity coming from those sources by that year as well.

China is the world's largest producer of hydrogen. However, out of this production only around 1% is green hydrogen. It is for this reason that China needs to find a way to produce more clean hydrogen that can replace the polluting types. With 1GW currently and 10GW planned, the industry still forecasted that by 2030 the capacity will be around 40GW if not more, which reflects how positive the outlook is towards the deployment of GH (Brown. A, 2022). Therefore, the country has also been making advances in their policies.

The numbers for China's industry speak for themselves, and the country's success in this area is irrefutable. What we will try to demonstrate in this paper is that much of this success can be attributed to the proper use of the levers commented in the theoretical framework. Therefore bellow, a study regarding their initiatives and actions taken by the country in each section.

3.1.1. Regulation

The theoretical framework of this paper lists a number of instruments, including targets, standards, or patents, which provide clarity to developers and signal relevance to investors. To communicate the implementation of these instruments, China, as well as other countries, have communicated their efforts through policy documents and road maps over time. In the case of the Chinese government, the most relevant policy document released in 2019, could be China Hydrogen Alliance (CHA), which was a document that shared prospects of GH demand and consumption in the country. Although this might be considered the most relevant, previous policies mentioning green hydrogen had been published like the *National Innovation-Driven Development Strategy and the Action Plan for Innovation in the Energy Technology Revolution (2016–2030)* which promoted developing hydrogen. But relevant documents have also been published after the CHA, like its *Medium- and Long-Term Plan for the Development of the Hydrogen Energy Industry (2021–2035)* in 2022, or *Guidelines on Promoting the High-quality Development of Petrochemical and Chemical Industries* which promotes the used of green hydrogen, that same year.

The China Hydrogen Alliance mentioned above is also responsible for introducing some standards and definitions of what should be considered renewable hydrogen. It follows three distinctions: low carbon hydrogen, clean hydrogen, and renewable hydrogen. Then it defines them according to two measures, maximum CO_2 emissions per kg of hydrogen and if the production comes from renewable energies. Low carbon hydrogen is when the maximum emissions are up to 14.1 kg and it does not require for the production to come from renewables; then clean hydrogen is defined as the type that allows until 4.9kg of CO_2 emissions and does not require that the energy comes from renewable energy, and finally, renewable hydrogen which allows a maximum of 4.9kg of CO_2, but does have to be produced strictly from renewable energies (Gong. X.,2022). This distinction is very useful, because clearly understanding the different types will then provide further clarity if the specific types are mentioned in policies, or as criteria for other incentivizing instruments.

Having established clear definitions, it is important to set clear objectives as well. Targets do just that. Targets help motivate production, but also help contrast evolution and benchmark against other countries on how you are doing. Although, many experts say that China has been conservative with them, it is worth reviewing the targets that they have proposed to stay in the lead for renewable hydrogen creation. The CHA document for example, sets a target of 100,000 - 200,000 tons of renewable hydrogen production, as well a fleet of 50,000 hydrogen fueled vehicles by 2025. In that same policy document, they also stated a target supply cost of GH of CNY40/kg by 2025, and CNT30/kg by 2030, and finally CNY20/kg by 2050.

Now that we have discussed some of China’s national policies, and the targets and definitions that they mention to set the basis of the GH industry, it is now worth mentioning what many agree is the reason for the country’s success in this race: regional policies. Local and regional policies outnumber the national, and some studies even mention that provincial policies are more ambitious in terms of targets than national ones. Inner Mongolia, for example, which is a region of China aims to produce 500,000 tons of green hydrogen, which is five times what the national target is for that year. This ambition is replicated in other areas, and provinces are making their own policies and competing for hydrogen production. In 2021, eleven national level policies were published as opposed seventy-eight on a provincial level.

3.1.2. Intervention

In the same way that China places emphasis on GH policy development and investment, as we will discuss later, they have not stablished specific interventionist instruments for green hydrogen. Their approach with government intervention has been to renewable energies, which is why we will discuss these instruments on a more renewable sector level and then mention the ones that are more targeted to green hydrogen briefly.

