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Green hydrogen production and export potentials in the EU and neighbouring regions

Case studies from Georgia and Spain

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Summary

The growing ambition of climate targets within the European Union, necessary for maintaining global warming below 1.5 °C, have put green hydrogen (i.e. produced from renewable electricity) in the spotlight of decarbonisation pathways for sectors where replacing fossil fuels consumption is most challenging. Consequently, reliable assessments of potential supply and demand for this clean fuel are increasingly necessary for the European Union to pave its way forward. In this research a framework is develop to study countries' possibilities to deploy large scale production, use and exports of green hydrogen. This framework combines technical calculations of demand and supply with economic cost assessments and a criteria approach that widens the scope of the analysis in order to encapsule as many determining factors as possible for a successful hydrogen transition. The framework is then applied to the cases of Georgia and Spain. The results show that both countries would need large shares of green hydrogen in their energy systems in order to achieve climate neutrality. Moreover, it is found that they have the renewable resources to provide this demand and still be able to, combined, supply up to 44% of European demand for green hydrogen by 2050 at competitive costs via exports, as long as technology keeps improving and measures like stringent carbon pricing are implemented. However, both countries are in need for improvements in order to realize their potential. Spain is found to be overall in a better situation but needs to implement specific support mechanisms for hydrogen and create a better environment for financing and innovation. Georgia, on the other hand, must significantly improve its general long-term energy strategy and policy stability and continue its economic development in order to be at the frontline of future green hydrogen deployment. Overall, this research aims to serve as useful insight for Georgia and Spain and as a tool for future research and design of hydrogen strategies, as this framework is potentially expanded upon and applied to different regions.

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Abbreviations and acronyms

AEM Alkaline Electrolyte Membrane

BAU Business As Usual

CAGR Compounded Annual Growth Rate

CAPEX Capital Expenditures

CCS Carbon Capture and Storage

CF Capacity Factor

CO2 Carbon Dioxide

CSP Concentrated Solar Power

EBRD European Bank for Reconstruction and Development

ED Energy Demand

EI Energy Intensity

ET Energy Transition

ETS Emissions Trading System

EU European Union

FCH Fuel Cell and Hydrogen Joint Undertaking

GDP Gross Domestic Product

GHG Greenhouse Gas

GSE Georgian State Electrosystem

HE Hydrogen Economy

HYACINTH Hydrogen Acceptance in the Transition Phase

ICCT International Council on Clean Transportation

IEA International Energy Agency

IPBES Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services

IRENA International Renewable Energy Agency

LCOE Levelized Cost Of Electricity

LCOH Levelized Cost Of Hydrogen

LEAP Low Emission Analysis Platform

LNG Liquefied Natural Gas

MCA Multi-Criteria Analysis

MENA Middle East and North Africa

O&M / OPEX Operation and Maintenance Expenditures

OECD Organisation for Economic Co-operation and Development

PEM Polymer Electrolyte Membrane

PV Photovoltaic

R&D Research and Development

RCA Revealed Comparative Advantage

RES Renewable Energy Sources

SMR Steam Methane Reforming

SOEC Solid Oxide Electrolyser Cell

TOE Tonne of Oil Equivalent

TPEC Total Primary Energy Consumption

TPES Total Primary Energy Supply

UK United Kingdom

UN United Nations

VRES Variable Renewable Energy Sources

1. Introduction

In recent years, green hydrogen (i.e. hydrogen produced from renewable energy sources) has attracted growing attention in Europe and around the world as an important piece of the future sustainable energy system. Hydrogen can be used in a wide range of applications and forms as feedstock, fuel, or energy carrier, and most important, does not emit carbon dioxide (CO2) or any other greenhouse effect gases (GHG) when burned. With the Paris agreement, the European Union (EU) is moving forward in the transition towards clean energy and GHG emissions reduction to contain the future and present impacts of climate change. More recently, the EU has added to the Paris Agreement goals by stating the aim for the EU to become a carbon neutral economy by 2050 (European Commission, 2018).

Renewable electricity is expected to decarbonise a large share of the EU energy consumption, but not all of it. In sectors where electrification is challenging or not possible due to technical requirements, alternative clean technologies will be needed for deep decarbonisation efforts. Some of these harder to mitigate sectors include specific transport types like long-haul, shipping and aviation and industries like iron, steel, or basic chemicals, in particular ammonia. Hydrogen has the potential to help bridge some of this gap, and the EU has deemed it essential to achieve carbon neutrality by 2050 in a recent official hydrogen strategy (European Commission, 2020).

Currently, hydrogen is used on very few applications, representing a small fraction of the EU's energy mix and it is mostly entirely produced from fossil fuel sources around the world via different conversion routes, resulting in global of emissions of around 830 MtCO2/year (IEA, 2019). This is generally referred to as grey or brown hydrogen, depending on the fossil fuel used as feedstock. Adaptations to these processes exist which can produce low-carbon hydrogen, such as the combination with carbon capture and storage technologies (CCS), in what is called "blue hydrogen". However, to produce zero-carbon hydrogen, the focus is mostly on electrolysis of water powered by renewable electricity. This is commonly named "green hydrogen" (Routes to Hydrogen Production, 2020).

Therefore, in the coming decades hydrogen production has to be low carbon to start with and ultimately green. It also must be scaled-up significantly and become cost competitive with fossil fuel options (IRENA, 2020a). The production cost of green hydrogen is mostly driven by the costs of renewable power (Hydrogen Council, 2021b). So potential low cost and large capacity for renewables are necessary for any region to produce green, cost competitive hydrogen in the future.

In the EU, increasing exploitation of renewable resources is expected to be met by higher costs and declining approval amongst the population (Wietschel et. al, 2020). Consequently, the idea of producing hydrogen in resource rich regions with less intensively used land and then importing to the EU is being discussed as a potential alternative. This arises the need for countries with potential to become hydrogen producers and exporters to be identified and analysed in order to be able to comprehensibly assess how global supply and demand will develop in the future. This will in turn allow the EU to establish concrete strategies to integrate hydrogen into its energy system and develop a hydrogen economy. Here, two countries are analysed to assess their potential to produce excess green hydrogen and export it to the EU. On one hand, one country within the EU is selected, Spain. On the other, a neighbouring country to the EU is chosen, Georgia. The following Theory section expands on the countries and the motivation for studying them, but overall both countries have promising renewables resources, close vicinity to other EU countries, and have recently shown interest in developing green hydrogen (Ministerio para la transición ecológica y el reto demográfico, 2020b; Bennett, 2020).

At the moment, it is common for this type of analyses to be limited to technoeconomic aspects, mainly the capacity for potential production and cost development in a particular country. The work of Li et al. (2018) on Japan; Ennassiri et al. (2019) on Morocco; or Mraoui & Menia (2019) on Algeria are just a few examples of that. This approach, albeit also necessary, does not capture the full societal transformation needed for a country to make a shift towards a hydrogen economy and become a large-scale producer, and how well it is positioned to do so. Factors like market developments, economic capabilities, political stability, or transport infrastructure, amongst others, can heavily influence the ability of a country to deploy a hydrogen production chain (Wietschel et. al, 2020). The kind of research needed to embrace all those variables is far beyond the scope of a Master Thesis project. Nevertheless, the approach of analysing potential producing countries beyond their technical promise can still be applied to some level.

Therefore, this research aims at combining technical analysis of potential supply, demand, productions costs and exports for green hydrogen in Spain and Georgia with a broader analysis on the overall state of both countries and how that impacts their possibilities to indeed transition into hydrogen economies and thrive, even exporting surplus production. The framework develop can also be applied to other countries and expanded upon. Other projects are also currently working on investigating this frame more generally, like the German HyPat project (HyPat, 2021).

Together, this intends to provide a clearer and more accurate picture of hydrogen (export) potentials in both countries within the context of the EU's future energy system. Accordingly, the following main research question is formulated:

How well are Spain and Georgia positioned to transition into a hydrogen economy and become large scale producers of green hydrogen and potential exporters to the EU?

To tackle this main question, several sub-questions are posed to help guide the research process:

1. *What is the potential demand for hydrogen in Georgia and Spain energy systems by 2030 and 2050?*
2. *Which challenges and impacts does the implementation of hydrogen have in these energy systems?*
3. *At what cost can hydrogen be produced in Georgia Spain by 2030 and 2050?*
4. *How much hydrogen can Georgia and Spain export long term?*
5. *What other factors impact countries' possibilities to develop green hydrogen and what is the current state of these factors in Georgia and Spain?*

The first two sub-questions are designed to project future developments of the Spanish and Georgian energy systems and establish how hydrogen can be integrated, to what extent, and what that will entail. Sub-question 3 looks to establish cost projections for hydrogen in these countries and sub-question 4 assesses whether surplus production for exports is possible, and how much. Lastly, sub-question 5 widens the scope of the research to more qualitative, interdisciplinary aspects of this countries in order to understand their overall position to begin developing a hydrogen economy. This process will deliver thorough analysis and results on both countries which are integrated in the discussion section to answer the main research question.

2. Theory

In order to achieve the climate goal set in the Paris Agreement of keeping global warming to 1.5 °C GHG emissions must drop to net zero by 2050. A recent report published by the International Renewable Energy Agency (IRENA) has found that current policies and strategies in place will still amount to 36.5 GtCO2 emissions in 2050, a similar value to recent years, as seen in Figure 1 below (IRENA, 2021b). Therefore significant further efforts are needed to bridge that gap in the coming decades. All sectors must reach almost net zero emissions, with negative emissions from different carbon removal related technologies providing the additional carbon reductions needed.

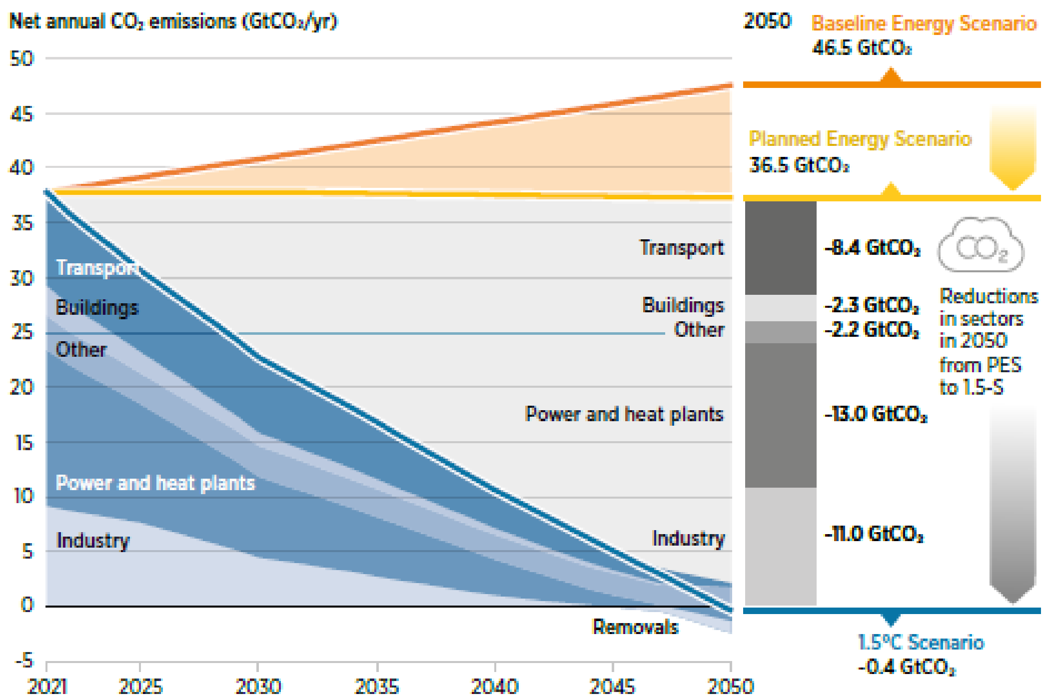

Figure 1. CO2 emissions abatement necessary for climate neutrality according to the scenarios from IRENA (2021b).

This report identifies energy conservation and efficiency, electrification of end use sectors and deployment of renewables as the main drivers of the energy transition. However, it also points at the key role of carbon removal technologies and hydrogen. Particularly, it states that 10% of the needed 36.9 GtCO2 reduction in the next 30 years must come from the use of hydrogen and derived synthetic products and feedstocks, which would account for 12% of the total primary energy consumption (TPEC). Hydrogen deployment in this scenario occurs mainly in the industry and transport sectors, where it accounts for 12% and 26% of CO2 emissions abatement respectively, as seen in Figure 2 (IRENA, 2021b).

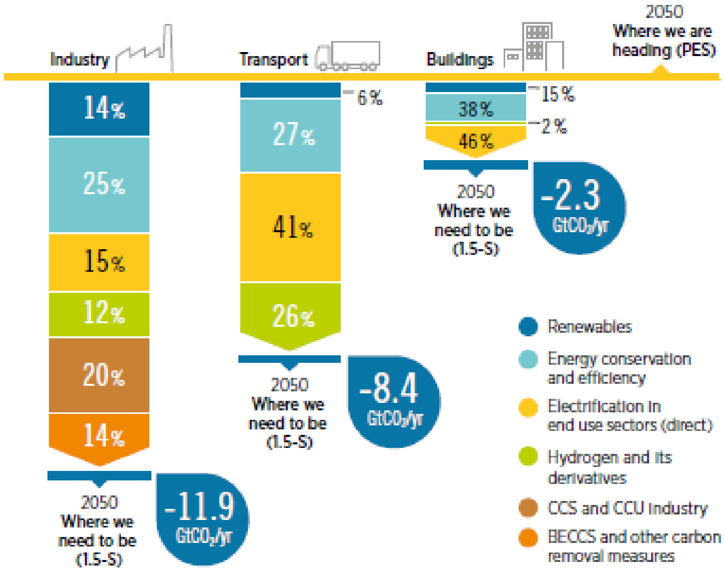

Figure 2. CO2 emissions abatement by sector and technological solution, according to scenarios from IRENA (2021b).

In the 1.5 °C scenario described in this report, global hydrogen demand would increase from around 120 Mt annually today to 613 Mt in 2050, of which at least 66% would have to be green hydrogen, with blue hydrogen providing most of the rest.

This large deployment of production will require a scale up of the different hydrogen production technologies and processes existing today, especially those with the potential to produce low-carbon hydrogen. Parallelly, end use sectors and applications will need to be identified, transformed and/or adapted to use hydrogen as fuel or feedstock. The next two sections offer a brief overview of the existing hydrogen production routes, related products, and end-use applications.

2.1. Hydrogen production

As briefly mentioned in the introduction, several production routes exist for hydrogen. Currently most of it is produced through several processes that use fossil fuels as feedstock. Today around 76% of hydrogen is produced from natural gas (IEA, 2019). The remaining 24% is almost exclusively produced from coal, mainly in China. The most widespread production route from natural gas is steam methane reforming (SMR) using water as an oxidant and source of hydrogen. However, the life-cycle emissions derived from these processes are high: 10 tCO2/tH2 for natural gas (grey hydrogen), 12 tCO2/tH2 from oil products (brown hydrogen) and 19 tCO2/tH2 from coal (black hydrogen) (IEA, 2019). Combining hydrogen production from fossil fuels with CCUS technologies is one way to produce low-carbon hydrogen. This is referred to as blue hydrogen. Furthermore, hydrogen can be produced from natural gas via molten metal pyrolysis, releasing solid carbon, in what is referred to as turquoise hydrogen.

Hydrogen can also be produced from the electrolysis of water. Water electrolysis is an electrochemical process which splits water into oxygen and hydrogen. Three main electrolyser technologies exist today: alkaline electrolyte membrane (AEM), proton exchange membrane (PEM) electrolysis and solid oxide electrolysis cell (SOECs) (IEA, 2019). If the electricity used to power electrolysers is from the grid's power mix, the end-product is known as yellow hydrogen; if nuclear power is used, the term pink hydrogen applies; finally, hydrogen produced from electrolysis of water powered by renewable electricity is what is commonly known as green hydrogen.

Hydrogen is a low energy density gas, which complicates its storage and transportation. However, it can be converted into hydrogen-based fuels and feedstocks which are easier to handle or even end-use product for some applications. Some of the main hydrogen-based downstream products and processes are shown in Figure 3 (Wietschel et al., 2020) and described below:

- Ammonia, a compound of hydrogen and nitrogen which is primarily used as feedstock for nitrogen fertilisers and can also serve as a chemical storage form for hydrogen (IEA, 2019).
- Synthetic hydrocarbons: hydrogen can be combined with CO2 or other carbon sources to produce synthetic hydrocarbons like methane or synthetic liquid fuels like methanol or diesel. These products have higher energy densities than pure hydrogen or ammonia and therefore can be useful in applications where the direct use of hydrogen is not feasible. They can also more easily transported. Caveats are the low chain efficiencies and the need of carbon (IEA, 2019).

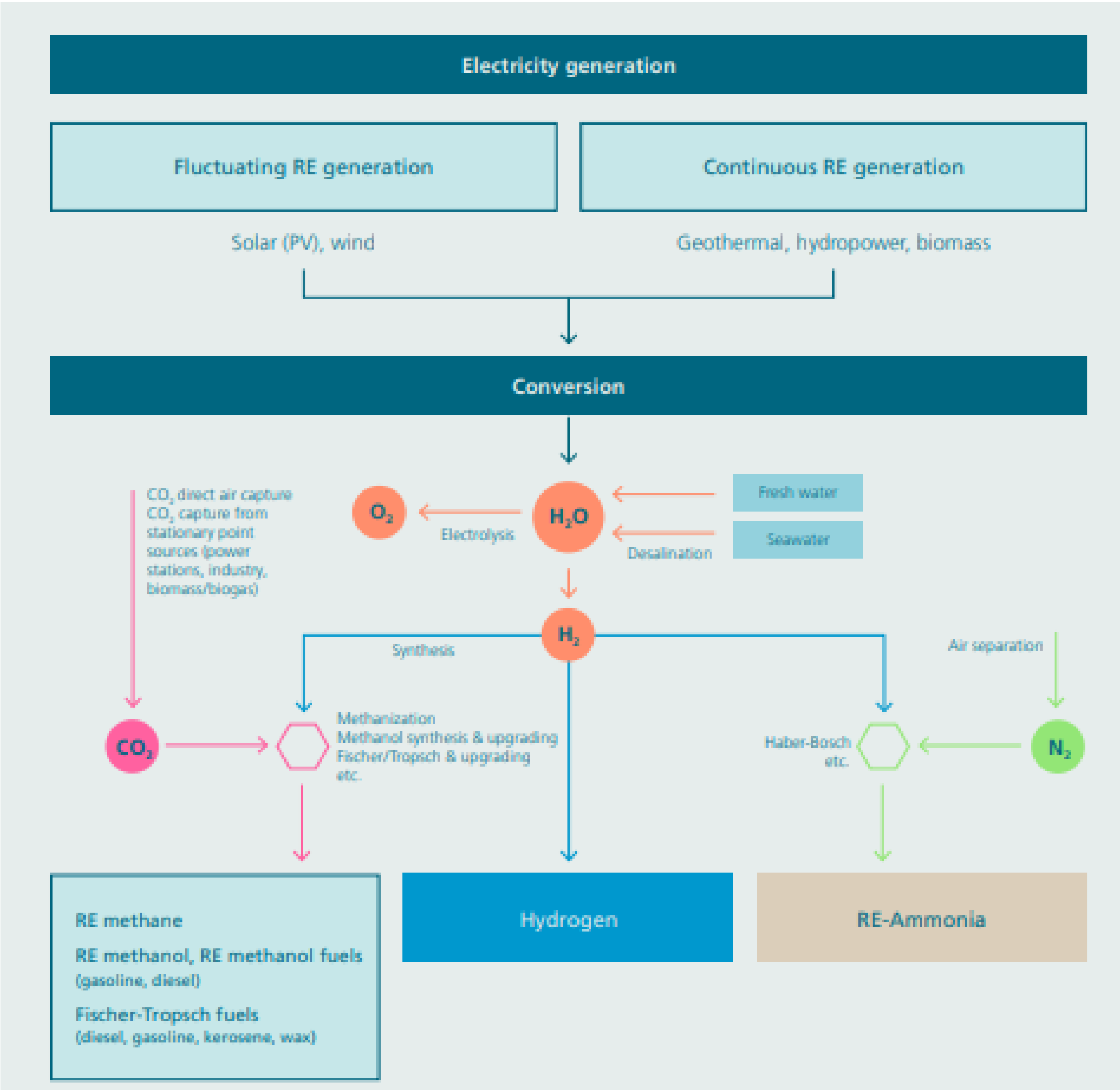

Figure 3. Conversion routes for green hydrogen products (Wietschel et al., 2020).

2.2. Hydrogen end-use applications

Current use of hydrogen is dominated by industrial applications. Particularly the chemical industry accounts for around 93% of worldwide consumption, with most of it (53% of total) used for the production of ammonia (Velazquez Abad & Dodds, 2017). Potential changes in this sector revolve around the introduction of CCS technologies in the processes or replacement of the used hydrogen which as much low-carbon or green hydrogen as possible. Also in the industrial sector, hydrogen can be used to substitute fossil fuels in steel production, oil refining and as a source of high temperature heat (IEA, 2019). However, hydrogen has the potential to be used in other sectors as well, especially in applications where direct electrification proves challenging. In the transport sector hydrogen fuel cells can be used to power vehicles which are either too large or require long driving ranges, such as buses or trucks. The same approach can also be applied to trains in areas difficult to electrify. In the shipping and aviation sectors, hydrogen can be used as feedstock for producing low carbon high energy fuels. Finally, hydrogen shows promise to be used in the heat and power sector, mainly by being blended into the existing gas network for heat delivery in buildings and as an alternative to balance power generation in an increasingly variable electric grid (IEA, 2019).

2.3. Cost, limitations, and EU context

At the moment, cost of production is a major barrier holding back green hydrogen deployment. Green hydrogen is 2-3 times more expensive than blue hydrogen in average (IRENA, 2020a), and up to 5 times more expensive than grey hydrogen (Hydrogen Council, 2021b). The main cost component of green hydrogen production is the cost of renewable power (IRENA, 2020a). Figure 4 below (3rd Energy Transition report, 2021) shows cost breakdowns for green hydrogen with different technologies across different countries, and electricity costs prove to constantly be the major cost component. A low cost of electricity is therefore necessary for producing competitive green hydrogen in the future.

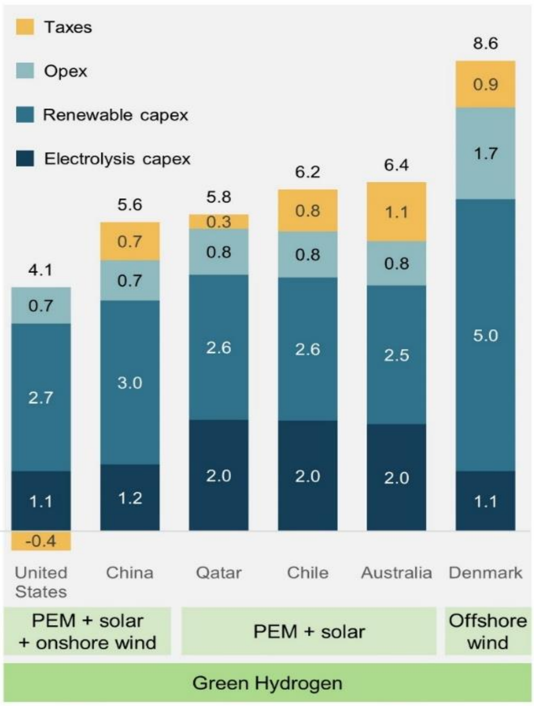

Figure 4. Cost breakdown of green hydrogen for different countries and technologies in US$/kgH2 (3rd Energy Transition report, 2021).

Such deployment of electrolyser capacity would in turn require massive amounts of renewable electricity. The EU is already targeting to meet 80% of electricity demand with renewables by 2050 (European Commission, 2018), and the share of electricity in final demand is projected to at least double in that time. The combination of these factors would put significant pressure on Europe's power system and its infrastructure. Some studies suggest that it could be technically possible for all European regions to meet own electricity demands and power sufficient hydrogen generation (Kakoulaki et al., 2021). However, it is questionable whether such massive deployment of both renewables and hydrogen production plants could cause issues of acceptance, environmental conflicts because of land use or water supply, or not be economically feasible in some regions with less optimal renewable resources.

Because of this, the possibility of importing green hydrogen produced in neighbouring, resource rich countries (both in the EU and beyond) has recently emerged as a strong opportunity to be discussed (Wietschel et al., 2020). Studies have, for example, looked at countries such as Morocco and also at the wider Middle East and North Africa (MENA) region (Boretti, 2020; Ennassiri, Belhaj, & Bouzekri, 2019; Mraoui & Menia, 2019; Shah, 2020). The trade-off between costs of importing hydrogen and costs of producing it in non-optimal regions is one of the aspects that needs to be analysed when assessing the most efficient strategies for hydrogen deployment in the EU. Furthermore, possibilities for large scale production must be analysed and studied in different regions and countries to be able to assess the best options and allow policy makers and stakeholders to make informed decisions that increase the chances of succeeding in achieving climate neutrality in the EU by 2050. In this research two countries with seemingly good potential are analysed: Georgia and Spain.

2.4. Georgia context

Georgia is a country amidst a significant transformation of its energy sector. In the past decade, its economic policy has focused on creating a liberalised and privatised environment, which has helped to deregulate the electricity sector and increase competition, thus improving security of supply, as well as starting the transition to an overall cleaner and more sustainable energy system. Georgia has been a net importer of most of its total primary energy supply (TPES) for some years now, these mainly consisting of natural gas and oil products. National production is mostly dominated by hydropower, making up 80% of its domestic electricity mix - with gas providing the rest -, and bioenergy in the form of traditional wood, used for heat and cooking in many rural areas (IEA, 2020a). However, the country's geographical conditions indicate potential for further deployment of other renewables like solar and wind, as shown in Figure 5 and Figure 6 (Global Wind Atlas, n.d.; Solar resource maps and GIS data, n.d.).

Figure 5. Wind resources in Georgia, as Mean Power Density (W/m2) (Global Wind Atlas, n.d.).

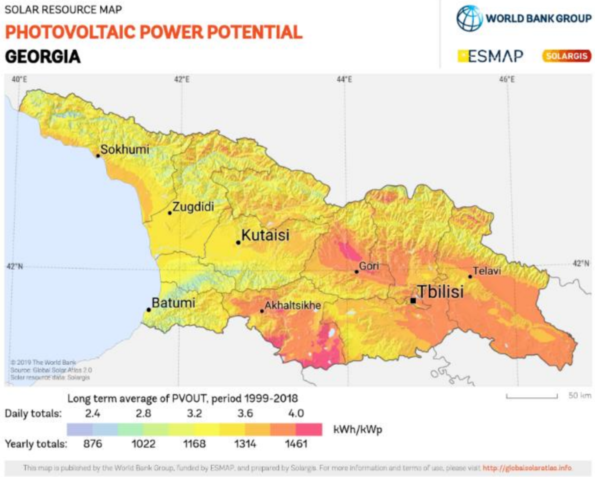

Figure 6. Solar energy resources in Georgia, as specific photovoltaic output per kWp and per day (Solar resource maps and GIS data, n.d.).

This, coupled with strategic geographical location, could make Georgia a promising hydrogen-producing country which could export to the EU, since it sits at a crossroads of the main gas and oil pipeline connections between Europe and the Middle East, as shown in Figure 7 (Esen, 2016), and also has port access to the Black Sea for marine transport.

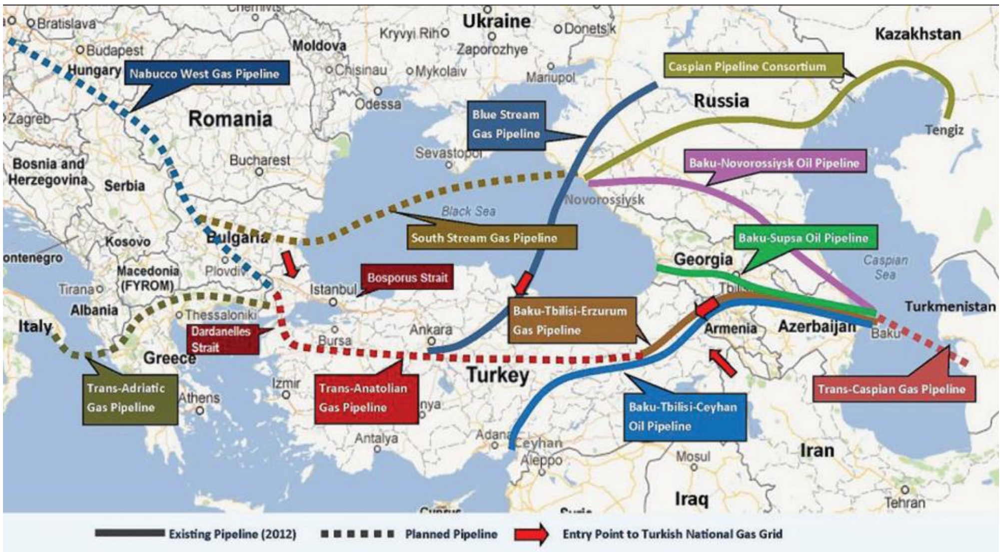

Figure 7. Existing and planned oil and gas pipelines connecting Europe to the Middle East (Esen, 2016).

However, even if some funds are already allocated to hydrogen research, detailed, systematic assessments of the hydrogen potential in the country are lacking and a recent report by the International Energy Agency (IEA) on Georgia's energy policies did not mention hydrogen at any point (IEA, 2020a).

On broader terms, the Government recently updated the Nationally Determined Contribution plan where it sets targets like 15% emissions reduction in the transport and energy sector within an overall target of 50% reduction from 1990 levels (Ministry of Environmental Protection and Agriculture, 2020). There is a binding target of 35% renewables in final energy consumption by 2030 (Parliament of Georgia, 2019). However, there is no long-term strategy or target for climate neutrality.

Moreover, Georgia does not have an official hydrogen strategy or roadmap yet, but has recently shown interest in the topic, asking for cooperation of the European Bank for Reconstruction and Development (EBRD) on technical analysis (Bennett, 2020).

2.5. Spain context

According to previous studies Spain, together with the United Kingdom (UK), is one of the most promising countries within Europe as a future hydrogen producer and exporter to the rest of the EU, as shown in Figure 8 below (Lux et. al, 2021).

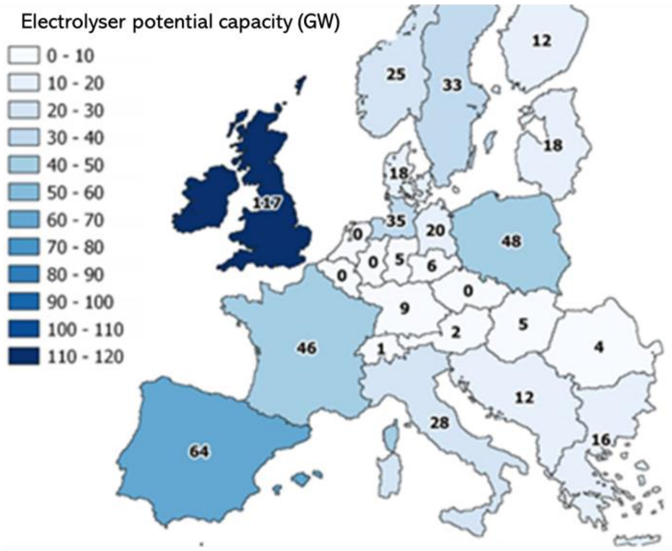

Figure 8. Potential electrolyser capacity in 2050 hydrogen focus scenario (Lux et. al, 2021).

Recent policies have put Spain at the frontline of the renewable energy deployment in the EU, and its geographical conditions offer significant upside in a diverse portfolio of renewable generation technologies: mainly solar and wind, as shown in Figure 9 and Figure 10 (Solar resource maps and GIS data, n.d.; Global Wind Atlas, n.d.), but also hydro and untapped potential for biomass and marine-related technologies in some regions.

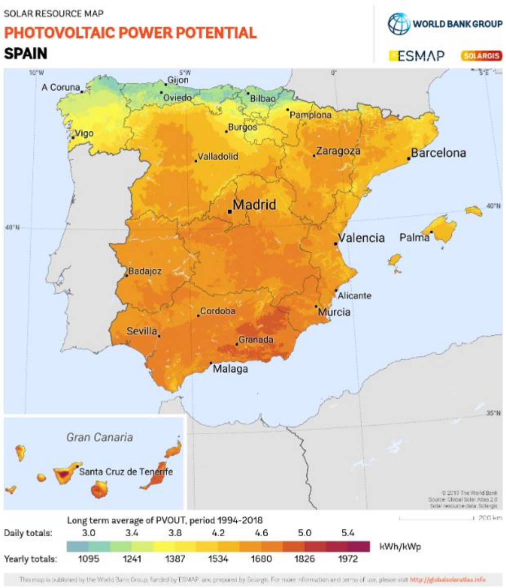

Figure 9. Solar energy resources in Spain, as specific photovoltaic output per kWp and per day (Solar resource maps and GIS data, n.d.).

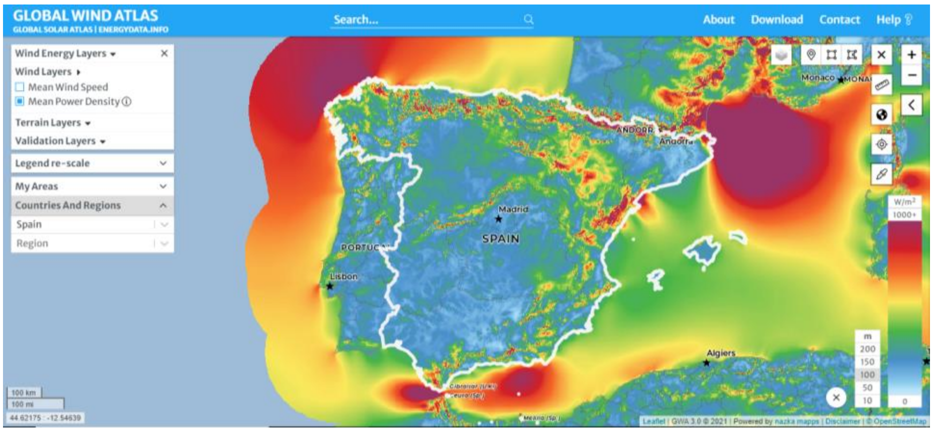

Figure 10. Wind resources in Spain, as Mean Power Density (W/m2) (Global Wind Atlas, n.d.).

The Spanish government has recently published an official hydrogen strategy which will be updated every three years in the way to national energy and climate goals set for 2030 (Ministerio para la Transición Ecológica y el Reto Demográfico, 2020c). This document still does not include specific legislations or concrete, binding actions, but lays out which steps and transformations within the different sectors and stakeholders involved must take place for the deployment of a hydrogen industry in the country. The main goal is to achieve 4 GW of installed electrolyser capacity by 2030, which would represent 10% of the total installed capacity goal of the EU (European Commission, 2020).

Spain also has a broader official climate plan, in which a target to generate 74% of its electricity from renewable sources by 2030 is set. 59 GW of renewable power capacity are expected to be installed in the coming decade, mainly solar photovoltaic and wind energy (Ministerio para la Transición Ecológica y el Reto Demográfico, 2020c). So within the context of this research these goals must be accounted for and reconciled with the additional renewables demand that results from large scale hydrogen production, in order to assess its feasibility from a renewable resources potential perspective.

2.6. Research framework

As explained in the introduction, the aim of the research is to assess the potential for green hydrogen production, use, and exports in Georgia and Spain and also to develop a framework from which countries can be analysed in a broader sense in their possibilities to transition towards a hydrogen-based energy system that can eventually produce surplus production of green hydrogen. The research uses different methods and tools to gather a wide variety of results that to together form a picture as accurate as possible of potential hydrogen developments, in this case in Georgia and Spain. These are detailed under the Methods section, but mainly consist of modelling of energy systems, techno-economic calculations and projections, and a multi criteria analysis (MCA). The relation between these tools, their outputs, and the overall research framework to answer the main research question is summarized in Figure 11 below.

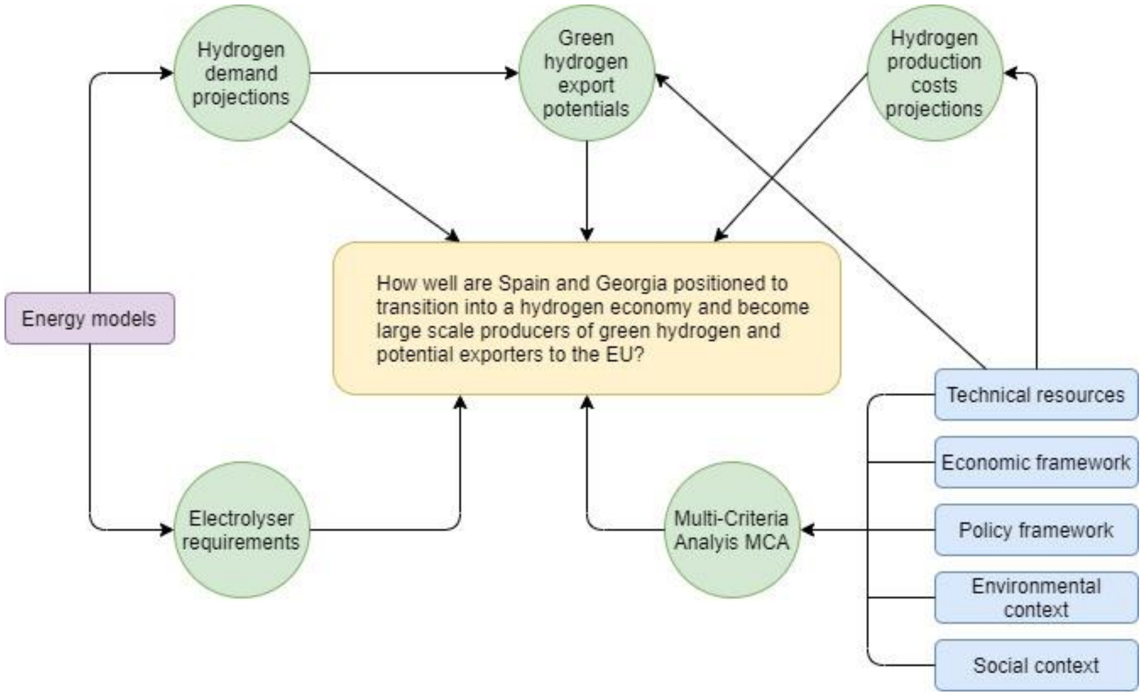

Figure 11. Schematic summary of the overall research framework.

The energy models will be described more in detail under the Methods section, but the general theoretical approach is based on projecting future energy demand in the countries in 2030 and 2050 under different scenarios with and without hydrogen. For this, three scenarios, are developed.

First, a Business As Usual (BAU) scenario is set up to calculate future demand. This scenario is based on past developments continuing and does not account for any policies tackling renewables, energy efficiency or other climate mitigation measures in the energy system, even if they are already in place in a specific country The reasoning behind this is to be able to show very drastically the impact different policies and measures make on energy consumption and its profile. Secondly, a scenario titled Energy Transition is set up. This includes the countries' most up to date policies and targets in energy efficiency and savings, electrification of energy demand when possible, and large expansion of renewables. Finally, a Hydrogen Economy scenario is created. This includes all the policies, targets, and measures of the Energy Transition scenario, and adds the possibility to deploy hydrogen as a clean alternative fuel in the system when technically possible. In this last scenario, a clear goal of climate neutrality by 2050 is established and targeted.

This model is set up on the Low Emissions Analysis Platform (LEAP). LEAP is a software tool for energy policy analysis and climate change mitigation assessment developed at the Stockholm Environment Institute. It can be used to track energy consumption and production in all sectors of an economy (Heaps, 2021). It is selected mainly due to its user-friendly functioning and the possibility to base analysis on setting up different scenarios at national levels.

While the rest of more quantitative methods are almost entirely addressed under the Methods section, the following section describes the theory and reasoning behind the criteria framework developed in this research and presents the set of criteria utilised.

2.6.1. Criteria framework

This framework aims at capturing a broad picture of a country's potential to deploy hydrogen at a large scale. The transition towards a fully decarbonised energy system and a hydrogen economy still faces significant challenges, both at the global scale and at specific country levels. The IEA (2019) points to three key areas where different challenges currently slow progress for hydrogen and downstream products and technologies: policy and technology uncertainty; value chain complexity and infrastructure needs; and **r**egulations, standards, and acceptance.

For countries to transition into hydrogen economies and become large scale producers of hydrogen, and potentially exporters, significant investments and governmental action will be needed. In the end, countries best positioned to overcome the aforementioned challenges will generally be preferred by investors and/or stakeholders and have a better change of successfully implementing a hydrogen value chain that helps to fully decarbonise the energy system and the country's economy.

Based on these challenges, this framework is divided into five main areas:

1) Technical resources
2) Economic framework
3) Policy framework
4) Environmental context
5) Social context

For each of the main areas of the framework, a set of criteria is defined to identify and analyse the country's possibilities of successfully developing a hydrogen economy. These are presented in Table 1 below and explained in the next sections.