China has a history of subsidizing fossil fuels to remain competitive, but these have proven not fully effective and have been accused of not reflecting the negative externalities on the environment (Espa & Rolland, 2015). However, fossil fuel subsidies were much more abundant that renewable subsidies. Which is why reports mentioned that the country needed to shift their subsidies targeted at oil, coal, and others, to renewable energies if they want to increase their production. Therefore, this is what they have been doing in the past decade. The way in which China is subsidizing this sector in through feed in tariffs, which is one of the instruments commented above. In 2010, 10.97 billion CNY in the form of subsidies were directed at energy generation. This, however, was not enough the make energies like solar, wind, or biomass competitive. Luckily, since then, the country has been increasing the amount directed at subsidies, being one of their latest almost 3 billion CNY in 2022.

Related to tax credits, which was another of the mechanisms proposed in the theoretical framework, China has also made some advances. With regards to fiscal and tac incentives, they took measures. With regards to VAT for example, from 2013 to 2015 solar projects were eligible to a 50% VAT tax refund. Similarly, biomass and wind projects enjoyed a VAT of 13% and 8,5%, compared to the general 17% VAT in China. Likewise, with income tax, biomass, wind, solar, can enjoy 50% tax exemptions during the first three years (Zhao et al., 2016).

Although these mechanisms are aimed at renewable energies in general, and there is no specific subsidy policy or tax incentive policy for green hydrogen at a national level, this is also a step towards green hydrogen development. Firstly, because the obvious response from China would be to in the future apply this same mechanism to the GH sector, and secondly because renewable hydrogen requires a renewable energy source; so, the more renewable energy deployment, the more positive this is for green hydrogen. And although China is not targeting green hydrogen directly, they are specifically targeting industries that are closely related. A recent example would be the central government subsidizing up to 235$ million to all Beijing, Shanghai, and Guangdong to promote hydrogen fuel cell vehicles. These actions point in an obvious direction towards more interventionist policies from China towards GH production.

3.1.3. Investment

Like we stated before, the lack of interventionist mechanisms on GH is overcompensated by the emphasis China places on investment in R&D and infrastructure. Similar to what happens with policies and targets, the major country finds investing in technology and innovation key. This includes the effort of many Chinese private companies as well as public bodies like the State Council, the National Energy Commission (NEC) or the Ministry of Science and Technology (MOST), among others.

In relation to research and development, since the year 2017 projects related to hydrogen have received over 250 billion CNY. Similarly, the country confirmed a 7% GDP increase related to expenditure in technology (Delaval B. et al, 2022) and R&D between the years 2021 and 2025. These funds are directed at initiatives such as the National Key R&D program, which is a state led program that funds green hydrogen projects. An important actor in China's R&D which are also responsible for advancements are research institutes and universities. Shenzhen University and Nanjing Tech University, for example, have recently discovered a new electrolyzing method called SES which involves sea water. Or the Dalian Institute of Chemical Physics is also responsible for demos of green hydrogen projects. These efforts to research have then resulted in an increase in the number of patents related to green hydrogen specifically since 2015. To support this, the MERICS study we have already mentioned states that in the period between 2010 and 2015, 40% of the academic literature related to green hydrogen, belonged to China.

In the same way that the public sector in China is investing in R&D, private companies in the country are spending their income to improve the industry. A recent example would be Sinopec, the state-owned private petroleum giant, which is building the world's largest factory of GH production estimated to produce up to 20,000 tons a year. Another example would be Shell China, which have invested in a electrolyzer to supply green hydrogen for FCV projects. Similar to Shell's project is the chemical manufacturer Ningxia Baofeng. The company is also building a plant which they estimate will produce up to 27,000 tons of GH in the future. These are some examples of companies which have developed projects related to green hydrogen, but this is not necessary their main activity. There are, however, many leading companies based in China whose sole purpose and product is dedicated to GH. Some names might be PERIC Hydrogen Technologies, engages with hydrogen technology in general, or SinoHy, leader in water electrolysis.