Table 1. Criteria developed for the analysis of a country's potential to develop hydrogen.

Area	Criteria
1) Technical resources	A) Renewable energy resources
	B) Natural gas supply
2) Economic framework	A) Synergy between national economy and hydrogen value chain
	B) Infrastructure experience and potential
	C) Access to finance
	D) Presence of relevant industrial clusters
	E) Experience with technology promotion, innovation, and research and development (R&D)
	F) International trade potential
3) Policy framework	A) Climate change policy
	B) Hydrogen development and hydrogen relevant policies
	C) General policy stability
4) Environmental context	A) Land use conflict
	B) Water supply sustainability
5) Social context	A) Acceptance of hydrogen and fuel cell technologies
	B) Regional acceptance of renewable energies

2.6.1.1. Technical resources

Criteria 1A: Renewable energy resources

The high production costs of low-carbon hydrogen (and especially green hydrogen) is the main cause of technological uncertainty and acknowledged in literature as one of the biggest challenges for the implementation of a hydrogen economy (Wietschel et al., 2020). A recent report estimated the funding gap for green hydrogen to become cost-competitive with conventional alternatives at 50 billion US$ (Hydrogen Council, 2021b).

According to IRENA (2020a), the largest cost component of green hydrogen production is the cost of renewable electricity. It is also a cost component whose development over time will be region specific. Reductions in electrolyser system and capital expenditures (CAPEX) costs will be driven by industrialisation and larger scale manufacturing, which are developments that occur at a global scale as technology advances. Therefore, availability of cheap renewable electricity resources is a major driver for cost competitiveness of green hydrogen in particular regions or countries.

Criteria 1B: Natural gas supply

Although its long-term focus is on green hydrogen, the EU recognises the limitations of a short-term expansion of this technology and the need for low-carbon or blue hydrogen as a transition fuel (European Commission, 2020). This indicates that countries would benefit from having potential in both production routes. Since low-carbon or blue hydrogen is produced from fossil fuels, cheap availability of especially natural gas becomes a relevant parameter to a country's chances of scaling up hydrogen production and developing a hydrogen infrastructure.

2.6.1.2. Economic framework

Criteria 2A: Synergy between national economy and hydrogen value chain

As previously mentioned, one of the main challenges for introducing a hydrogen economy is the diversity and complexity of its value chain. Countries where sectors relevant to the hydrogen value chain are already prominent have a significant advantage in this transition, as well as more industrial experience and qualified labour.

Criteria 2B: Infrastructure experience and potential

The transition to a hydrogen economy across its value chain means development of the necessary infrastructure, such as storage technologies and sites, transportation, and distribution networks (via adapted gas pipelines and/or freight transport) or refuelling stations for hydrogen vehicles. More developed countries with advanced infrastructure in place will be better positioned to develop these and encourage hydrogen supply and demand.

Hydrogen transport and distribution will also require development of specific infrastructure such as adapted gas pipeline grid, freight delivery networks or refuelling stations for fuel cell vehicles (IEA, 2019). Analysis suggest that hydrogen distribution can become competitive when industry scales up and high levels of utilisation are achieved along the value chain, but significant investments and long-term commitments from governments will be of vital importance (Hydrogen Council, 2020).

A recent comparative analysis showed that technology maturity along the value chain is crucial for a successful transition to a hydrogen economy (Partidário, Aguiar, Martins, Rangel, & Cabrita, 2020). If critical conditions are not met, producing green hydrogen will not be enough to substitute fossil fuels.

Criteria 2C: Access to finance

Key to scale up production of hydrogen and develop the necessary infrastructure will be investment interest and commitment. Accordingly, the investment environment in a country will play a major role in transitioning towards a hydrogen economy. Both general access to finance and attractive financing for hydrogen projects are part of this and include the availability of capital, financing costs and the existence of specific financing schemes for green hydrogen (or low carbon technologies in general) (Boie, Ragwitz, & Held, 2015).

Criteria 2D: Presence of relevant industrial clusters

A study from the Hydrogen Council (2021b) highlighted in its results concrete short-term opportunities in clusters and market niches for hydrogen technologies to scale up and start being deployed without the need for large scale infrastructure and with reduced risks for investors.

Currently most hydrogen is produced in coastal regions of Europe for oil refineries and chemical industries (Nazir et al., 2020). According to the IEA (2019), these industrial port areas are key locations where hydrogen clusters could be developed, since they can gather several hydrogen demand key drivers such as the aforementioned industries, short-distance trucking, and the shipping sector. Encouraging these clusters to embrace the move towards greener hydrogen production will in turn drive scale through the hydrogen value chain and spur further development of the hydrogen economy in the country. Small demand centres can also flourish in the vicinities of these clusters by taking advantage of nearby lower-cost supply of low-carbon hydrogen.

Hence the presence of such potential hydrogen clusters (either industrial centres, port areas, or both) can indicate solid ground for a country to take the first steps towards a hydrogen economy.

Criteria 2E: Experience with technology promotion, innovation, and R&D

While some of the technologies at different levels of the hydrogen value chain are mature already (Noussan, Raimondi, Scita, & Hafner, 2021), further research innovation in, for example, PEM electrolysers or fuel cells is still needed. Because of that, government's willingness to invest on hydrogen related R&D and technology promotion programs will also play a role in successfully developing a large-scale hydrogen economy.

Criteria 2F: International trade potential

Hydrogen is also considered a potential energy carrier to be traded at a global scale, similar to the present logistics for liquified natural gas (LNG). Many international strategies point to the idea of producing hydrogen in favourable regions and export it to countries with high demand and few options for national production. In consequence, countries well positioned not only to meet own energy demands with green and low carbon hydrogen but to export it will greatly benefit from international attention and support (Noussan et al., 2021). Furthermore, a country that already has the trade experience and relations for products closely related to hydrogen will have a smoother transition to also exporting hydrogen.

2.6.1.3. Policy framework

Criteria 3A: Climate change policy

Ambition and commitment to climate change action is still the main driver for widespread use of clean hydrogen and low-carbon energy in general (The Hydrogen Council, 2021b; IEA, 2019) The challenge in this case stems from the uncertainty behind government's policies and support for the energy transition. Without clear and binding commitments to sustainable energy systems in the long term, financial incentives of hydrogen technologies become much less attractive to investors, which slows down technological learning and scale up of these technologies. A recent report from Bloomberg New Energy Finance (2020) directed towards investors highlighted legislated, net-zero, climate targets as one of seven key signposts to keep watch on in countries targeted for potential hydrogen investments.

Criteria 3B: Hydrogen development and hydrogen relevant policies

Policy frameworks that support revenue from low-carbon hydrogen projects are also essential and lacking in most countries and regions at the moment (IEA, 2019). In some cases this can signal a lack of long-term strategy, but it is also a product of technological uncertainty. However, some countries have recently begun to establish specific strategies and roadmaps for hydrogen energy and technologies (IRENA, 2020a). The existence of such documents, even if not liable polices yet, indicate not only commitment to the net zero target but also lay out the role and importance of hydrogen as an energy carrier in this transition. This can incentivise investments and also facilitate infrastructure planning and development, the clearer the targets and objectives set are.

Moreover, the current state of regulations and standards are a major barrier for hydrogen uptake. Studies in various countries highlight the lack of adapted legislation across sectors that considers hydrogen technologies (Ren, Dong, Xu, & Hu, 2020; Saccani, Pellegrini, & Guzzini, 2020). Furthermore, important standards need to be agreed upon at an international scale concerning vehicle refuelling, gas composition for end-users and for international trade, safety measures or lifecycle measurement of environmental impacts, amongst others (IEA, 2019).

As far as more specific policies and regulations go, a recent report highlighted emissions regulations for heavy transport and decarbonisation policies and incentives for industry as two of the key signposts that will precede the scale up of a hydrogen economy in a certain country (Bloomberg New Energy Finance, 2020).

Criteria 3E: General policy stability

Finally, overall policy stability has proven to affect the deployment of renewable technologies as it impacts the reliability of the climate change policies in place, dissuades investors and can affect international relations related to the energy trade (Boie et al., 2015).

2.6.1.4. Environmental context

Criteria 4A: Land use conflict

A recent assessment calculated that the scale at which green hydrogen would have to be produced to decarbonise the European energy system, even in a combined scenario with blue hydrogen, will require an area approximately 40% of Spain's total area of solar panels (The Hydrogen Council, 2021a). Furthermore, electrification of other sectors and full decarbonisation of the power supply will require even further extensive deployment of renewable power capacity. Consequently, the implementation of a hydrogen economy might in some regions encounter challenges of conflicts over the use of land resources. This means that some regions with otherwise good potential for hydrogen production might not be able to fulfil that promise due to space restrictions or land use management policies that limit the deployment of renewable energy.

Criteria 4B: Water supply sustainability

Similarly, hydrogen production either from electrolysis or gas reforming requires a marginal amount of water (The Hydrogen Council, 2021a). However, water footprints are highly sensitive to local conditions and when electrolyser plants scale up to gigawatt-scale regions prone to water stress might face challenges related to water management derived from the increased demand, which might contribute to overall uncertainty around hydrogen projects in the area. These impacts can also be amplified in the coming decades by climate disruption causing increased droughts in some regions.

2.6.1.5. Social context

Finally, citizens attitude towards hydrogen also is a determining factor for its success and expected to be a significant challenge depending on local culture, traditions, and technology acceptance (Nazir et al., 2020). Concerns may arise from different topics as well, such as safety perception of hydrogen transport and use (Shan & Wang, 2020), willingness to adapt to different user devices (cars, boilers) (Saccani et al., 2020) or conflicts for the use of resources in the country (The Hydrogen Council, 2021a).

Criteria 5A: Acceptance of hydrogen and fuel cell technologies

Ideally, this criterion could be evaluated on a country basis. However, specific studies of hydrogen acceptance do not exist for most countries, so instead information on general population attitudes towards hydrogen might be analysed. In this regard, the previously mentioned HyPat project is looking into hydrogen acceptance as part of its work on a broad evaluation framework for hydrogen. Furthermore, a project was completed recently entitled “Hydrogen acceptance in the transition phase (HYACINTH)”, funded by the Fuel Cell and Hydrogen Joint Undertaking (FCH) (Project Information, n.d.), whose results could provide interesting input into this framework, and which presents region specific results for seven European countries, Spain being one of them.

Criteria 5B: Regional acceptance of renewable energies

In case hydrogen-specific data on social acceptance is inexistent or limited in a specific country, existing studies on acceptance of renewable energies in general could be a good proxy for future acceptance of hydrogen. Again, this information might not exist in some countries, but its availability is generally more extended than for specific acceptance of hydrogen technologies.

To assess al these criteria and turn qualitative information into quantitative results, a multi criteria analysis (MCA) is set up. MCA is a common analysis tool for policy and decision makers that allow comparison between different options based on criteria and objectives previously described (IPBES, n.d.).

3. Methods

This is fully desk-based research. It follows the path established by the different research sub-questions. It combines a quantitative technological analysis approach with a more qualitative Multi Criteria Analysis (MCA). Sub-questions 1 through 4 conform the technological analysis part, while sub-question 5 is answered with the MCA part. The steps to follow and methods utilised are explained below.

3.1. Sub-questions 1-2: Energy Model

The aim of the first two research sub-questions is to assess the potential demand size for hydrogen in the energy systems of Georgia and Spain, its requirement, and the role it can play in achieving climate neutrality. Because the aim is not limited to only specific hydrogen use and supply, but to the overall impact on the energy systems, the modelling scope extends to the whole energy system of Georgia and Spain. To do so, a model of the energy system is built for each country using the LEAP software in combination with Microsoft Excel for data management and intermediate calculations.

The model is structured from a demand perspective using a top-down approach. The country's economy is divided in the sectors presented in Figure 12 below. For each sector, energy demand data is used. On the other hand, generation modules are created for each electricity and heat production technology deployed in the countries. The input data used for this generation technologies can be found in Appendix A.

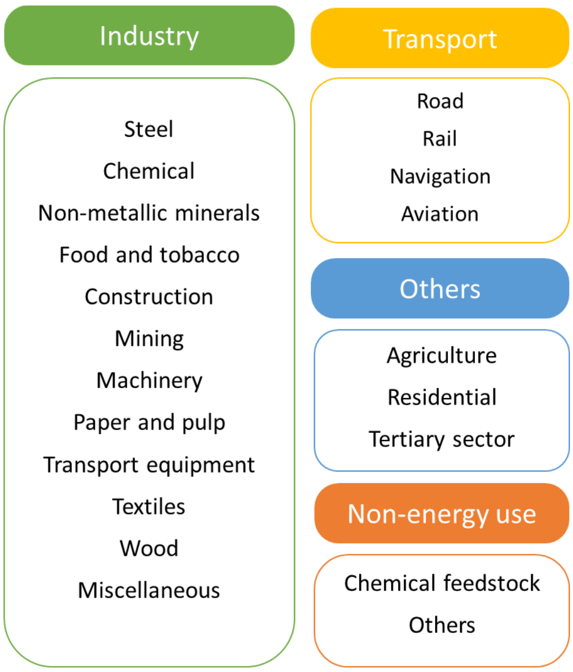

Figure 12. Economic structure used in the model of the Georgian and Spanish energy systems.

First of all, historical data from the year 2000 until 2018 both for energy demand and electricity generation is incorporated in the model. Data is retrieved from several sources: the national statistical offices of Spain and Georgia are two of them. Further energy statistics and related data is also retrieved from the online databases of the Enerdata website, an energy research consulting company (About Enerdata, n.d.). Due to data availability restrictions, the model base year is established in 2018 and 2019 is the first simulated year. In line with the overall research framework around the goal of climate neutrality by mid-century, the last simulated year in the model is 2050. From historical data, future energy demand is projected until 2050. At this point, three different scenarios are set up. This are summarized in Figure 13 and explained below.

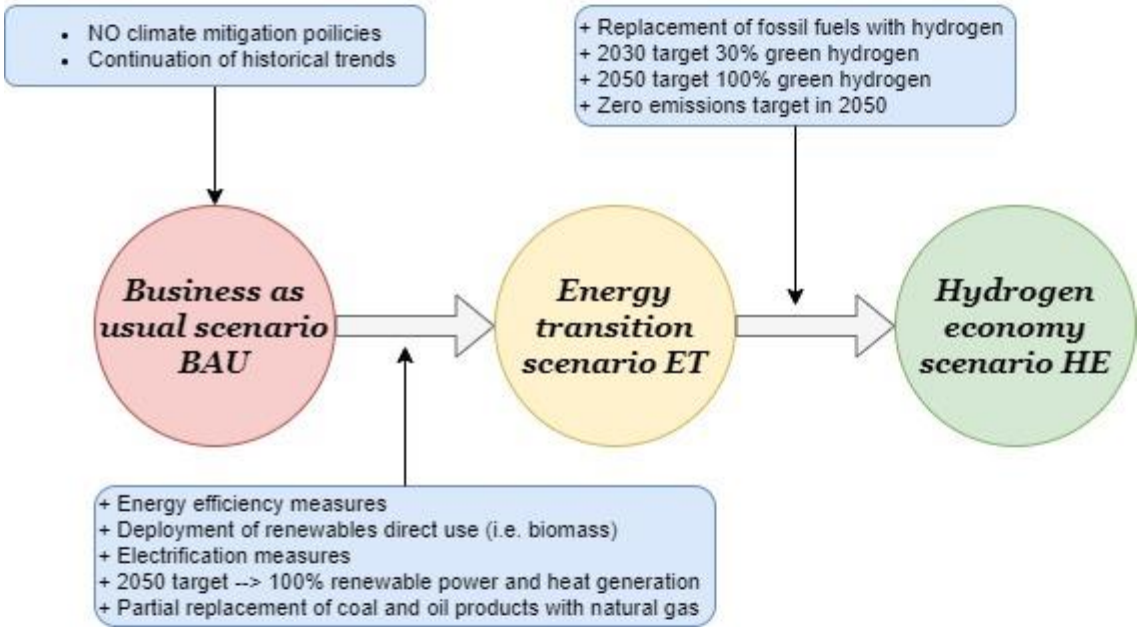

Figure 13. Structure and key assumptions of the different scenarios build into the LEAP energy models.

- ***Business As Usual Scenario (BAU):*** in this scenario, energy demand and supply is overall assumed to continue developing as it has so far during this century. As introduced in the Theory section, here existing policies to deviate from these trends are not accounted for, only past developments in actual energy supply and demand. To calculate future energy demand (ED) demand, a top-down approach is used based on sectorial energy intensities (EI). Energy consumption in most sectors is calculated using energy intensity per unit of Gross Domestic Product (GDP) and Compounded Annual Growth Rates (CAGR). The main formulas used for these calculations are shown below:

$$ED_{end\ year} = ED_{base\ year} * (1 + CAGR_{EI})^{(end\ year - baseyear)} * (1 + CAGR_{GDP})^{(end\ year - baseyear)}$$

$$EI_{sector} = \frac{ED_{bsector}}{GDP}$$

In the residential sector, as well for road transport, energy intensities are calculated per capita, as population (POP) is deemed a better indicator of total energy consumption in these cases. For them, the main formula used to calculate future demand is as follows:

$$ED_{end\ year} = ED_{base\ year} * (1 + CAGR_{EI})^{(end\ year - baseyear)} * (1 + CAGR_{POP})^{(end\ year - baseyear)}$$

$$EI_{sector} = \frac{ED_{bsector}}{POP}$$

Growth rates for GDP, population and energy intensities are all calculated using the formula below:

$$CAGR = \left(\frac{value_{end\ year}}{value_{base\ year}}\right)^{\left(1/_{(end\ year - base\ year)}\right)} - 1$$

The Organisation for Economic Co-operation and Development (OECD) has both past data and long-term projections of GDP until 2060 for member countries, like Spain. For Georgia, no such projections are available. Instead, historical data is retrieved from the Statistics Office of Georgia, and short-term projections and recent trends on GDP annual growth rate in the country (Georgia Overview, 2021; Georgia's Economy to Grow 3%, 2021) are used to estimate GDP values in 2030. Long-term, it is assumed that Georgia will catch up with modern economies and experience similar developments as OECD countries. Therefore, the average long term GDP growth rate projected for OECD countries until 2050 is used in these calculations as the growth rate for GDP in Georgia in the period 2030-2050.

Historical data and long-term projections for population in both Spain and Georgia are retrieved from the United Nations' (UN) Population Division (Department of Economic and Social Affairs, 2019).

In this scenario, the energy mix for each economic sector, as well as for electricity generation, are assumed to keep developing similarly to recent trends, as previously mentioned. Lastly, with the energy mix shares and projected demand per each subsector, demand profiles are built per fuel and subsector for the target years of 2030 and 2050. These profiles are incorporated into LEAP, where interpolation is used to estimate demand during all the other years.

- ***Energy Transition Scenario (ET):*** this scenario is built upon the BAU scenario, using its demand profiles as a starting point. From there, several measures and policies are assumed to be implemented in order to transition to a decarbonised energy system.
    - Energy efficiency measures that save final energy consumption based on actual national targets. This is applied equally to all sectors as % reduction of final energy demand.
    - Electrification is gradually adopted in all sectors possible and to different extents depending on the sector (mainly residential, tertiary and passenger road transport). This is applied to the energy mix of the different sectors.
    - Direct use of renewables (such as biomass, biogas, or municipal waste) increases in sectors where is possible to different extents. This is applied to the energy mix of the different sectors.
    - Partial replacement of coal and oil products by cleaner natural gas in some sectors where direct electrification or renewables use is not possible. This is applied to the energy mix of the different sectors.
    - Increased renewables deployment in power sector. Official expansion plans for both countries are used for 2030, while if needed, installed capacity is increased in 2050 based on technical resources in the country. In both cases a 100% renewable power system is assumed by 2050. This is applied to the electricity generation module as installed capacity projections. For this model's purposes, it is assumed that enhanced power systems in both countries can operate even with 100% variable renewable energy sources (VRES) by mid-century, either by using storage technologies or demand side management.

Input data for electricity and heat generation and further specific assumptions can be found in Appendix A.

- ***Hydrogen Economy Scenario (HE):*** this scenario is built upon the ET scenario above. It assumes the same measures and policies but incorporates the use and production of hydrogen as an available clean fuel and energy carrier. The scenario assumes the same amount of final energy demand per sector. As introduced in the Theory section, the aim of this scenario is climate neutrality of the whole energy system by 2050. With this scope in mind, remaining fossil fuel use in Georgia and Spain under the ET scenario is replaced with hydrogen, as long as its technologically possible. The model does not consider economic viability or difficulty of transitioning to hydrogen in use in particular sectors, only if end-use is feasible. A hydrogen production module is established in LEAP with two possible technologies: SMR of natural gas and water electrolysis powered by electricity. Although there are several other possible production routes, this analysis focuses only on these because on the one hand, SMR of natural gas accounts for around 76% of current production at the moment (IEA, 2019); and on the other hand, water electrolysis powered by renewable electricity is the main focus from institutions to produce carbon-free hydrogen in the future. In the model, it is assumed that by 2050 all required hydrogen is produced from water electrolysis, while in 2030 still 70% is being produced from SMR.
  Input data and assumptions for hydrogen production can be found in Appendix A.