3.2. Case study 2 – The US

The United States is, just like China, one of the most important players in the green hydrogen sector. They are currently, in 2023, one of the top three countries with the highest capacity for hydrogen production, and a report by Rystad Energy (leader company in energy research), confirms they will maintain this leading position at least until 2030. On the topic of forecasting, the market for green hydrogen is expected to grow more than 50 times the value it has currently. A report by Precedent Research suggests that the market will go from 4 billion USD in 2022, to over 300 billion in 2032. It is growth that is expected in the GH industry in US, but it is no luck, we will demonstrate in this section that it is due to the trust there are putting in their ongoing regulation, intervention, and investment policies.

Part of their success in the GH field can also be attributed to their vast access to renewable resources. Let us remind that this is relevant because green hydrogen can only be labeled "green" if it is produced with renewable energy, therefore, the more access to RE, the more energy available to produce GH. And, according to data from IRENA, the United States was the second country with the highest installed capacity of renewable energy sources in 2022, with 113,015 MW, in the world. Not only this but compared to other energy sources like coal or natural gas they have been gaining importance in overall generation, more specifically, in 2020, renewables generated 21% of energy generation in the US, while nuclear occupied 20%, coal 19% and natural gas 40%. These renewable sources, of course, were incentivized following many of the policies that are stated in the main theoretical framework of this paper.

All throughout the first two decades of this century, several policies like tax incentives, subsidies or grants were used. Some more creative Renewable Portfolio Standards (RPS), which forced energy providers to use a certain percentage of RE, or Mandatory Green Power Options (MGPO), were first introduced in the US as well. Back then, the popular RE were mostly solar, wind and biomass energies, so these policies just applied to those. But now it is different, and the US is promoting GH and including it in a number of different policies that are discussed underneath.

3.2.1. Regulation

The US has been publishing energy-related regulation documents since 1992, back when they published the *Energy Policy Act*, that was then updated in 2005. Two years from that, they published the *Energy Independence and Security Act in 2007*, where they promoted renewable fuel production as well as research into topics like carbon capture or energy storage. More recently in 2022, they developed what is probably the most important document related to guiding GH production in the US, and that is the *DOE Clean Hydrogen Strategy and Roadmap*. This document provides insights to national decarbonization goals, planned applications in different sectors, evaluated regional potential and different actions that have been or will be taken by the country. This roadmap is part of the Infrastructure Investment and Jobs Act (Public Law 117.18), but it is important to mention the latest act called The Inflation Reduction Act published this year 2023, which also suggests intervention measures that we'll discuss above. Most of the documents mentioned in this paragraph are introduces because it is where mechanisms like targets, or subsidies that will be discussed below are first introduced.

One of the mechanisms that we defined in the framework related to regulation are standards. The US is one of the countries in the world that, together with China, Germany, Australia, and a couple more countries, has active standards. A report by the IRENA explains the two standards in the country (IRENA,2023). The first one is the California Air Resources Board Low Carbon Fuel Standard (LCFS), which is regional and only active in the state of California and provides an incentive scheme based on credit for hydrogen. It also provides a definition of what they consider low carbon hydrogen, which is one that produces no more than

10,51gCO2/MJ of compressed hydrogen. The second standard is national, and it is named the US Department of Energy (DOE) Clean Hydrogen Production Standard. Resembling the one in California, this standard also provides a definition of clean hydrogen which in this case entails 4kgCO2/kgH2. These standards are key, and they pave the way by stablishing a clear definition providing clarity for hydrogen producers. Another regulation mechanism that has been adopted in the US very early on is renewable portfolio standards (RPS). Around 15 states have implemented RPS since the beginning of the century and a study by Menz F. in 2005 stated that it was one of the most effective measures to promote renewable energy production (Menz, 2005).

Targets are also abundant in US regulation related to GH. Firstly, they are committed to goals stablished in the Paris Agreement in 2015, so some general targets related to the energy sector that impact GH are: a) a 50% reduction in GHG emissions in the US by 2030, b)100% carbon pollution-free electricity by 2035, and c) net zero emissions no later than 2050 (Chen et al., 2021). Secondly, the have also stablished production targets, which are 10 million tons annually in 2030, 20 million tons annually in 2040, 50 million tons annually in 2050, according to the DOE document previously cited. Of course, this projection will only occur if technology related to GH improves and if the cost of clean hydrogen falls. But the US has also made some ambitious targets relating the cost of green hydrogen, like the price of it being as little as 1$ per 1kg in 2031.

3.2.2. Intervention

The US have peen pioneering interventionist measures for quite some time, and they are doing it as well in the green hydrogen industry. With mechanisms like production tax credits, feed-in-tariffs, and carbon credits, they are paving the way for hydrogen production.

The US has a history of using production tax credits (PTC) on renewable energy projects, which allows producers to enjoy a lower cost of capital. They were actually first stablished in the Energy Act in 1992 for wind projects at $0,015/kWh ($15/MWh) which was set to expire in 1999 but has since them been postponed many times. 20 years later, in 2019, the tax credit was $0,025 kWh for biomass and geothermal energy, and 40% or 60% of that credit amount for wind depending on depending on the year of starting construction. More recently, with the IRA Act that we mentioned in the regulation section, a PTC is set to be placed on green hydrogen as well. The document suggests implementing a 1$/kg of H for blue hydrogen, and a 3$/kg for green hydrogen.

Feed-in-tariffs are also a common subsidy used to incentivize renewable energy production in the US. To this day many states had adopted the policies, some examples might be California, Oregon, Washington, Vermont, or Oregon. FITs in the US are generally set as long-term contracts, are applied to different sources of energy, be it solar, wind, biomass or other, and are usually of two different types. The first type is utility-based, where investor-owned utilities (IOUs) set FITs in place to achieve utility-specific goals. And the second type is state level, which are mandated in the state. Different states have different types, Wisconsin state, for example, does not have a common state policy, therefore utilities like We Energies or Madison Gas set their own FIT programs. Although this policy does not yet include green hydrogen as an energy source, the success of this policy suggests that it might be implemented in the future.

Finally, the US also employs the use of Carbon Credits and Carbon Offsets, in fact there is a Carbon Market that can be divided in the two types. The first one is the compulsory or cap-and-trade market, where companies can buy and sell their carbon credits to comply with government or institutional limits of carbon emissions. However, in the US there is not a national market, in fact the most common and ambitious cap-and-trade market is the California Carbon Market (Shen et al.,2014). The second type is the voluntary market, where both individuals and companies can purchase tax credits from companies or sustainable projects. These projects of course must be registered in a carbon offset program also called registry, and in the US there a few, some might be the American Carbon Registry, or the Verified Carbon Standard (Verra). This is relevant because there are upcoming initiatives like the one from the firm South Pole, which is trying to integrate low-carbon hydrogen into carbon markets.

3.2.3. Investment

Investment in the US plays a very significant role in the progress of renewable energy and green hydrogen production. Since 2004 till today, the numbers of investment to RE in the country portray an increasing trend (Figure 4). In fact, North America, but mostly the US, enjoyed the second highest investment in renewables in 2019 and 2020, attracting 53 billion USD the last year of the two. Investment per capital for example went from 127USD in 2019, to 179 USD in 2019, that is a 41% percentage increase, compared to a 34% in India, or a 5% in Europe. This refers to investment attracted into the country, but domestic investment, in particular green hydrogen investment, has also been ambitious as we will see right after.

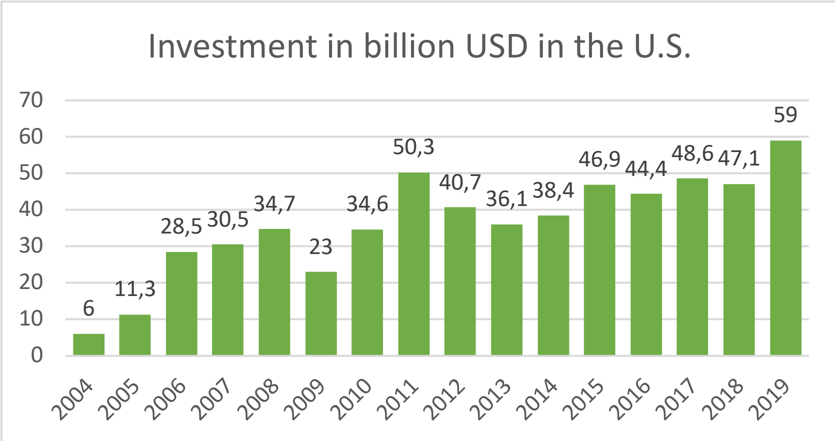

Figure 4. Investment in billion USD in the US.
Source: Statista.