3.2. Sub-question 3: Cost calculations

Hydrogen production costs in Georgia and Spain in 2020, 2030 and 2050 are calculated for the following hydrogen production routes:

- Grey hydrogen from SMR using natural gas
- Grey hydrogen from SMR using natural gas with carbon pricing on CO2
- Blue hydrogen from SMR using natural gas + CCS with carbon pricing on CO2
- Green hydrogen from water electrolysis using grid electricity
- Green hydrogen from water electrolysis using stand-alone solar photovoltaics (PV)
- Green hydrogen from water electrolysis using stand-alone wind power
- Green hydrogen from water electrolysis using stand-alone hydropower

Due to the large uncertainties surrounding production from electrolysis, such as electrolyser load hours and capital costs development or future renewables costs, two projections are calculated for the electrolysis production routes: a low estimate with the lower possible cost assumptions and a high estimate with the higher possible costs.

All costs are calculated by breaking down the cost's components of each technology into fuel costs (electricity or natural gas), operation and maintenance (O&M or OPEX) costs, and CAPEX costs, then integrating them into a final Levelized Cost of Hydrogen (LCOH) in €/kg H2. In Table 2 below the technological assumptions for SMR production are shown.

Table 3 presents the gas prices used in calculations for Georgia and Spain. Since no specific price projections exist for the Georgian region, it is assumed that developments follow the same trend as projected for the EU. For renewable electricity, as well as SMR, a lower interest rate is used in line with average energy projects for mature technologies. For electrolysers, a higher value is assumed as in literature because of the uncertainties and immaturity of this technology. A high assumption is also made for carbon pricing, using high estimate projections in literature.

Table 2. Technology input data for SMR hydrogen production costs calculation.

	2020	2030	2050	Sources
H2 energy content (Lower Heating Value) (kWh/kg)	33.33	33.33	33.33	(Hydrogen Storage, 2021)
CAPEX (€/kW$_{H2}$)	910	910	910	(IEA, 2020b)
Lifetime (years)	25	25	25	(IEA, 2020b)
Interest rates (%)	4%	4%	4%	(Feldman, Bolinger, & Schwabe, 2020)
Efficiency (%)	76%	76%	76%	(IEA, 2020b)
Capacity factor (CF) (%)	95%	95%	95%	(IEA, 2020b)
O&M costs (% of CAPEX)	4.7%	4.7%	4.7%	(IEA, 2020b)
CO2 certificate costs (€/tonne CO2)	68	87	135	(State and Trends of Carbon Pricing 2021, 2021)
CO2 capture (%)	90%	90%	90%	(IEA, 2020b)
CO2 capture costs (€/tonne CO2)	30	30	30	(Keipi, Tolvanen, & Konttinen, 2018)
CO2 transport and storage costs (€/tonne CO2)	25	25	25	(Keipi et al., 2018)
Natural gas emission factor (EF) (tonne CO2/MWh)	0.201	0.201	0.201	(EPA, 2008)

Table 3. Natural gas prices used in hydrogen costs calculations.

		2020	2030	2050	Sources
Natural gas price (€/MWh)	Georgia	19.7	17.7	21.4	(Georgia Economy Data 2000-2019, n.d.; Natural gas price Forecast: 2021, 2022 and long term to 2050, 2021)
	Spain	30.7	17.7	21.4	(IEA, 2021; Natural gas price Forecast: 2021, 2022 and long term to 2050, 2021)

Below, the LCOH calculation is detailed. For all production technologies, the next main equation is used:

$$LCOH\ (€/kg\ H2) = fuel\ costs\ (€/kg\ H2) + CAPEX\ (€/kg\ H2) + O\&M\ costs\ (€/kg\ H2)$$

To annualize investment, the corresponding annuity factors (α) are calculated based on interest rates (r) and economic lifetime (t) using the following formula:

$$\alpha = \frac{r * (1+r)^t}{(1+r)^t - 1}$$

And depreciation investment costs per kg of hydrogen produced are:

$$CAPEX_{SMR}\ (€/kg\ H2) = \frac{CAPEX\ (€/kW_{H2}) * \alpha * H2\ energy\ content\ (kWh/kgH2)}{CF(\%) * 8760h}$$

$$CAPEX_{electrolyser}\ (€/kg\ H2) = \frac{CAPEX\ (€/kW_e) * \alpha * H2\ energy\ content\ (kWh/kgH2)}{energy\ efficiency\ \eta\ (\%) * CF(\%) * 8760h}$$

O&M costs are calculated as a % of CAPEX costs.

Fuel costs, either natural gas or electricity, are derived as follows:

$$Fuel\ costs\ (€/kg\ H2) = \frac{H2\ energy\ content\ (kWh/kgH2) * fuel\ price\ (€/MWh)}{energy\ efficiency\ \eta\ (\%) * 1000}$$

When introducing carbon pricing and/or CCS, these cost components are incorporated as additional components into the main LCOH equation. These additional components are calculated as follows:

- CO2 certificate costs:
    - For grey hydrogen with carbon pricing:

$$CO2\ costs\ (€/kg\ H2) = \frac{H2\ LHV\ (kWh/kgH2) * EF\ (tonne\ CO2/MWh) * CO2\ price\ (€/tonne\ CO2)}{energy\ efficiency\ \eta\ (\%) * 1000}$$

    - For blue hydrogen with carbon pricing:

$$CO2\ costs\ (€/kg\ H2) = \frac{H2\ LHV\ (kWh/kgH2) * (1 - carbon\ capture(\%)) * EF\ (tonne\ CO2/MWh) * CO2\ price\ (€/tonne\ CO2)}{energy\ efficiency\ \eta\ (\%) * 1000}$$

- CCS costs for blue hydrogen:
    - CO2 capture costs:

$$CCS\ capture\ costs\ (€/kg\ H2) = \frac{H2\ LHV\ (kWh/kgH2) * carbon\ capture\ (\%) * EF\ (tonne\ CO2/MWh) * CO2\ capture\ cost\ (€/tonne\ CO2)}{energy\ efficiency\ \eta\ (\%) * 1000}$$

    - CO2 transport & storage costs:

$$CCS\ capture\ costs\ (€/kg\ H2) = \frac{H2\ LHV\ (kWh/kgH2) * carbon\ capture\ (\%) * EF\ (tonne\ CO2/MWh) * CO2\ transport\ \&\ storage\ cost\ (€/tonne\ CO2)}{energy\ efficiency\ \eta\ (\%) * 1000}$$

In Table 4 the technological assumptions for electrolysis cost calculations are presented. Table 5 shows the capacity factors used for each production route analysed. For grid-connected production, full load hours technically possible for electrolysers is used, according to literature (Bloomberg New Energy Finance, 2020), and alkaline electrolyser are assumed to be used because of their lower cost and longer lifetime. When off-grid, electrolysers have to follow renewables generation patterns, which requires the flexibility provided only by PEM electrolysers (IRENA, 2018). Therefore, the system's capacity factor in this case will entirely depend on the renewable energy load hours. So the specific load hours for solar PV, wind, and hydro from Georgia and Spain are established as for the LEAP model in Table 17 under Appendix A.

Table 4. Electrolyser data inputs for green hydrogen costs calculations.

	2020	2030	2050	Sources
CAPEX Alkaline (€/kW$_e$)	500 - 1400	400 - 850	200 - 700	(IEA, 2020b)
CAPEX PEM (€/kW$_e$)	1100 - 1800	650 - 1500	200 - 900	(IEA, 2020b)
Lifetime Alkaline (years)	30	30	30	(IRENA, 2020a)
Lifetime PEM (years)	20	20	20	(IRENA, 2020a)
Interest rates (%)	7%	7%	7%	(ICCT, 2020)
O&M costs (% of CAPEX)	2%	2%	2%	(IRENA, 2018)
Efficiency Alkaline (%)	63-70%	65-71%	70-80%	(IEA, 2020b)
Efficiency PEM (%)	56-60%	63-68%	67-74%	(IEA, 2020b)

Table 5. Capacity factor for the different electrolysis production routes on Georgia and Spain.

		2020	2030	2050
Georgia	Grid-connected	91%	91%	91%
	Stand-alone PV	15%	17%	20%
	Stand-alone wind	40%	40%	40%
	Stand-alone hydro	35%	35%	35%
Spain	Grid-connected	91%	91%	91%
	Stand-alone PV	17%	20%	25%
	Stand-alone wind	25%	25%	30%
	Stand-alone hydro	20%	20%	20%

Table 6. Electricity costs in €/MWh used for hydrogen production costs calculations. Source: own calculation, details can be found in Appendix A.

	Georgia			Spain		
€/MWh	2020	2030	2050	2020	2030	2050
Grid	47.7	45.7 – 46.2	40.6 – 41.8	122.7	60.6 – 62.2	29.2 – 31.8
Stand-alone PV	38.3 – 51.6	31.9 – 36.9	17.7 – 22.6	31.7 – 42.6	26.5 – 30.5	14.8 – 18.8
Stand-alone wind	36.5 - 47	29.1 – 30.8	18 – 20.6	57.2 - 74	45.4 – 48.2	23.3 – 26.8
Stand-alone hydro	38.7	38.7	38.7	38.7	38.7	38.7

Table 6 above shows the electricity prices used in this section calculations. These are obtained from own calculations based on current costs and past developments. Details on these calculations and assumptions can be found in Appendix A.

3.3. Sub-question 4: Production and export calculations

In this sub-question, the results from sub-questions 1 and 2 are used to derive further interesting results for Georgia and Spain: mainly the electrolyser requirements to meet the established hydrogen demand and renewables potential left for potential green hydrogen exports.

For the electrolyser capacity calculations, a range is assessed to cope with the large uncertainties about system load hours surrounding this result. So two values are calculated, one with the lowest possible capacity factor and one with the highest, as established in Table 5.

Finally, export potentials are assessed for both countries long-term. An average electrolyser efficiency of 73% in 2050 is assumed for this calculation, similarly to the one used in the LEAP energy model, as described in Table 24 under Appendix A. The renewables potentials are based on technical potential for renewable energy resources from literature. These technical potentials are summarised in Table 7 below:

Table 7. Technical renewable energy resources potential in Georgia (UNPD, 2012; *Georgian Hydro Power LLC, n.d.) and Spain* (Bailera & Lisbona, 2018; Kakoulaki et al., 2021; Lisbona, Frate, Bailera, & Desideri, 2018) *in TWh of annual generation.*

Potential renewable energy generation (TWh)	Georgia	Spain
Biomass	8.9	-
Wind	8.1	1174.5
Hydro	46	57.8
PV	169.8	445.5
Others	-	131.4

To estimate export potentials, renewable generation demands for a carbon neutral system (including green hydrogen production), as established in sub-questions 1 and 2, are subtracted from the total technical renewables potential. The remaining potential is assumed to be fully exploited and exclusively used to produce green hydrogen for exports.

3.4. Sub-question 5: Multi Criteria Analysis MCA

For the last sub-question MCA is used to evaluate how well-prepared overall Georgia and Spain are to begin a hydrogen transition. The overall research framework and selected criteria are presented in the Theory chapter. The actual MCA for this research will focus on four of the five main areas that conform the criteria framework: the technical resources, the economic and political frameworks, and the environmental context. Social acceptance is out of the scope of this research and therefore not included in this analysis.

Below the indicators selected to analyse each set of criteria are presented. Each indicator has a numerical value that is normalized to a score of 0-1, 1 being best situation possible for hydrogen development, and 0 worst. The scores for each of the indicators under every criterion are averaged to provide a final normalized score of 0-1 corresponding to each criterion. These criteria scores are again averaged to provide a final score for every main analysis area.

3.4.1. Technical resources

For the technical resources area, which encompasses just two criteria, two indicators are selected, one for each. They are shown in Table 8 below.

Table 8. Criteria indicators, value ranges and data sources for the technical resources area of the analysis.

Criteria	Indicator	Value range	Data sources
1A) Renewable energy resources	Untapped renewable energy technical potential	0-100%	(Georgia Energy Balances 2000-2019, n.d.; Evolución de la demanda, n.d.; Estructura de la generación, n.d.)
1B) Natural gas supply chain	Share of own production in natural gas supply	0-100%	(Georgia Energy Balances 2000-2019, n.d.; Spain Energy Balances 2000-2019)

First, excess renewable energy resources are calculated. Using the same technical potentials as in Table 7 under section 3.3 and the sources in Table 8 above for generation and demand, the share of technical renewables potential available after meeting current demand is calculated:

$$RES\ untapped\ potential\ (\%) = \frac{technical\ RES\ generation\ potential - electricity\ demand}{technical\ RES\ generation\ potential}$$

Gas production is simply divided by total consumption to calculate the corresponding indicator score.

$$Share\ of\ own\ production\ in\ gas\ supply\ (\%) = \frac{annual\ natural\ gas\ production}{annual\ natural\ gas\ demand}$$

For this set of criteria, a weighting is applied to calculate the overall score for the analysis area. This is because, albeit natural gas can play a role in facilitating the transition towards a hydrogen-based economy, renewable resources are far and above the most important aspect in this regard. Therefore, criteria 1A is weighted 0.9 and 1B 0.1 to calculate the overall scores as follows:

$$Technical\ resources\ criteria\ score = renewable\ energy\ resources\ score * 0.9 + natural\ gas\ supply\ chain\ score * 0.1$$

3.4.2. Economic framework

The indicators selected for the criteria on the economic framework are shown in Table 9. They combine straightforward indicators that already have a final value to be used with own calculations based on existing data. Indicators with value ranges different than 0-1, for example the quality of overall infrastructure index (1-7), are normalized to their equivalency in a 0-1 range for the final scores. On the other hand, binary qualitative indicators are simply given a value of 0 or 1.

Table 9. Criteria indicators, value ranges and data sources for the economic framework area of the analysis.

Criteria	Indicators	Value ranges	Sources
2A) Synergy between economy and hydrogen value chain	Share of economic activities relevant to hydrogen economy	0-100%	Own calculation
	Share of exports relevant to hydrogen economy	0-100%	Own calculation
2B) Infrastructure experience and potential	Quality of overall infrastructure index	1-7 (best)	(Quality of overall infrastructure, n.d.)
2C) Access to finance	National credit rating	0-100	(Global Competitive Index 2017-2018: Country Credit Rating, n.d.)
	Venture capital availability	1-7 (best)	(Venture capital availability, n.d.)
2D) Industrial clusters / niche markets	Presence of industrial centres for oil refining and/or production of steel, fertilizers	Existent/Non-existent	(Fertilizer Consumption, n.d.; Fernández, 2021; Spain Steel Production, n.d.; IEA, 2020a)
	Presence of industrial port areas	Existent/Non-existent	(Dolbaia, 2016; González, 2012)
2E) Research, development, and innovation	Innovation aggregated indicator	1-7 (best)	(Global Competitive Index 2017-2018: Innovation, n.d.)
2F) International trade potential	Revealed comparative advantage	0-1	Own calculation

For criteria 2A, the share of economic activities and exports that are relevant to a potential hydrogen economy is used as the indicator. This puts a value on the general concept of how much of a country's economy could benefit from added value of a hydrogen value chain, as well as how easy would it be for a country to adopt hydrogen at large scales. For the national economic activities, industrial production is used, so supply of services is not accounted for. Using national supply and use data (Annual Spanish National Accounts, 2020; Supply and use tables 2018-2019, n.d.), a list of industrial products is identified that can be linked to a hydrogen value chain. Then the aggregated industrial production of this products is divided by total industrial production to find the relevant share of economic activities, as the formula below indicates:

$$Share\ of\ economic\ activities\ relevant\ for\ H2 = \frac{production\ of\ product\ groups\ relevant\ for\ H2\ (M€)}{total\ industrial\ production\ (M€)}$$

Data used in both countries is from 2019. For the exports analysis, a similar approach is used: international trade statistics are gathered from a United Nations database (UN Comtrade Database, n.d.), and total monetary value of exported products relevant to hydrogen is divided by total exports for each country as formulated below:

$$Share\ of\ exportss\ relevant\ for\ H2 = \frac{exports\ of\ product\ groups\ relevant\ for\ H2\ (M€)}{total\ national\ exports\ (M€)}$$

Again, data used is from 2019, albeit more recent ones being available, to avoid data anomalies derived from the Covid-19 economic crisis. The list of products accounted as relevant for hydrogen can be found in the last section of Appendix A.

In criteria 2F, revealed comparative advantage (RCA) is used as an indicator for export potential. RCA is defined as:

> "The Revealed Comparative Advantage is defined as the ratio of two shares. The numerator is the share of a country's total exports of the commodity of interest in its total exports, and the denominator is share of world exports of the same commodity in total world exports. The RCA takes a value between 0 and (infinity). A Country is said to have a revealed comparative advantage if the value is more than one." (What is Revealed Comparative Advantage, n.d.).

$$RCA\ of\ certain\ product/country = \frac{product\ exports\ country \big/ total\ exports\ country}{product\ exports\ world \big/ total\ exports\ world}$$

For this analysis, a list of products with relevance for hydrogen, which can be found in Appendix A, is selected, and given a value of 0 if the country does not have a revealed comparative advantage and 1 if it does. Then the values for all the products are averaged to obtain the value for the criteria indicator. The RCA data for both countries is retrieved from *The World Integrated Trade Solutions* website.

3.4.3. Policy framework

The policy framework is composed of only three criteria, but groups a variety of indicators, which are presented in Table 10 in the next page. Most of them are qualitative and binary in nature, so final scores for them is either 0 or 1.

For the indicator in criterion 2C, which ranges from -2.5 to +2.5, a value of 0 is considered to be 0.5 in a scale of 0 to 1. The original scale from -2.5-2.5 is therefore normalized to 0-1

Table 10. Criteria indicators, value ranges and data sources for the policy framework area of the analysis.

Criteria	Indicators	Value ranges	Sources
3A) Climate change policy	Long term strategy	Existent/Non-existent	(Ministerio para la transición ecologica y reto demográfico, 2020a)
	Net-zero target	Existent/Non-existent	(Ministerio para la transición ecologica y reto demográfico, 2020a)
	Liability of net-zero target	Binding/Non-binding	(Ministerio de la Presidencia de España, 2021)
	Renewable energy target	Existent/Non-existent	(Government of Georgia, 2017; Ministerio para la transición ecologica y reto demográfico, 2020c)
	Liability of renewable energy target	Binding/Non-binding	(Parliament of Georgia, 2019; Ministerio de la Presidencia de España, 2021)
	Existence of clear and enforced renewable energy support scheme	Existent/Non-existent	(Jimeno, 2019; Registro de régimen retributivo específico, n.d.; Government of Georgia, 2019)
	Participation in global energy partnerships	Yes / No	(Implementation indicators, n.d.)
	Energy efficiency policies	Existent/Non-existent	(Ministerio para la transición ecologica y reto demográfico, 2020c; NEEAP, 2015)
3B) Hydrogen development and hydrogen relevant policies	Existence of specific hydrogen roadmap/strategy	Existent/Non-existent	(Ministerio para la transición ecológica y el reto demográfico, 2020b)
	Hydrogen target	Existent/Non-existent	(Ministerio para la transición ecológica y el reto demográfico, 2020b)
	Liability of hydrogen target	Binding/Non-binding	(Ministerio para la transición ecológica y el reto demográfico, 2020b)
	Are stringent emission standards set for heavy transport?	Yes / No	(Transporte - Vehículos pesados, n.d.)
	Existence of concrete policies for industrial decarbonization	Existent/Non-existent	(Ministerio de la Presidencia de España, 2017)
3C) General policy stability	Political stability index	-2,5 – 2,5	(Political Stability – Country Rankings, n.d.)

3.4.4. Environmental context

Table 11 shows the indicators selected for the environmental context criteria. Baseline water stress is a good proxy for pressure on a country's water resources, and therefore on future sustainability of water supply. It is defined as:

> "Freshwater withdrawal as a proportion of available freshwater resources. It is the ratio between total freshwater withdrawn by all major sectors and total renewable freshwater resources, after considering environmental flow requirements." (FAO, 2018)

Baseline water stress is already an indicator with a value of 0-100% so it only needs to be normalized to 0-1 to calculate the final score in the MCA.

Table 11. Criteria indicators, value ranges and data sources for the environmental context area of the analysis.