The US is a firm believer in R&D. The OECD found a direct relation between R&D and GDP, where 1% increase in R&D in the US leads to an increase of GDP of 0,10% on average. But it also supports unemployment; R&D in the energy sector only, generated as much as 112,100 jobs in 2018. Which is why a section of investment is directed to this. An initiative, for example, by the department of energy in 2022 dedicated 125$million to small business which were carrying R&D for clean energy. Similarly, in relation to traditional renewable sources, the state announced a $6 million funding for 19 solar projects that are in early stages and that need financial support for development. For clean hydrogen projects there has also been significant investment, like for example recently when a 1 billion USD were attribute to the Clean Hydrogen Electrolysis Project to improve efficiency and support research and development phases.

There is also an emphasis on infrastructure and technology, and not just R&D and innovation. The DOE recently announced a 30$ million aid funds for projects that help integrate solar energy to the grid. Similarly, the government also chose several projects that had already developed the technology but need to scale it to a larger supply chain. Some of those projects are: LightSpeed which was awarded $1.6 million to make PV plants more resistant to external factors, or Guardian Devices which received $900,000 to make PV avoid potential fires in the systems. More specifically, for green hydrogen the Hydrogen Roadmap published also attributed 8 billion USD for Regional Clean Hydrogen Hubs to improve connective infrastructure.

These are all public efforts to invest in the increased production and a reduction of cost in hydrogen, but there is also an effort being done by private entities, in fact in the United States, business provide most of the R&D funding. About a year ago, a company called Green Hydrogen International announced a 60GW H2 project in Texas called Hydrogen City, which is supposed to compete for the title of biggest hydrogen project. But other companies which are not hydrogen focused are also catching up on the sector, like for example Plug Power Inc, and Olin Corporation forming a joint venture to build a hydrogen plant that will build 15 tons a day. It is this active investment from both public and private sectors that have and will propel green hydrogen production in US.

3.3. Case study 3 – Germany

Germany is also a country that is worth studying because of their fair share of initiatives to promote green hydrogen production. They are Europe's top energy consumer, and it is also one of the largest industrial countries in the continent, which is why finding alternatives to fossil fuels has been in Germany's agenda for quite some time now. However, speaking about Germany is not possible without first speaking about European Union (EU) because of how laws, in this case energy laws, work. The process generally starts with the EU setting a directive, regulation or policies that set specific targets, and then countries though their own legal system implementing their legislation to meet these. Hence, why it is interesting to study the case of Germany, which is advanced in comparison to other European countries, when they are all under the same European Union directives.

The European Union has put in place policies that we will study bellow to reach admirable levels of RE and GH production. From 2005 till 2014, there was a decreasing demand for fossil fuels and nuclear energy which matched an increasing demand for renewable energy. More specifically, renewable energy per capita was 2.5 times larger in 2018 than in 2005 (Almuni.M, et al. 2020). A report by Iberdrola showed wind capacity more than doubled from 109 GW in 2012, to 236 GW in 2021. Similarly, solar power experienced a fivefold increase from 2010 to 2020 in the EU. Production has increased, but just as positively the price of these energy sources has fallen to much more competitive levels. The levelized cost of electricity (LCOE) has decreased for most renewable technologies, for Solar PV it experienced an 88% decrease between 2010 and 2021, for onshore wind a 68% decrease and for offshore wind a 60% decrease as well.

Renewable energy in Germany has showed a positive trend compared to other countries in the EU. In 2013, Germany had the highest primary production of renewable energy (Pacesila et al., 2016). Three years later, in 2016, renewables already occupied a 29% of the gross electricity generation. This increase in RE generation has been driven by RE electricity demand; back in 2000s renewable energy accounted for roughly 6% of energy demand, in 2013 this percentage escalated to 25%, and in 2022 it was as much as 46% of german electricity demand. The outlook is also very encouraging for the country. In 2025, for example, electricity consumption is to reach in between 40 and 45 percent, and 80% by 2030. The theory says that this success in based in part to their policies, intervention, and investment, as they have been pioneers with it within the EU.

Now that renewable energies have found their space within the energy sector in Germany, they are advancing on other topics to accelerate the environmental transition, and the aim of the country is to set themselves as leaders of the development of green hydrogen. Currently, producing is still low, like in all countries, but this number is set to improve due to increased capacity, improved technologies, and declining costs. According to private company reports, that it is possible for yearly maximum supply capacity to reach 16GW in 2025, and 27GW by 2030.

Both this energy evolution in GH and RE, are part of what is called the Energiewende in Germany. This concept is important because it encompasses all the progress made by the country since the 1990s till today to ensure a sustainable transition.

3.3.1. Regulation

Because of the nature of energy laws like we explained in the first section of this case, both European regulation and legislation mechanisms and german ones will be explored, because one breads from the other.

Europe has several policies and regulation published related to renewable energy and green hydrogen. One of the first and most important documents is the *Renewable Energy Directive (RED)* published in 2009, which has then been revisited and updated in both in 2018 and 2021. Then came the *European Green Deal* in 2019, which is another relevant document whose aim is to make Europe carbon neutral touching other more general topics like clean water and air, affordable food, but also clean energy. Three years later, in 2022, pressured by the Russian and Ukrainian war the European Commission published another policy called *REPowerEU*, to accelerate the energy transition even further. These documents relate to renewable energy as a whole, but more specific documents have been released by the EU regarding Green Hydrogen. In 2020, for example, the *EU Hydrogen Strategy* was adopted. A year later, the *Fitfor55* package document that looked to revisit RE legislation, introduced a specific framework for GH.

Germany also first started with general regulation related to renewable energy back in the year 2000. That year they released the *Renewable Energy Act (EEG)*, which is a law that provided ground for much of the initiatives today. However, it is worth noting that Germany has RE in their radar long before that; in 1992 they signed the *United Nations Framework Convention on Climate Change*, and some years later they signed the Kyoto Protocol, which was a UN convention regarding climate change. Moving forward again, most important legislation documents belong to this century. After the EU launched their RED directive 2009, Germany released a national strategy called the *Energy Concept*, and some years after in 2011 the *Energy Roadmap 2050*. Regarding Green Hydrogen, Germany has amended their Energy Act, throughout the years, and more recently to include GH. Similarly, in 2020 they published a *Green Hydrogen Strategy* by the Ministry of Energy which stablished goals and an action plan.

In terms of certification and standards, the EU has a couple of mechanisms. The first mechanism or standard scheme are Guarantees of Origin (GoO). They are certificates that are issued and mentioned in articles 19 and 15 of the RED directive, which serve to certify that the electricity is in fact produced from a renewable source, or, in the case of hydrogen, that hydrogen, is produced by renewable energy. The second standard followed is called CertifHy, it derived from GoO and it is exclusive to the EU (White et al., 2021). It certifies not just the source of electricity, but the whole production process, the emission reduction, and the sustainability of it. Germany has developed their own GH standard scheme as well, and it is called TÜV SÜD. This standard defines requirements of the production process such as the type of process (which can be electrolysis or steam biomethane), or the emission reduction level. Once again, Germany has proven to be pioneer since very few countries in the European Union, have stablished their own standard except for France and UK.

Finally, targets were also mentioned in these policies and regulation. In the case of the EU, the updated RED document stated a GH consumption by the industry of 50% and by the transport sector specifically of 2,6%, both by 2030. Germany expects a GH demand of around 90 TWh, and their goals is to produce at least 14TWh, or more, and to import the rest.

3.3.2. Intervention

Regarding the first mechanism in the intervention part of the framework, we have, once again, tax credits, which are commonly used in Germany. The updated version of the Renewable Energy Act 2021 states that the renewable electricity required for the GH production process can be exempt of tax or present a tax reduction. In addition, there is an upcoming law Act called the Energy Levies Act, which although it is only drafted currently, plans to suppress other levies related to the process like heat and power levies (Holtermann. A.,2022).