Criteria	Indicators	Value ranges	Sources
4A) Water supply sustainability	Baseline water stress	0-100%	(FAO, 2018)
4B) Land use conflict	Estimate % of land needed for renewable power generation in carbon neutral system	0-100%	Own calculation
	% Of total country area cultivated	0-100%	(FAO, 2018)

For criteria 4B, two indicators are selected. One to assess potential land requirements for energy uses and the other to provide insight into how much of the country's area is already under use. For the latter, share of land cultivated is a good proxy since it's the land use category which occupies more area globally by far (Global Land Cover, n.d.).

As for land needed for energy uses, this is estimated using installed capacity of wind and PV from the LEAP energy model under the hydrogen economy scenario. A typical solar panel size of 1.5m2/250Wp (Andrews & Jelley, 2017) and wind land requirements of 0.3 ha/MW (Denholm, Hand, Jackson, & Ong, 2009) are assumed. Land requirements are calculated as follows:

$$Land\ requirements\ (\%) = \frac{installed\ wind\ (MW) * 0.3\ (ha/MW) + installed\ PV\ (MW) * 230\ (m^2/W) * \frac{10^4\ m^2}{1\ ha} * \frac{10^6\ W}{1\ MW}}{total\ country\ area\ (ha)}$$

As for the social context area of the framework, it is left out of the quantitative scope of this analysis for the MCA due to time limitations to develop and assess adequate indicators. And because of the lack of data for Georgia on the subject. However, it is addressed qualitatively both in the Results and Discussion chapters.

Lastly, the scores for each area are integrated into a final MCA score. To obtain this final score the values for each area are weighted using the expected value method. This is used to convert qualitative criteria weighting into quantitative values (Hellendoorn, 2001). The criteria are ordered according to their importance to a final result, and quantitative weights are calculated as follows.

For a set of criteria C1-C4 in order of importance C1>C2>C3>C4:

$$Weight\ C4 = 1/(4*n) = 0.06$$

$$Weight\ C3 = 1/(4*n) + 1/(4*(n-1)) = 0.15$$

$$Weight\ C2 = 1/(4*n) + 1/(4*(n-1)) + 1/(4*(n-2)) = 0.27$$

$$Weight\ C1 = 1/(4*n) + 1/(4*(n-1)) + 1/(4*(n-2)) + 1/(4*(n-3)) = 0.52$$

With n= number of criteria, in this case 4.

In this case, the order in which they are weighted is based on the importance they are generally given in literature when assessing potentials for hydrogen, both in general and for specific regions, and is as follows:

1. Technical resources
2. Policy framework
3. Economic framework
4. Environmental context

4. Results

4.1. Sub-questions 1-2: Energy Systems Models and Hydrogen Demand

4.1.1. Georgia

The first result from the modelled energy system of Georgia is the projected development of total demand under the different scenarios. In the graphs below final energy demand in Georgia until 2050 is shown as projected in the LEAP energy model. For the past 20 years final energy consumption in the country has followed an upward trend, almost doubling between the beginning of the century and 2018, the last year for which detailed energy balances are available. Going forward, in the BAU scenario (Figure 14) energy demand is projected to keep increasing at a similar pace, going from 4.3 million tonne of oil equivalent (Mtoe) in 2018 to 6.7 Mtoe in 2030 and 7.3 Mtoe in 2050. In the Energy Transition and Hydrogen Economy scenarios (Figure 15) total consumption also continues an upward trend until 2030, when it peaks at a slightly below 6 Mtoe. It is beyond 2030 when the biggest impact of the assumed energy efficiency measures under this scenario total consumption starts declining, decreasing to 5.1 Mtoe by mid-century.

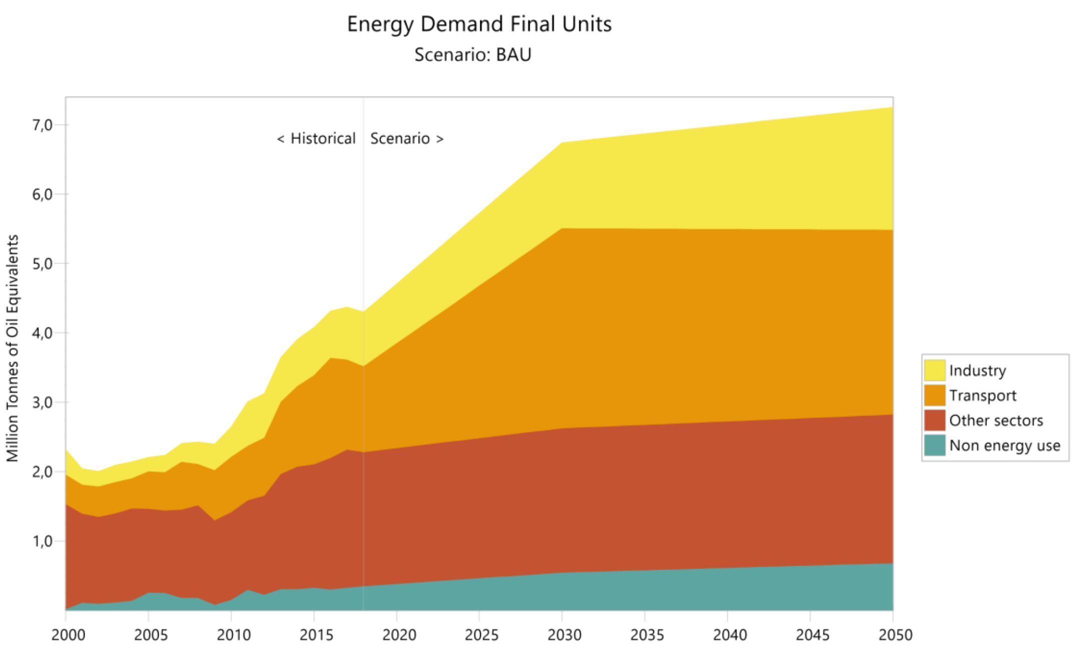

Figure 14. Final energy demand per sector in Georgia under BAU scenario.

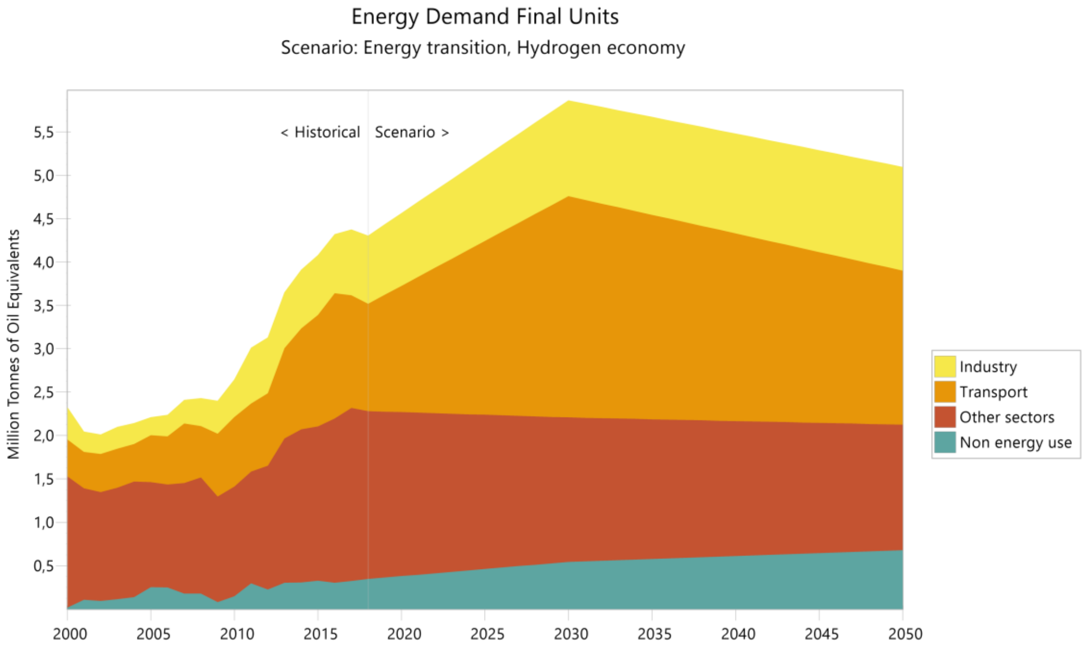

Figure 15. Final energy demand per sector in Georgia under the Energy Transition and Hydrogen Economy scenarios.

It is noteworthy than in all scenarios transport becomes the dominant demand sector for energy in Georgia, accounting for around 35% of total consumption. Demand in industry and for non-energy uses (mainly feedstocks for the chemical industry) also increases. Remaining energy consumption is grouped under other sectors and comprised of agricultural activities, the tertiary sector, and residential energy consumption. Energy demand in these sectors remains more stable in this model's projection. The growth in consumption in industry and transport can be explained by continued industrialization and economic growth of the country. Although Georgia's economy has been steadily growing for the last 15 years it has not created enough jobs, and many Georgians are still engaged in low-productivity agricultural activities (Georgia Overview, 2021). Therefore, and even though future projections hinge on the developments and response to the Covid-19 crisis, Georgia's economy is expected to recover in the coming years and continue its solid development and modernisation during the next decade (Georgia Overview, 2021). This explains the continued sharp increase in energy demand (mainly in transport and industry) until 2030 in all scenarios, since GDP growth rates are expected to recover to recent trends for this period in Georgia and many economic activities have not been modernised enough to decouple its energy consumption from economic development (Georgia's Economy to Grow by 3%, 2021).

Next off, the fuel mix of energy consumption in Georgia is analysed. The following graphs show the evolution of final energy consumption broken down into different fuel types for the three scenarios. In the BAU case (Figure 16) oil products (mainly gasoline and diesel) supply the increasing demand for energy in the transport sector and partly in industry as well, together with gas. Meanwhile, natural gas and electricity continue to be the main sources of energy in buildings and dwellings (residential and tertiary sectors). Overall natural gas provides 33% of final energy consumption, oil products 29% and electricity 24%.

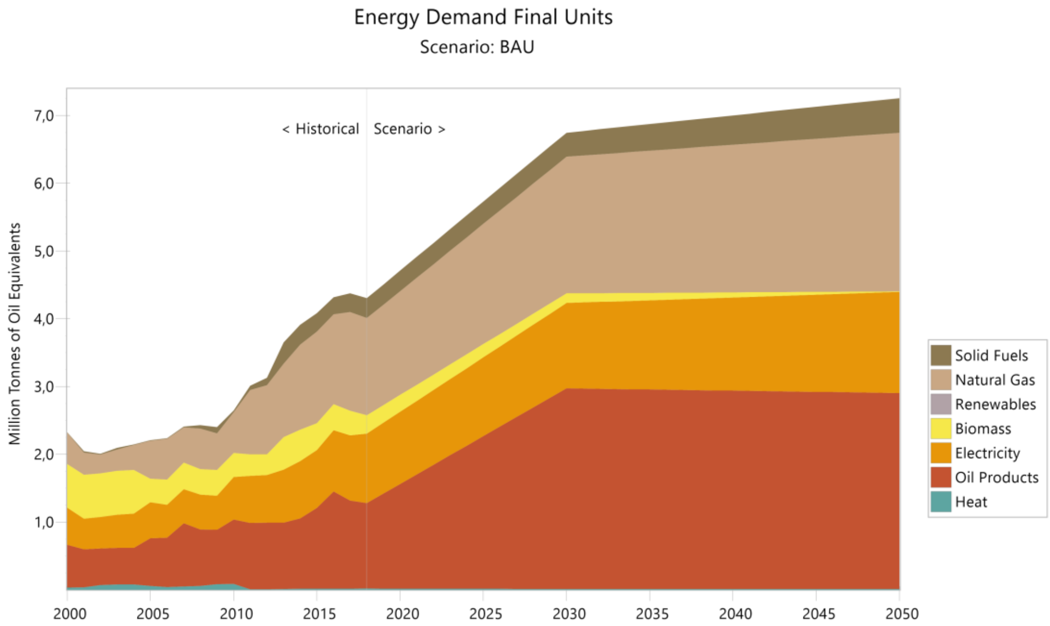

Figure 16. Final energy demand per fuel type in Georgia under BAU scenario.

In these graphs, the LEAP model groups together under biomass the consumption of clean biomass energy and traditional wood burning, which explains the large share of consumption biomass shows, particularly in historical trends. In Georgia, almost 22% of the population still do not have access to clean fuels for cooking or non-electric heating, which results in large amounts of wood consumption in dwellings (Ritchie & Roser, n.d.). This is assumed to be phased out at around 2030 in all scenarios as Georgia is assumed to improve and expands its gas network and also clean biomass stoves or other alternatives can replace traditional wood burning in areas where access to gas infrastructure proves more challenging.

In the Energy Transition scenario (Figure 17), direct electrification measures cause electricity to gradually overtake natural gas as the main form of final energy in Georgia, reaching a share of 40.5% of total consumption in 2050. The transport sector is where this has a major impact as electric vehicles take over the passenger road transport market. Also in residential and buildings consumption of electricity increases. Because of this, total demand for electricity in the Energy Transition scenario increases from 11.9 TWh per year in 2018 to 19.5 TWh in 2030 and 24 TWh annually by 2050, as shown in Figure 18. Power generation becomes 88% renewable in 2030 and carbon neutral by mid-century, as Georgia continues to exploit its vast hydropower resources and deployment of wind and solar PV energy replace generation from gas-fried thermal power plants.

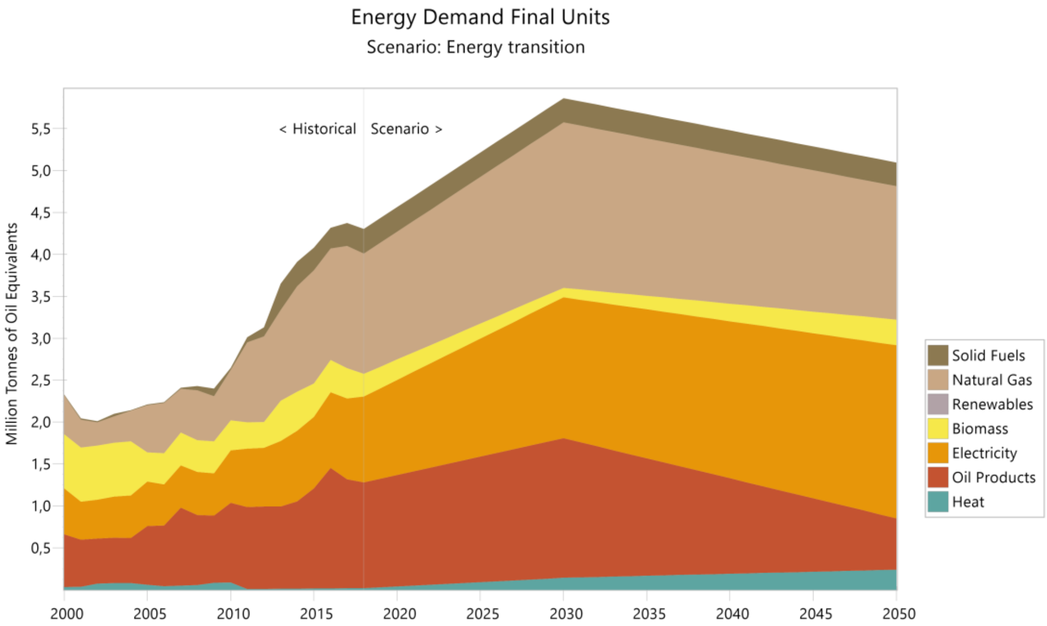

Figure 17. Final energy demand per fuel in Georgia under Energy transition scenario.

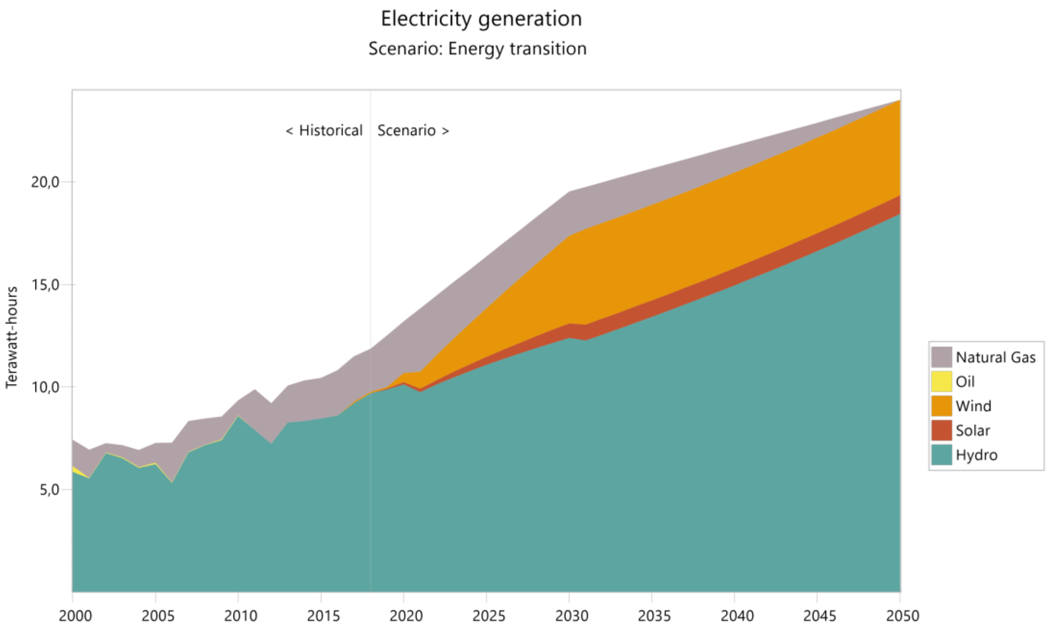

Figure 18. Power generation by technology in Georgia under Energy transition scenario.

Another change in this scenario is the expanded use of renewable biomass. As seen in Figure 17, biomass consumption increases after 2030 even though traditional wood is phased out, indicating replacement with renewable biomass. By 2050, 267 ktoe of biomass are consumed in Georgia, both for heat generation in buildings and homes and in some industries.

Furthermore, district heating, which exists on a very small scale in Georgia, expands in the future and provides 20% of energy demand in the residential sector by 2050. This could be an additional resource for decarbonising the residential and building sectors in largely populated areas like main cities in the country, as heat plants in Georgia could be powered by either solar thermal energy or geothermal energy, as it has in recent years at a very small scale. Other direct use of renewables such as biofuels is not considered in this model.

However, the most important result from this scenario is that direct electrification measures and direct use of renewable energies like biomass are not sufficient to achieve carbon neutrality of the energy system in 2050, as already seen in Figure 17. Even in the energy transition scenario Georgia still consumes 2.5 Mtoe of fossil fuels by mid-century.

It is true that part of this fossil fuel consumption shifts from more emission intensive sources (like coal and oil in industry, gasoline in transport or wood in the residential sector) to a cleaner fuel in natural gas. Furthermore, a significant reduction of 62% in overall supply of fossil fuels is observed in comparison to the BAU scenario, as demonstrated in Figure 19. Nevertheless, this does not change the fact that non-clean energy sources still provide 49% of overall final consumption in this proposed scenario, mostly in the industrial sector (including non-energy feedstocks) and in freight transportation.

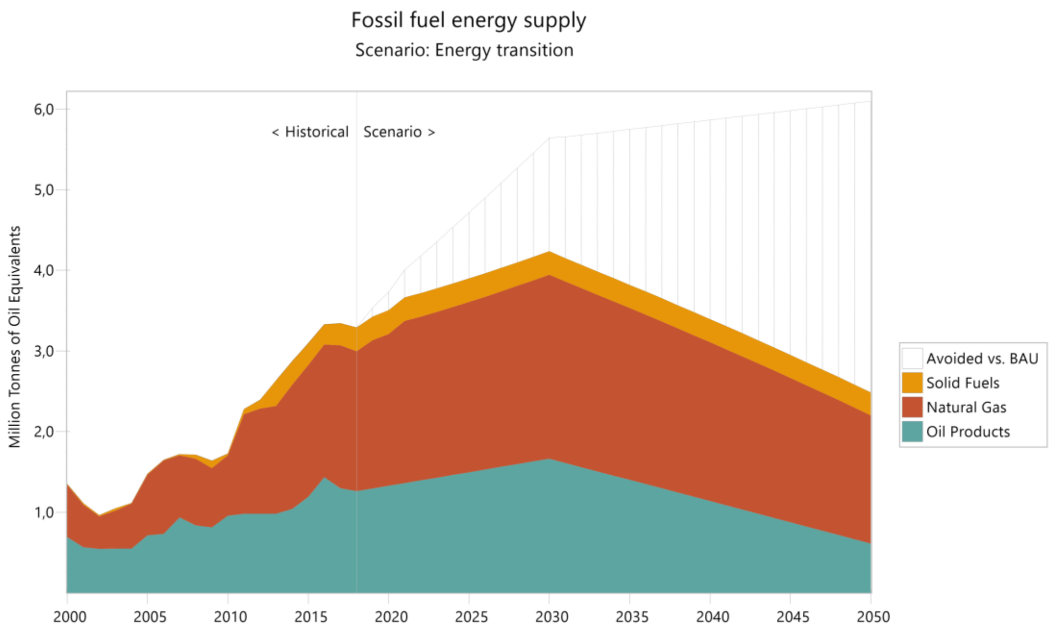

Figure 19. Final consumption of fossil fuel energy per fuel in Georgia under Energy transition scenario and avoided compared to the BAU scenario.

With the deployment of hydrogen as an alternative fuel and energy carrier in the Hydrogen Economy scenario, most fossil fuel consumption is abated. As seen in Figure 20, electricity and hydrogen (both from 100% renewable sources in 2050) together provide 84% of total energy demand in Georgia by mid-century. Specifically, hydrogen covers already 15% of the country's energy needs by 2030 and increases to 41% by 2050 in this scenario.

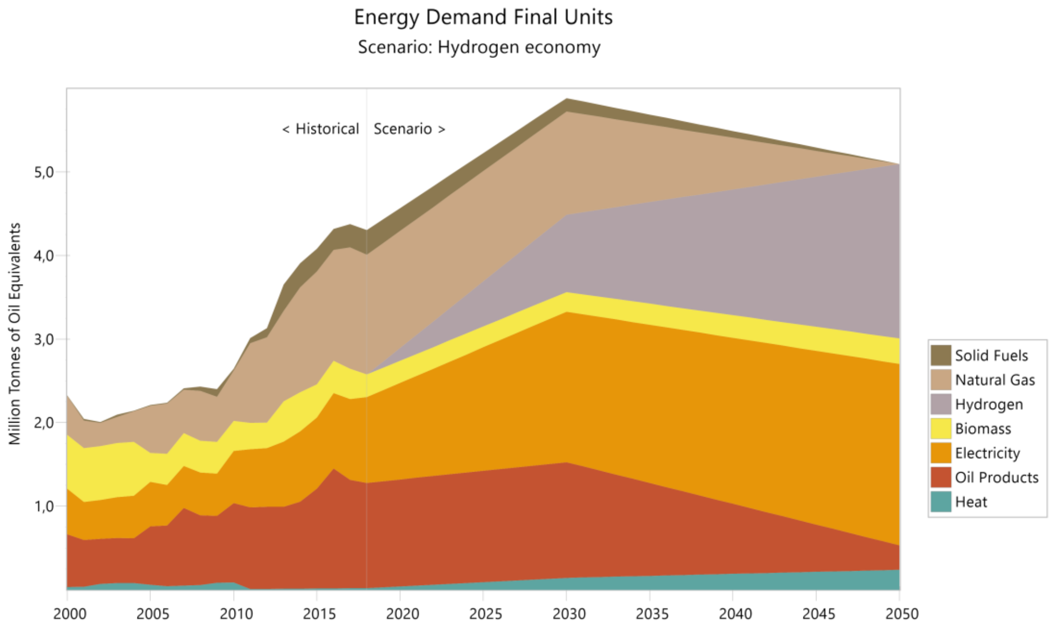

Figure 20. Final energy demand per fuel in Georgia under the Hydrogen economy scenario.

This is a high value compared to EU projections, which establishes hydrogen use at 25% of total demand in its higher estimates (European Commission, 2020). This is caused by a variety of factors.

Firstly, since in this research other synthetic fuels are not considered, hydrogen can be understood for not only direct use but also use of downstream processes like methanol or ammonia, synthetic hydrocarbon fuels or even biofuels, amongst other competing renewable technologies. So in this model some of this potential demand for different renewable fuels is hidden under hydrogen consumption.

The main disparity occurs in the industry sector. Some reports see hydrogen providing up to 30% of industry demand (including non-energy uses) in the EU by 2050 (Moya, Tsiropoulos, Tarvydas, & Nijs, 2019). However, in this model hydrogen accounts for 39% of industrial consumption in Spain and 51% in Georgia. This difference is due to the underlying assumptions of the model, which establish a target for climate neutrality in 2050 under the hydrogen economy scenario. Therefore, both electrification and hydrogen use is pushed further than in EU projections in order to replace all fossil fuel consumption in the industrial sector.

As for the transport sector, the model projects a 54% share of hydrogen in Spain and 59% in Georgia by 2050, while the EU establishes that number at 50% (Moya et al., 2019). Although smaller than in industry, the differences observed in this case are still relevant to the overall result of 41% share of hydrogen in energy consumption in Georgia by 2050. In this case, the observed differences come from different assumptions on the degree of electrification of the sector, specifically of freight road transport. Uncertainty in this regard is quite high. A recent report from IRENA (2021b) defended that electric vehicles could comprise 70% of total heavy-duty vehicles by 2050; contrarily, the Hydrogen Council (2020) reported that fuel cell heavy-duty vehicles could break even with electric alternatives as soon as next year, as seen in Figure 21 below (Hydrogen Council, 2020), and become the cheaper of the two in the coming decades due to the smaller batteries and shorter refuelling times. The same also holds true for family vehicles with longer driving ranges. Because of this, in the energy model developed in this research it was assumed that fossil fuel use in road freight transport would be entirely replaced by hydrogen, as well as a share of passenger transport as well, corresponding to larger cars with longer driving ranges.

As for the residential and building sectors, they do not have a significant impact on hydrogen demand in this model. The deployment of hydrogen is limited to some use (around 5%) in the tertiary sector as a source of heat and power for buildings. This is because there other alternatives projected to be more competitive in this sectors, such as heat pumps (Hydrogen Council, 2020). Moreover, according to the Hydrogen Council (2020), hydrogen could only be competitive as a clean source of heat and power in buildings if blended into an existing gas network and used with current gas boilers. However, this has a limited potential to lower emissions, and could potentially have lock-in effects for these fossil technologies, making it overall counterproductive.

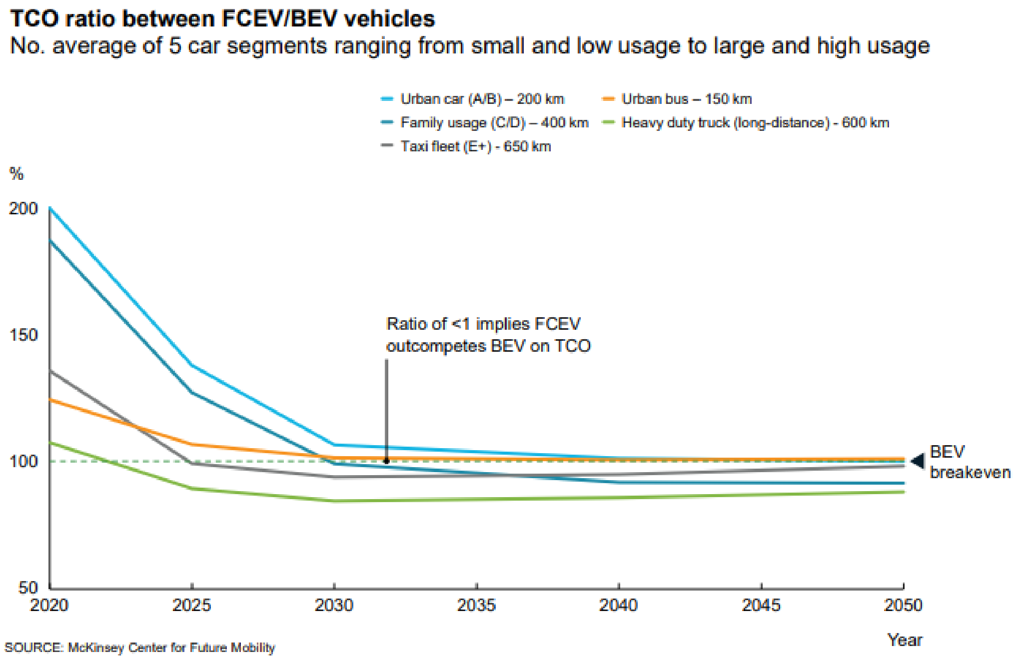

Figure 21. Total Cost of Ownership (TCO) comparison between Fuel Cell Vehicles (FCEV) and Battery Electric Vehicles (BEV) for different types of vehicles (Hydrogen Council, 2020).

So the different assumptions on transport technologies and the boost to achieve climate neutrality in the industrial sector explain the disparity of this model with other projections regarding hydrogen demand. While in the transport sector hydrogen competes directly with electrification, in industry is just a consequence of aiming for climate neutrality. Actually, electrification of industry assumed in this model is even higher than projections for the sector by IRENA (2021b), at around 43% in Georgia and 50% in Spain compared to 35% in the IRENA report.

In this model, hydrogen replaces oil and derived products like diesel in industry and specially the transportation sector, and also coal in industry as well. But the largest impact it has on Georgia's energy system is replace natural gas consumption across all sectors, including as a chemical feedstock for the production of fertilizers and other products. Consequently, fossil fuels consumption in the country declines drastically, especially after 2030, and by mid-century is limited to only the use of some oil products (bitumen and lubricants) as feedstock for road construction or plastic production, amongst other non-energy uses. Figure 22 shows the large impact of hydrogen deployment on fossil fuel consumption in this scenario compared to the BAU and Energy Transition cases.

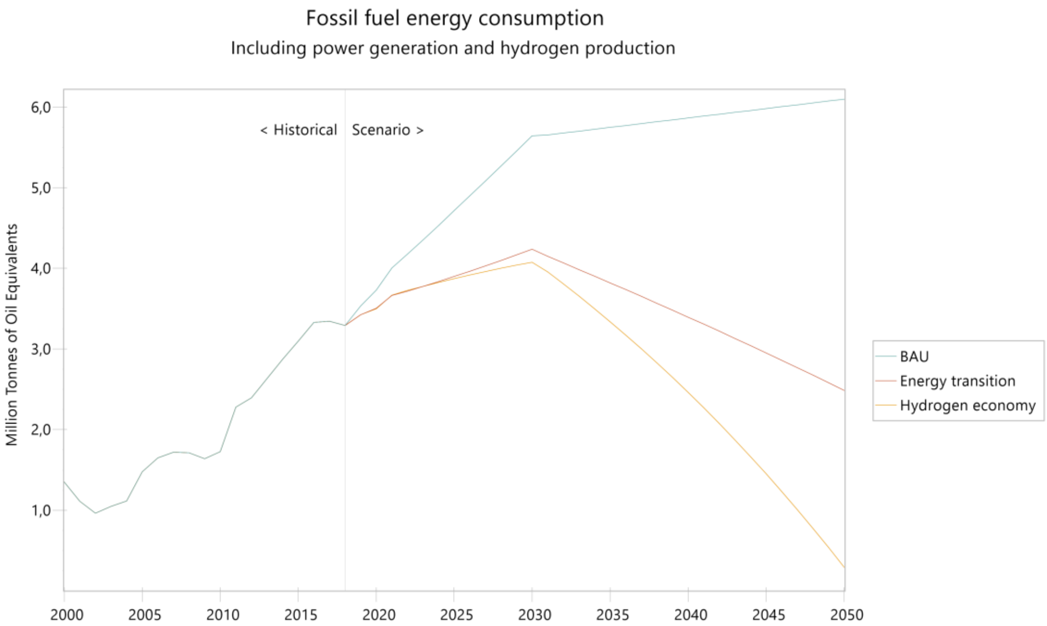

Figure 22. Comparison of fossil fuels total consumption across all the scenarios.

However, all the hydrogen needed in this scenario cannot immediately be produced via electrolysis of water, as it is an emerging technology with no current production capacity installed in the country. Therefore, at least 70% of hydrogen up until 2030 is produced still via SMR using natural gas as feedstock. Consequently, overall demand for natural gas would actually be higher in this scenario than in the Energy Transition one during the coming decade. After that, though, the scale up of electrolysers and production of hydrogen from renewable electricity and water will replace production from SMR.

Since Georgia's national production of natural gas is negligent and therefore the country imports practically all of its gas, the Hydrogen Economy scenario has the added benefit of gradually phasing out the need for natural gas imports in comparison to the other scenarios (as shown in Figure 23), in turn significantly improving the country's energy self-sufficiency and security long-term.

Figure 23. Comparison of natural gas imports in Georgia across the different scenarios.

The main impact of such a large-scale deployment of hydrogen production from electrolysis is the increased electricity demand. Figure 24 shows that in the Hydrogen Economy scenario Georgia would need to provide 25.8 TWh of electricity annually by 2030 and 58.5 TWh by 2050 to cover its own demand and hydrogen production. That is a 32% increase compared to the Energy Transition scenario by 2030 and more than double by mid-century. This extra demand is mainly covered by a large deployment of solar PV, as seen in Figure 25, since hydro and wind resources are already hugely exploited by 2050 in the Energy Transition scenario. So Georgia, under this Hydrogen Economy scenario, needs to tap into the solar resources of the country, underutilised at the moment and in the other projected scenarios.

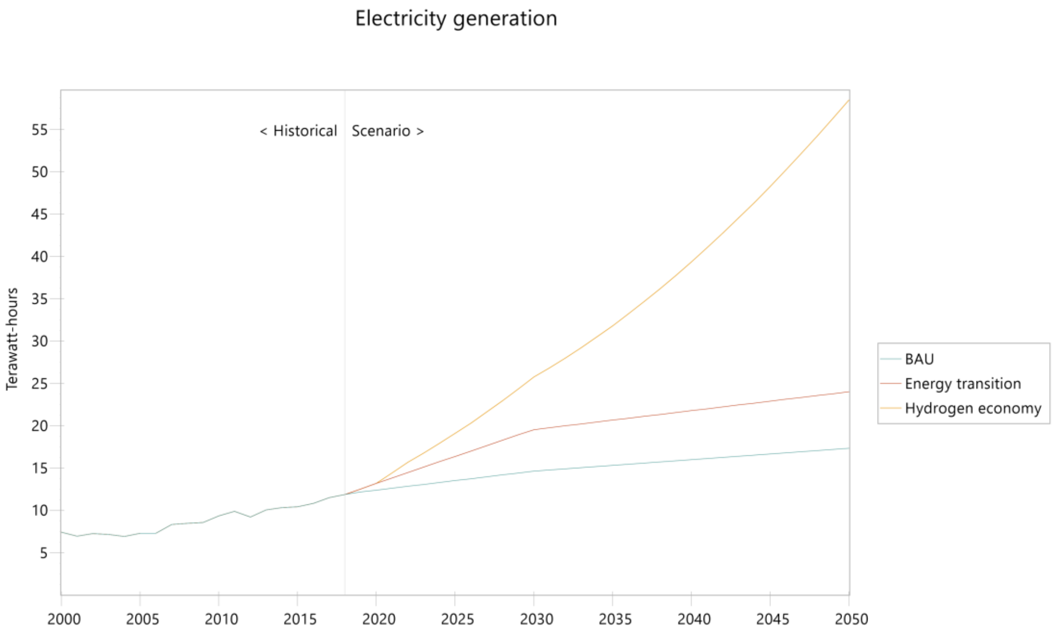

Figure 24. Comparison of total electricity generation in Georgia across the three different scenarios.

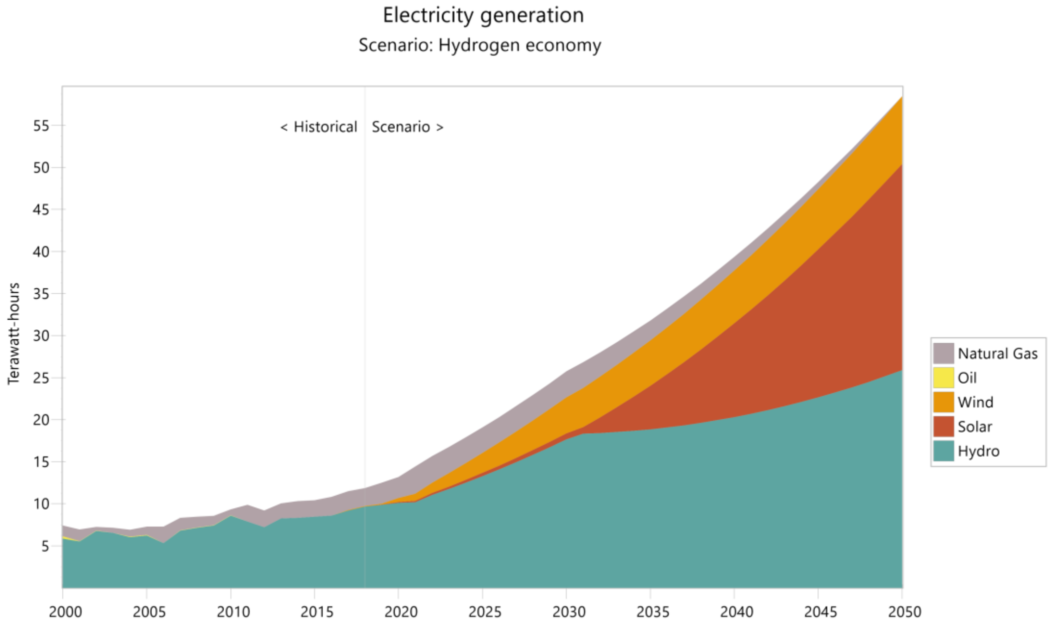

Figure 25. Electricity generation by technology in Georgia under Hydrogen Economy scenario.

In order to be able to provide all this electricity and not depend on imports from neighbouring countries, Georgia would require a massive deployment of generation capacity after 2030. This extra needed capacity would mostly come from solar PV, as seen in Figure 26.

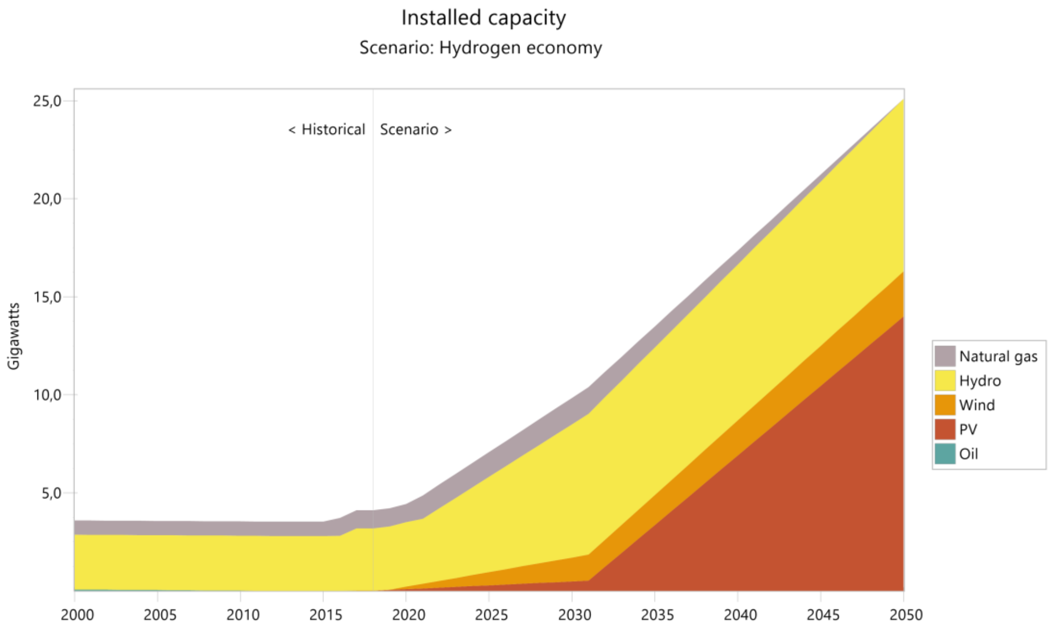

Figure 26. Cumulative installed capacity per technology in Georgia under the Hydrogen economy scenario.

4.1.2. Spain

In this section, similar results from the energy models are presented, this time for the case of Spain. and show the projected evolution of energy demand in Spain under the three analysed scenarios. After a few years of decline in final consumption following the financial crisis of 2007, energy demand started rising again in 2015. In the calculated BAU scenario (Figure 27) this trend continues, and total demand increases from 81.2 Mtoe in 2018 to 86.7 Mtoe in 2030 and 102.9 Mtoe in 2050.