Similarly, at a European level, the European Commission has proposed to introduce a round of subsidies in the form of auction to help GH producers. The first one they have proposed is a 800€ million auction, that many argue is a response to remain competitive after the US released their policies in their recent IRA Act, discussed above. Along the topic of subsidies, Germany is also one of the first countries in the EU to set up a feed-in-tariff system, and theirs roots back to the beginning of this century. This mechanism allows a fixed flow of income for the energy produced in energies like solar, wind, biomass, or hydraulic. And, although this is not a FIT set-in motion for green hydrogen, this does favor the production of it, and does not change the fact that Germany is incentivizing GH in other ways, such as the German National Innovation Program (NIP) fund which has a budget of 1.4billion EUR.

Finally, just like in China and the US, in the European Union there is a common carbon credit system, or Emissions Trading System (ETS), which is how they generally call it. This system, stablished in 2005, operates like a cap-and-trade, like what occurs in the US, target GHG emission limits are set which will decrease progressively until they reach zero eventually, and on the mean time companies and other institutions trade emission allowances to compensate emissions. To complement the EU ETS system, Germany recently launched their own ETS mechanism in 2021. The system only applies for the transport and building and aims to achieve a 65% decrease in GHG emissions since 1990.

3.3.3. Investment

Investment efforts like the 800-million-euro subsidy auction mentioned in the previous section, is just one example of the investment efforts made by the EU. In case of the EU there are around 10 different programs and funds for this purpose. The Recovery and Resilience Facility (RRF) is one of those funds that the Commission uses to then support initiatives like RepowerEU and provide funding. In the case of the RRF the European Union has invested as much as 10 billion euros to hydrogen (European Parliament, 2023). In the same way that the EU Commission appoints different funds the task of allocating investment, in Germany they employ the High-Tech Forum (HTF), which is the body appointed to carry out the High-Tech Strategy 2025 (HTS). The HTS is key in the development of innovation, technology and R&D, and many strategies, including the National Hydrogen Strategy we mentioned in regulation, are based on it.

In the field of research and development there are also initiatives to be commented. Another one of these European funds is called LIFE Program and it finances earlier stages of GH initiatives, as well as other climate and energy projects. Another example would be the Innovation Fund, which helps certain demonstration projects to increase innovation by funding as much as 60% of the costs. And finally, another example of a fund that helps R&D would be Horizon Europe. Although all these funds can allocate financing to german projects, they also help other European countries, but Germany also has their means to fund innovation and research for GH. In fact, in the national hydrogen strategy there is stated a €1.91 billion in hydrogen technology research. In addition to that, it also states a 50 million investment in research for fuel cell powered airplanes, and 600 million in funding through a program called Living Labs.

Infrastructure development has also received funding. Going back to the European funds we first mentioned, we have Connecting Europe Facility or InvestEU. Two funds which specialize in funding riskier projects whose objective is improving infrastructure. The german national hydrogen strategy highlights a commitment of €1.1 billion to develop facilities that produced hydrogen electricity- based fuels. In addition, in the transport sector they commit to as much as €3.5 billion to financially support hydrogen-based vehicles, as well as €3.4 billion in endowments to finance recharging infrastructure. Germany is not only investing in domestic infrastructure, but they are also collaborating internationally, and the H2Med is an example of this. This pipeline project will connect Spain, France, Portugal, and Germany to improve the transport of green hydrogen.

The private sector is also paying their dues to ensure they decarbonize the different industries. Companies from different sectors like energy, transmission, or transport, such as RWE Generation, Nowega, OGE, or BP are already building infrastructure projects that will help the development on green hydrogen production even further.

To conclude the case study analysis, a comparison summary table is shown in Figure 5, where the effort by each country in all three levers is shown.