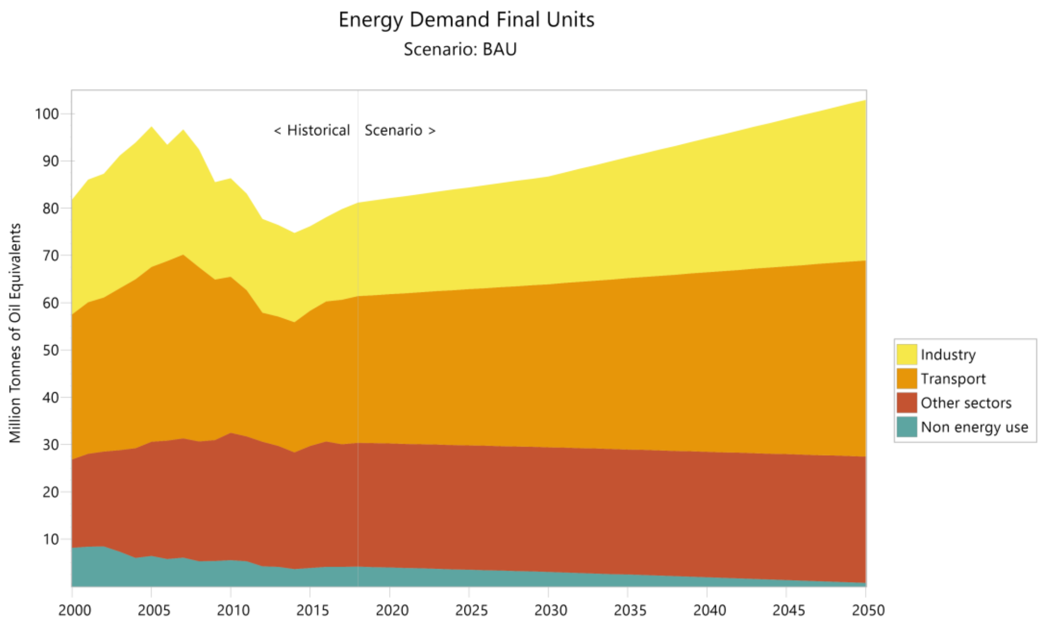

Figure 27. Total final energy demand per sector in Spain under BAU scenario.

On the other hand, in the Energy Transition and Hydrogen Economy scenarios (Figure 28), energy consumption starts decreasing after 2018 as stringent energy savings and efficiency policies are implemented, declining to 59.4 Mtoe in 2030 and reaching 50.7 Mtoe by mid-century. Although no drastic changes are observed in sectorial distribution, the more energy intensive sectors in industry and transport do see an increase in their share of total consumption. As for non-energy uses, historical trends continue and demand declines to almost 0 by 2050, which would indicate the fading of corresponding industries like chemical. This is a questionable development which might just be a side-effect of the top-down, simplified approach used in the projections.

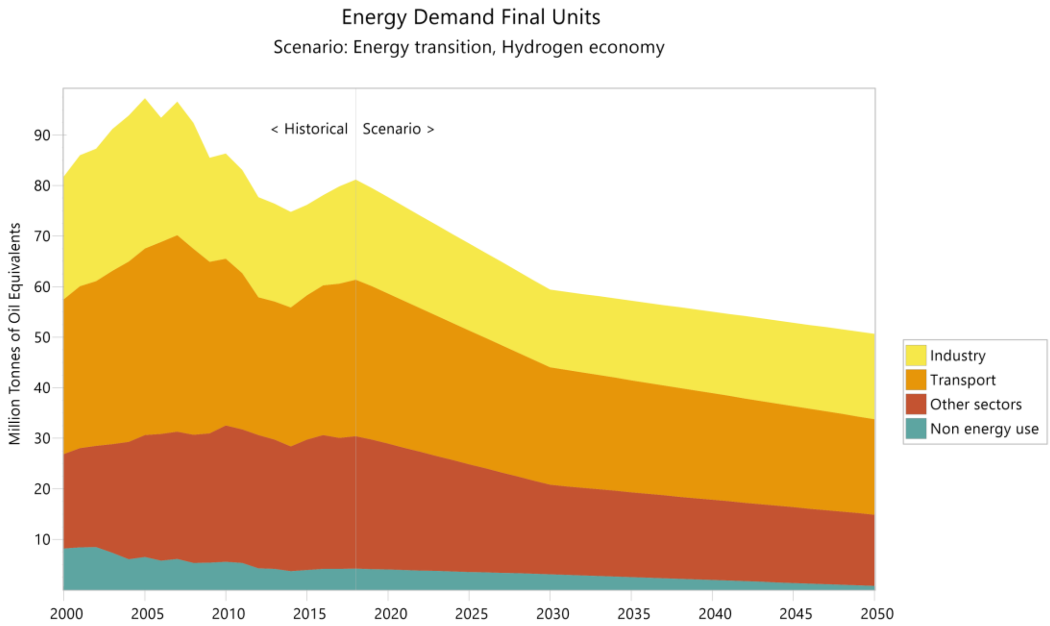

Figure 28. Total final energy demand per sector in Spain under Energy transition and Hydrogen economy scenarios.

As for the energy mix of final consumption, no significant variations are observed in the BAU scenario. As seen in Figure 29, oil products (mostly diesel) continue to provide around half of demand. Natural gas and electricity account for 17% and 25% respectively, both in the moment and in 2050.

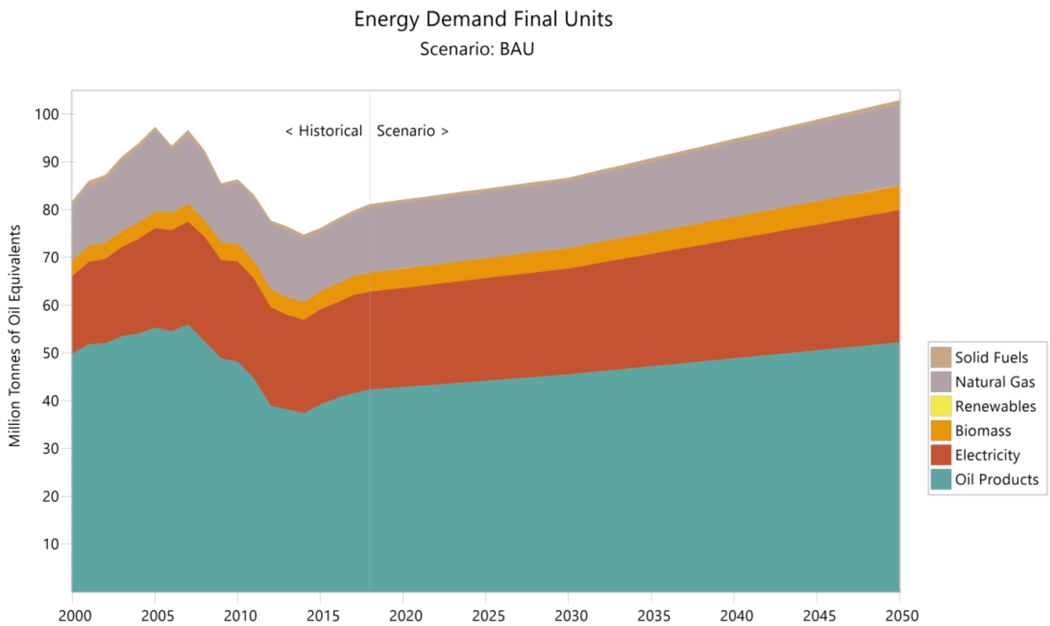

Figure 29. Total final energy consumption per fuel in Spain under BAU scenario.

The increase in electricity demand is mostly covered by further expansion of gas-powered thermal plants and wind farms under this scenario. Together they generate up to 58% of total electricity in the country by 2050, as Figure 30 shows.

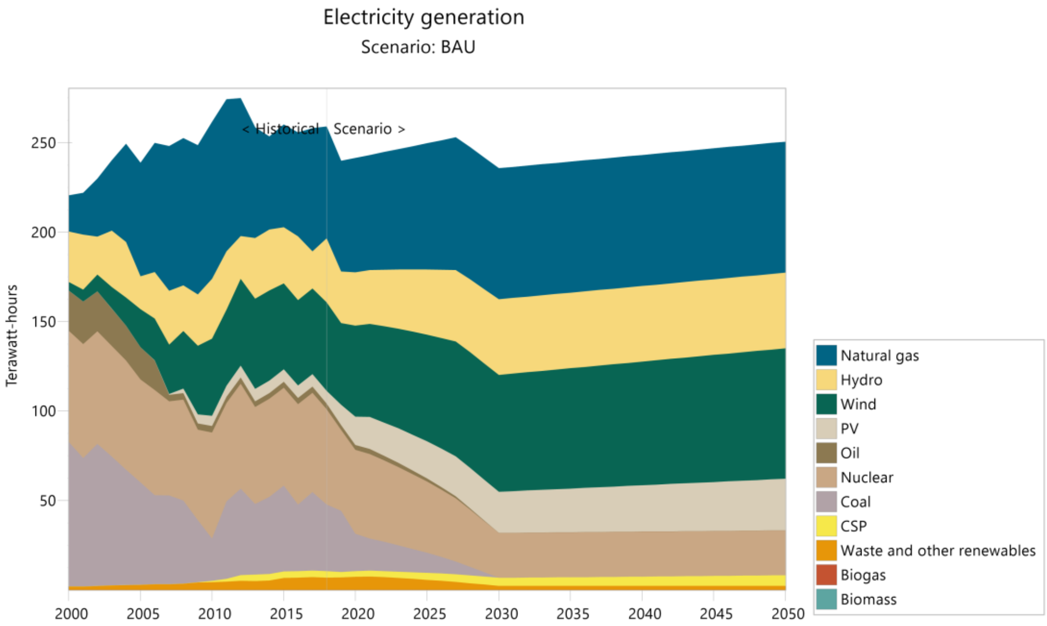

Figure 30. Power generation by technology in Spain under BAU scenario.

In the Energy Transition scenario, beyond energy efficiency measures as previously mentioned, electrification is pushed forwards, as is further deployment of renewable energies, as shown in Figure 31. As a consequence, electricity already becomes the most consumed form of energy in the country by 2030 and reaches a share of 54% of total final energy consumption by 2050. This is in par with projections for the EU (European Commission, 2018). The direct use of other renewable sources such as biomass also sees an increase, although this is not appreciated in the graph because biomass is coupled with traditional wood, which had some importance in the past but is phased out in the coming years, similarly to Georgia.

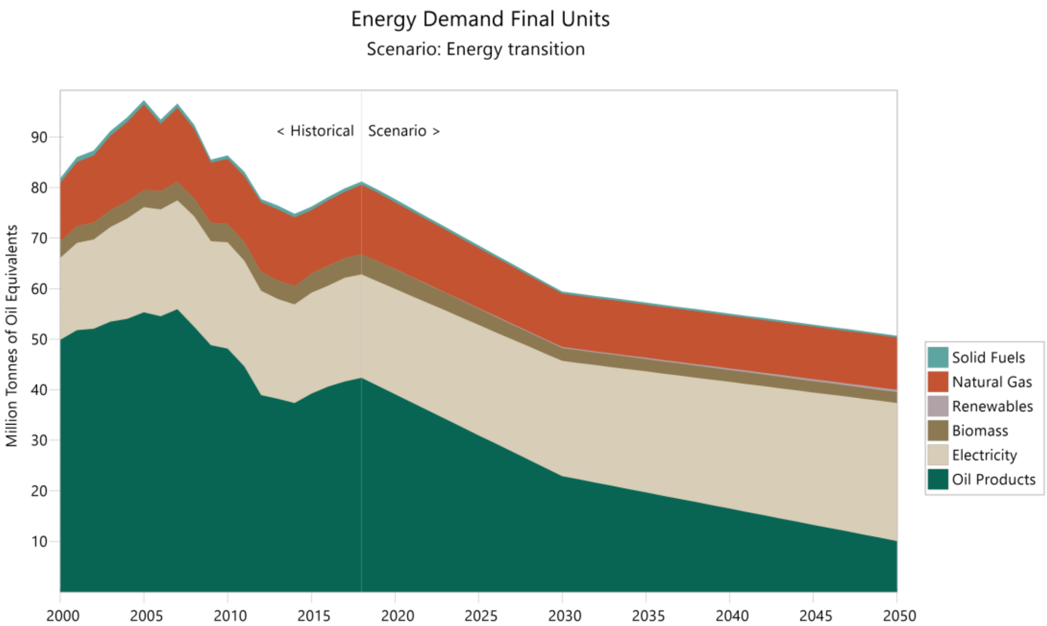

Figure 31. Final energy consumption per fuel in Spain under Energy transition scenario.

Power generation is where the impact of renewables deployment is more prominent. As shown in Figure 32, by 2030 coal and oil-fired power plants are phased out as 72.2% of electricity is generated from renewables, on par with national targets of 74% renewables in power generation by 2030 (Ministerio para la transición ecologica y reto demográfico, 2020c).

By 2050 the power system becomes 100% clean and renewable as gas plants and nuclear generators are also phased out according to national plans (Ministerio para la transición ecologica y reto demográfico, 2020a), replaced by a significant expansion of wind and solar energy generation.

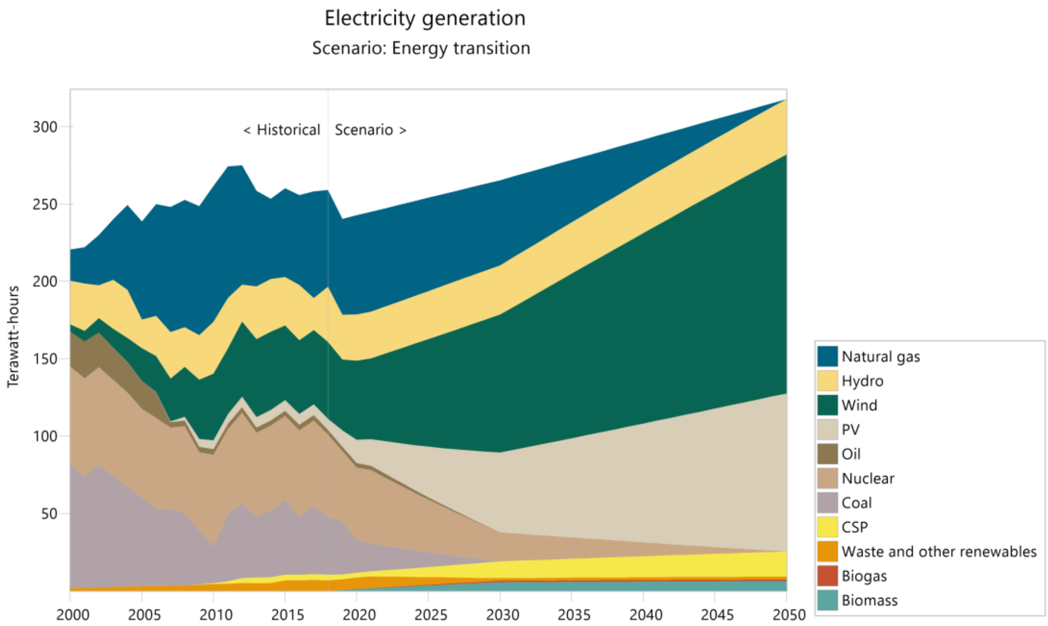

Figure 32. Power generation by technology in Spain under Energy transition scenario.

As is the case with Georgia, however, the measures projected in the Energy Transition scenario are not sufficient to fully decarbonise Spain's energy system. Figure 33 shows how, albeit a 74% reduction in fossil fuel use in this scenario, Spain is still consuming a total of 20.8 Mtoe per year of fossil fuels by 2050, mostly in the industry and transport sectors.

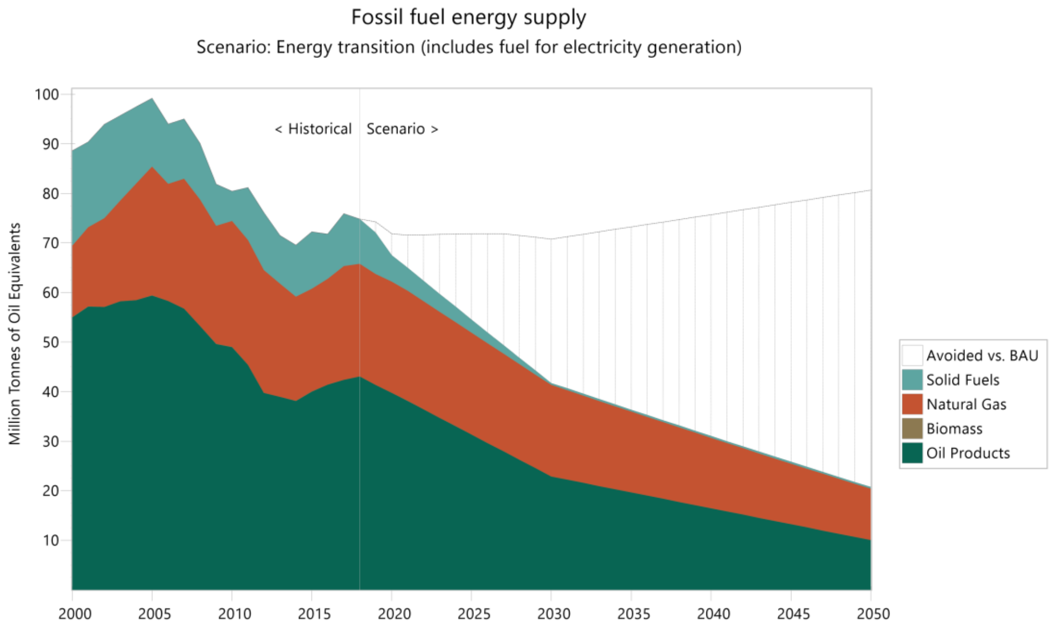

Figure 33. Final consumption of fossil fuel energy per fuel in Spain under Energy transition scenario and avoided compared to the BAU scenario.

Figure 34 shows that the implementation of a hydrogen infrastructure in the Hydrogen Economy scenario facilitates almost full decarbonisation of the Spanish energy system by 2050. Together, electricity and hydrogen (both produced from renewable sources) provide almost 94% of all country's long-term energy needs. Particularly, hydrogen supplies 13% of total demand by 2030 and up to 40% in 2050. Again, this is quite a high value compared to projections made for the EU (European Commission, 2020). The reasons for such a result derive from the construction of the energy model and are already analysed in pages 46 and 47 under section 4.1.1.

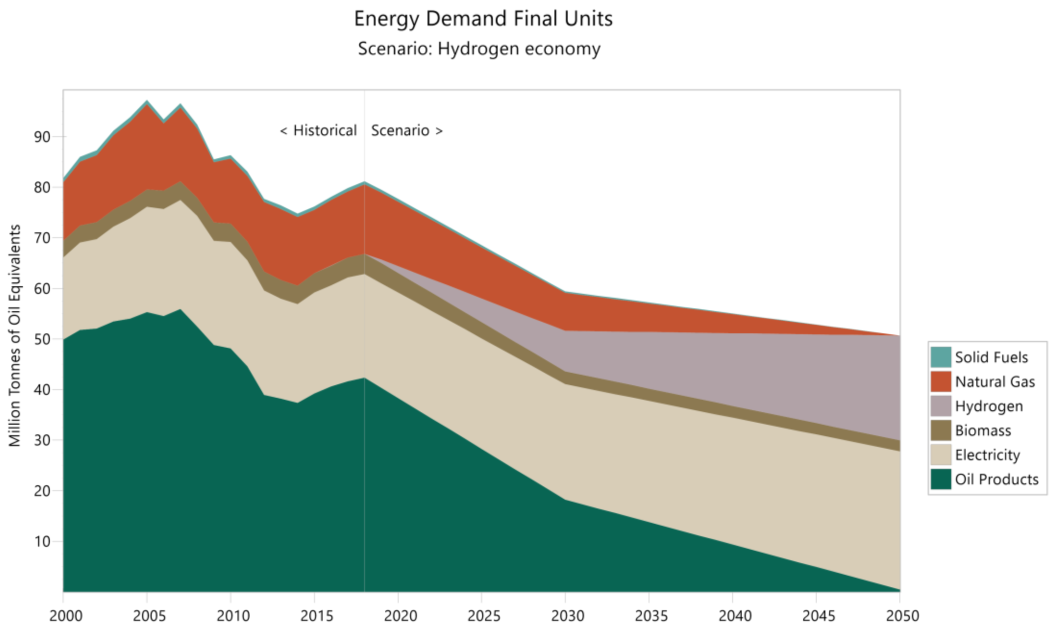

Figure 34. Final energy consumption per fuel in Spain under Hydrogen economy scenario.

As was the case with Georgia, at least 70% total hydrogen demand up to 2050 is assumed to be met still by either conventional SMR or SMR coupled with CCUS, but either way using natural gas as feedstock. This increases the demand for natural gas during this coming decade to similar levels as the BAU scenario, close to 25 Mtoe per year, as shown in Figure 35. Since Spain also imports practically all of its gas, this makes Spain dependent on natural gas trade partners and prices for starting the hydrogen transition during the next decade, but replacement of natural gas as primary and final energy by hydrogen produced with renewable electricity provides additional benefits in the long-term in terms of energy self-sufficiency and security in the country.