	Regulation			Intervention			Investments		
	RoadMap / Legislation	Def / standard	Targets	Subsidies	Tax Credits	Carbon Credits	R&D	Infrastructure	Large projects
China	*China's Hydrogen Alliance (CHA)*	Produced from RE and maximum 4.02 kg CO2	100.000-200.000 tons of GH (by 2025)	3.2 billion CNY in 2022	VAT and income tax up to 50% exemption	China Carbon Market is active	7% GDP increase in R&D expenditure	Actively investing	Synopec project - 20.000 tons of H2/year
USA	*DOE clean hydrogen strategy act* and *IRA 2023*	DOE clean hydrogen production standard	10 million tons annually (by 2030)	FITs in a number of states for RE	3$/kg production tax credit for GH	California Carbon Market	1 billion USD for Clean Hydrogen Electrolysis Projects	8 billion conective infrastructure	Hydrogencity - Texas Project 60 GW
Germany	*Eneryg Act* and *Green Hydrogen Strategy*	TÜV SÜD standard	14 TWh (by 2030)	NIP Program 1.4 billion USD	Energy Levies Act, tax reduction/exemption	European and National Emission Trading System	1.91 billion to technology	1.1 billion facilities and 7billion for FCV infrastrcuture	European project H2Med

Figure 5. Country comparison.

Source: Own elaboration

4. Discussion and conclusions

Finally, going back to the initial research question, we can conclude that there are determinants that can in fact shape the amount of renewable energy and green hydrogen production a country can generate. This was shown because the theoretical analysis backs the effectiveness of these determinants or levers, and also because in the case study analysis, all three leading companies had the majority of these levers in place. The first determinant would be regulation. The number of clear roadmaps and laws, standards, certification and targets a country sets, will determine the amount of production in a country. The second determinant is the number of incentives and the money spent on intervention measures that stimulate production. Mechanisms like subsidies, tax reduction policies, carbon credits, or feed-in-tariffs also have an impact on green energy generation. Finally, the last determinant is investment. Financial resources poured into research and development, innovation, technology, and infrastructure development will also drive production upwards.

Having stablished these determinants together has implications for different stakeholders like governments, managers, or regulators. If these parties want to stimulate renewable energy production, this might mean governments have to allocate a higher percentage of their expenditure in subsidies for producers. Or it might mean that managers have to set more ambitious targets for production or invest more in innovation departments. Or perhaps, that regulators have to pass more laws and have renewable energy and green hydrogen by a priority in policy design. But not only can these three parties benefit from this framework, many others can, such as financial institutions, utilities, distributors and producers.

This study shows that the leading countries with actual and projected highest green hydrogen production, have in fact been leaders when it comes to policy making, regulating, and investing as well. This backs the theory that suggest that the success in high production numbers is attributable to effective and proactive policy making. Therefore, the way in which this document provides value is by placing together a framework which is a combination of mechanisms organized in three different categories that can increase production and development even further. This is relevant, because there are academic articles like the ones we have mentioned in the literature analysis that mention the effectiveness of these policies individually, but there is not a current study that provides a holistic framework like the current one, which combines them into one framework and explores countries that have taken action in all those areas. In addition, another value point of this framework is that a country does not have to be endowed with specific resources like solar exposure or wind speeds and be more or less lucky; these levers can be applied to most countries in the world without previous requirements.

Naturally, the former study does have some limitations. The fact that it follows a case study structure, and it lacks quantitative data might appear like weaker evidence. Similarly, although it can be argued that this theoretical framework will result in an increase in green hydrogen production, it is hard to determine if the percentage increase will be equal in all countries, or if some may experience a greater or smaller increase due to different factors. Additionally, due to the fact that the topic of green hydrogen is very cut edge, the academic literature is still nascent, and this results in less information to work with. More specifically, each country in the case study might also show some limitations.

These limitations can be accounted for in further studies, and there are several items that might be worth investigating in the future. For example, it might be interesting to follow a more analytical and numerical approach and study in what proportion is each lever relevant in the hydrogen production process, and evaluating the weight and importance of each factor, and seeing their effectiveness. Similarly, in a few years it would be interesting to evaluate correlation and causality between the production numbers of GH, and their policies with a more quantitative approach, which was not possible in this study due to the fact that there is not enough data available on production yet. Finally, it would be interesting to find if there are other factors that affects GH production to further expand and complement the current theoretical framework.

Regardless of the value future investigations could bring, this academic article provides implications for the industry currently. Applying this theoretical framework for countries that are lagging behind in production would result useful. Countries are increasingly aware of the power of green hydrogen to decarbonize different industries like transport or manufacturing, but many still have not taken sufficient action, which is why this three-step framework of regulation, intervention, and investment, provides the ideal steps to unlock a country's GH future potential.

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