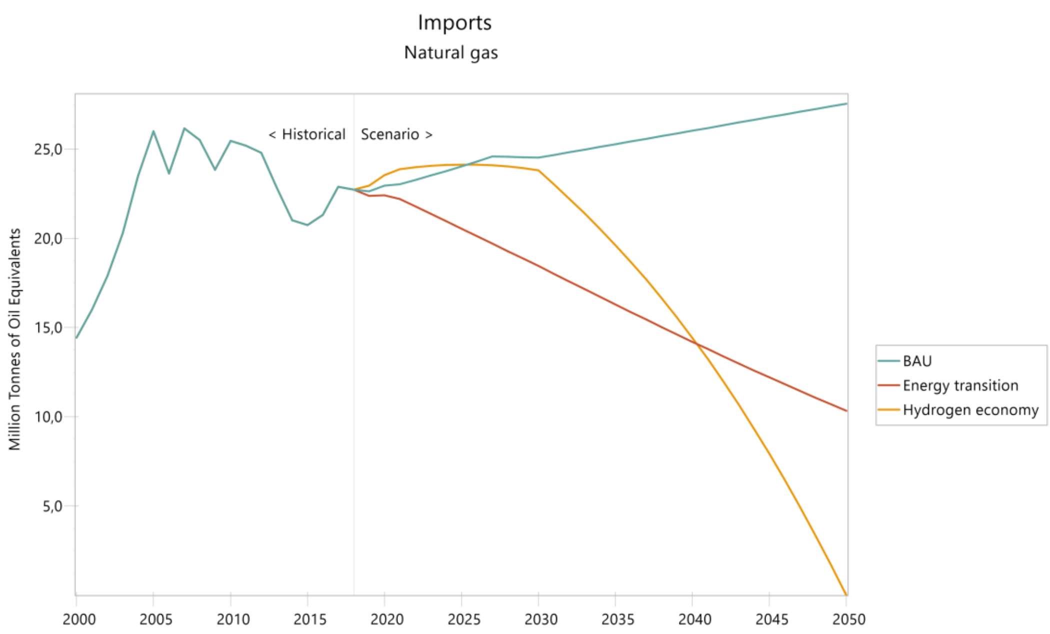

Figure 35. Comparison of natural gas imports in Spain across the three different scenarios.

Overall, Figure 36 demonstrates how in the Hydrogen Economy scenario the incorporation of hydrogen as an alternative clean is able to decarbonise those sectors of the Spanish energy system that direct electrification or renewables use could not in the Energy Transition scenario. Only some residual non-energy use of fossil fuels remains as feedstock for industries, similar to the Georgian case.

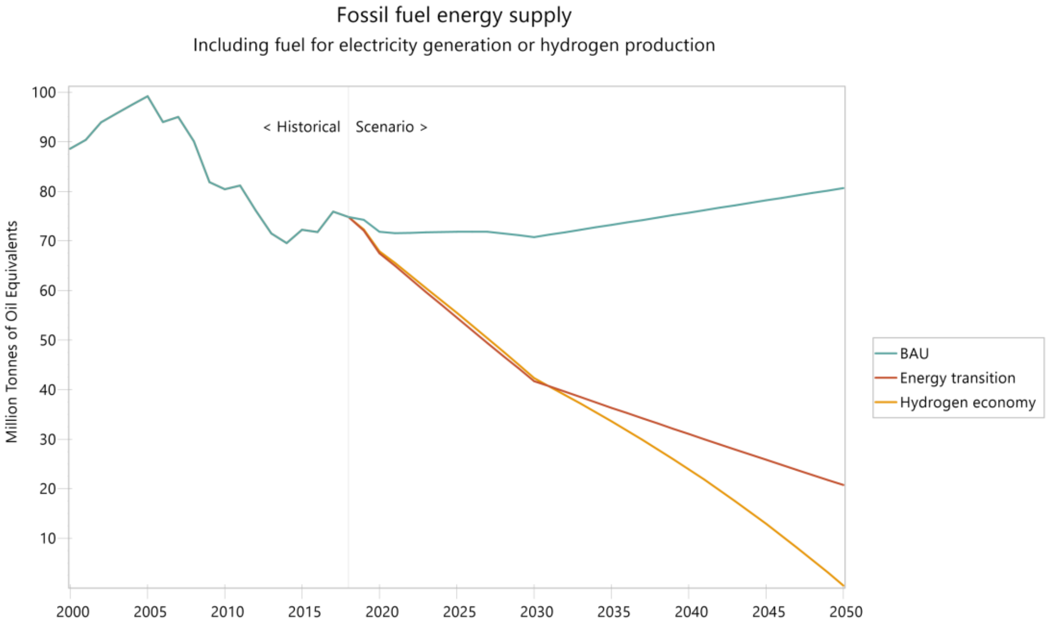

Figure 36. Comparison of total fossil fuels consumption in Spain across the three different scenarios.

In this scenario, the demand for electricity sees a large increase in Spain in order to be able to produce all the green hydrogen needed. As Figure 37 indicates, power generation more than doubles over the next 30 years, reaching 306.1 TWh by 2030 and 640.7.5 TWh of annual generation by 2050. That is also more than double the required electricity in the BAU and Energy Transition scenarios. By mid-century, when all electricity generation is fully renewable, most of this is supplied by solar PV and wind energy (up to 86% combined by 2050), as shown in Figure 38. Concentrated solar power (CSP) and hydro make some contributions as well, with thermal power from biomass and waste as well as other renewables (marine, geothermal energy) making up the rest.

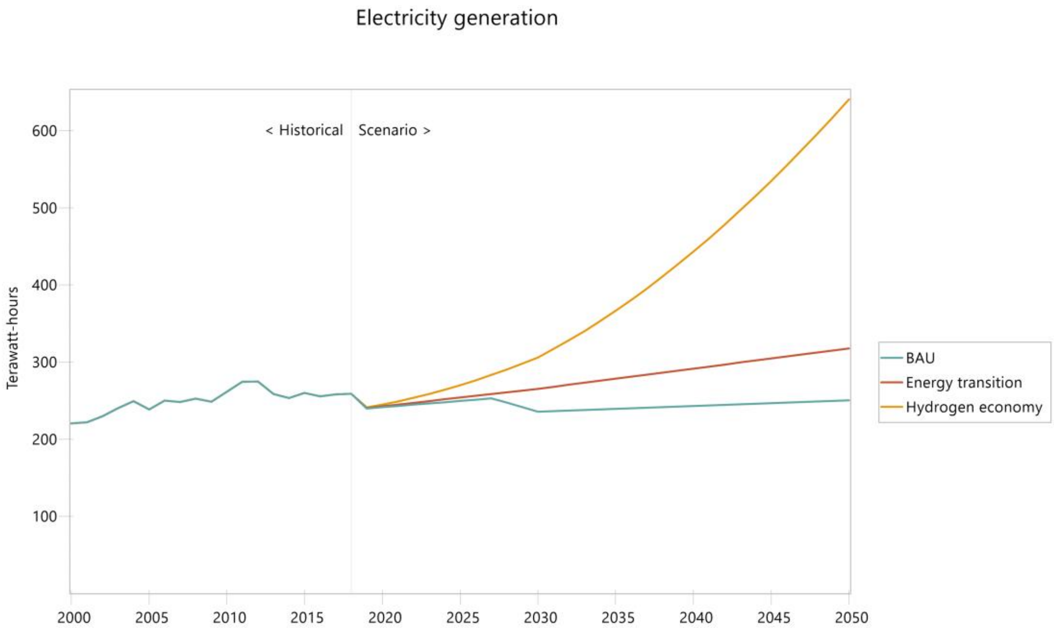

Figure 37. Comparison of total electricity generation in Spain across the three different scenarios.

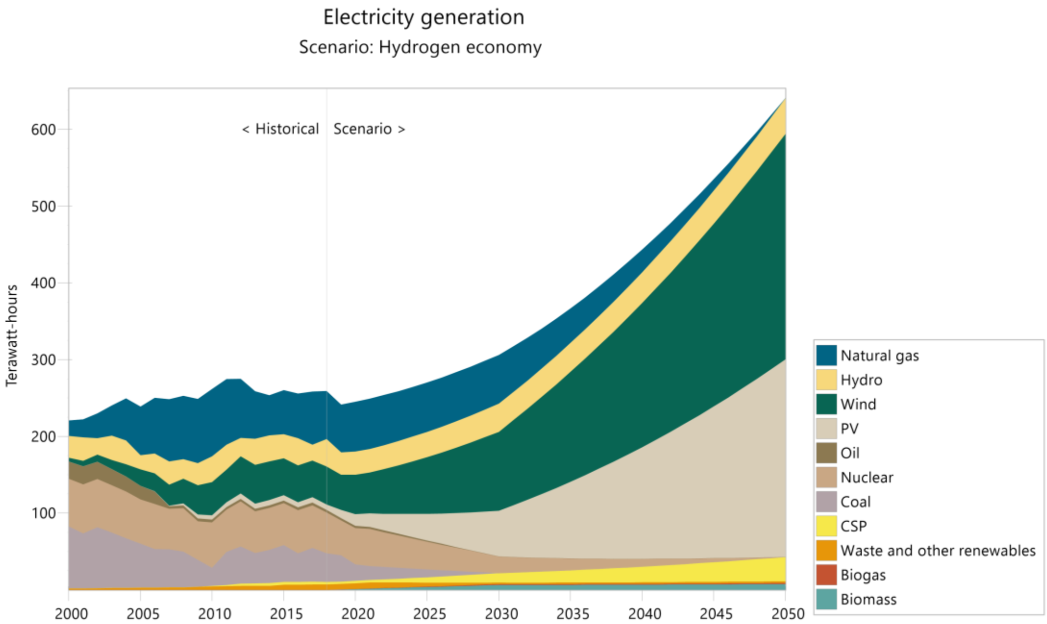

Figure 38. Power generation by technology in Spain under the Hydrogen economy scenario.

Finally, in order to achieve such levels of power generation under this scenario, Spain would need to deploy massive amounts of renewable capacity, especially wind and solar PV, as demonstrated in Figure 39. Installed capacity of wind energy is six times as much as in 2018, and PV's installed capacity outstandingly multiplies by 30 by mid-century.

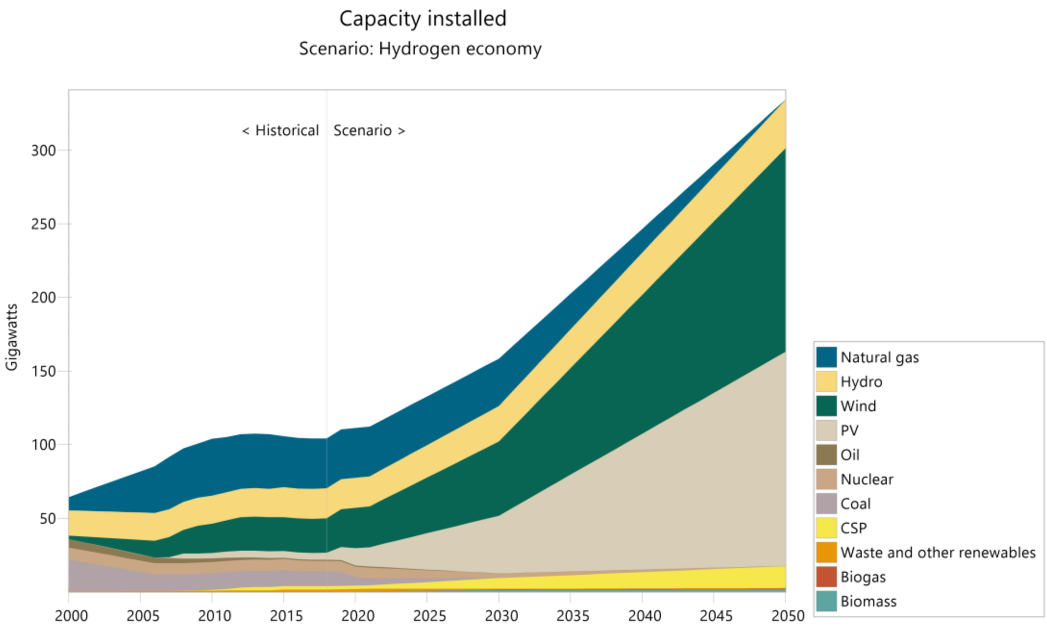

Figure 39. Cumulative installed capacity by technology in Spain under Hydrogen economy scenario.

4.2. Sub-question 3: Hydrogen production costs

4.2.1. Georgia

Below the levelized costs of hydrogen (LCOH) of the different hydrogen production routes based on SMR in Georgia are shown. In Georgia, with a high range pricing of CO2, blue hydrogen could already be competitive with grey hydrogen at the moment at costs slowly above 1.5 €/kgH2 (see Figure 41 and Figure 42) and become clearly the cheapest of the two in the next decades as grey hydrogen costs rise due carbon pricing increases. However, if no carbon pricing is established, blue hydrogen cannot compete neither now or in the future with the cheaper grey hydrogen at costs that will range between 1 and 1.2 €/kgH2, as shown in Figure 40.

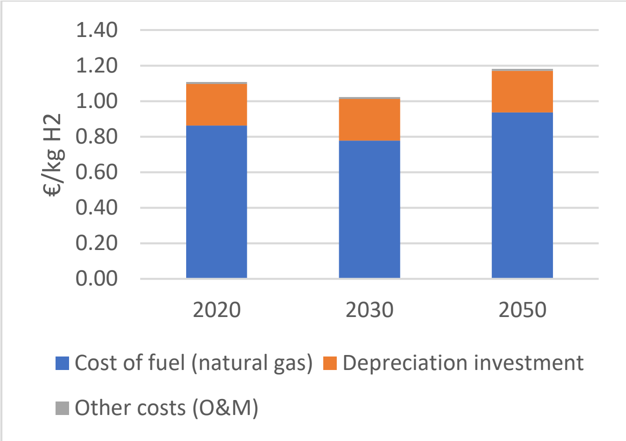

Figure 40. Production costs of hydrogen from SMR with natural gas and no carbon pricing in Georgia.

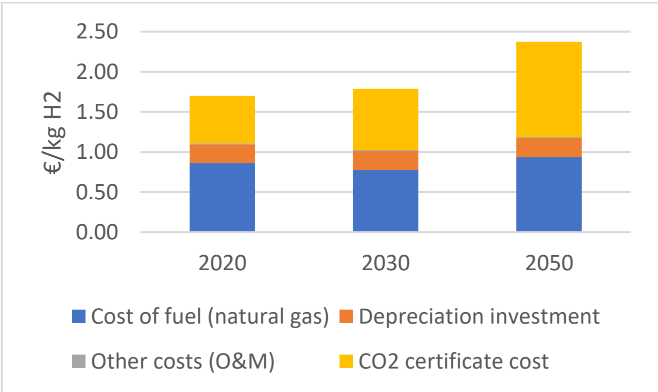

Figure 41. Production costs of hydrogen from SMR with natural gas and carbon pricing in Georgia.

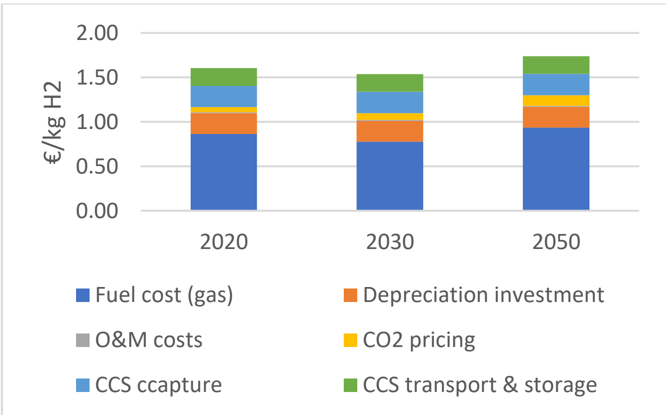

Figure 42. Production costs of hydrogen from SMR with natural gas and CCS, plus carbon pricing in Georgia.

Production routes based on natural gas reforming are also compared to the possibility of green hydrogen. Different production routes are analysed within electrolysis hydrogen production, depending on the source for electricity: grid-connected, stand alone with PV, stand-alone with wind and stand-alone with hydro. For each two projections are made, a high price and a low price one. Here the higher estimates are shown, because the lower estimates, as described in the Methods section, assume quite optimistic developments for electrolyser technology costs as well as levelized costs of electricity (LCOE) of renewables. However, they can be found in Appendix B.

At the moment, grid-connected production is cheapest amongst electrolysis options in Georgia at 3.3 €/kgH2, as shown in Figure 43. The main reason for this is that grid-connected production is not limited by load hours of its electricity source like stand-alone, which heavily influences annualised CAPEX costs. This is also why overall its main cost component is the cost of electricity, further increased by the costs of connecting to the power system. Albeit developments from the other configurations, this still holds true in 2030, as grid-connected production declines to 2.8 €/kgH2 and could be competitive with grey and blue hydrogen assuming high carbon pricing. By 2050 hydrogen from grid connected electrolysers could be produced at a cost of 2.2 €/kgH2.

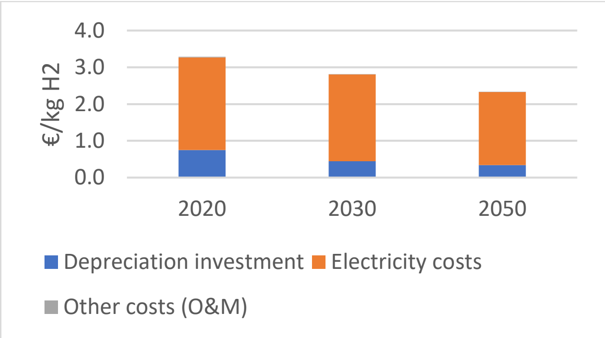

Figure 43. Production costs of hydrogen from water electrolysis powered by grid electricity – Georgia high projection.

In green hydrogen production from solar PV, the depreciated investment costs are much more significant due to the low load factor of solar energy and therefore of the overall system. Because of this, neither right now nor in the coming decade is stand-alone production with PV competitive with other alternatives, as Figure 44 shows. Costs in 2030 would still be above 6 €/kgH2. However, as scale up of electrolysers and continued development of solar PV significantly decrease prices of both technologies, overall systems costs are expected to continue declining long-term, and by 2050 this option could produce green hydrogen at a cost of 3.6 €/kgH2.

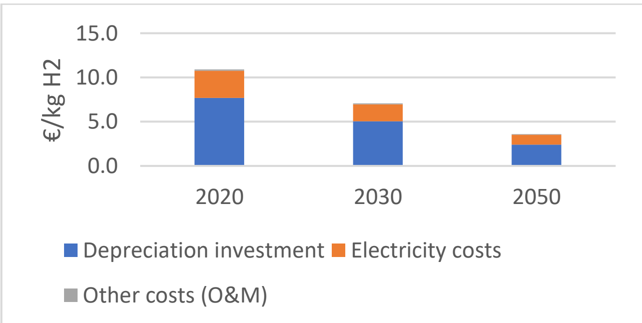

Figure 44. Production costs of hydrogen from water electrolysis powered by stand-alone solar PV - Georgia high projection.

Green hydrogen from PV is the production route most affected by the uncertainties surrounding electrolyser CAPEX costs in the future, do to tis lower capacity factor that increases pressure on depreciation costs of investment. Because of that, its higher estimate cost projection is quite high and not close to economically competitive with other alternatives in the future.

When comparing the costs of grid-connected green hydrogen and stand-alone with PV, it becomes clear than the biggest source of uncertainty in these projections is the cost of electrolyser. In the configurations in which electrolyser CAPEX is more prominent, differences between the higher and lower estimates are also bigger (see Figure 61 and Figure 62 in Appendix B). Consequently, production from PV in the future will benefit more from electrolysers scale up and further technological learning which drive down the CAPEX cost of the system, while grid-connected production of green hydrogen will benefit more from innovations and modifications in electrolysers that improve the systems' efficiency, as well as from decreased renewable electricity prices.

Wind powered green hydrogen has characteristics of both grid-connected and PV production. Its higher load factor diminishes the impact of CAPEX costs in this case, and total systems cost are more equally distributed between depreciation of investment and cost of electricity. Because of this current and near future costs are lower level than for PV. By 2050, stand-alone production of hydrogen powered with wind energy achieves a cost of 2.3 €/kgH2 (Figure 45), which considering this is a higher estimate cost projection, could make this option quite competitive with grey or blue hydrogen in the future if technology improves a bit more than assumed. In a best-case scenario, the lower estimate projections see green hydrogen powered by wind as the cheapest option overall to produce hydrogen in Georgia by 2050 (see Figure 63 in Appendix B).

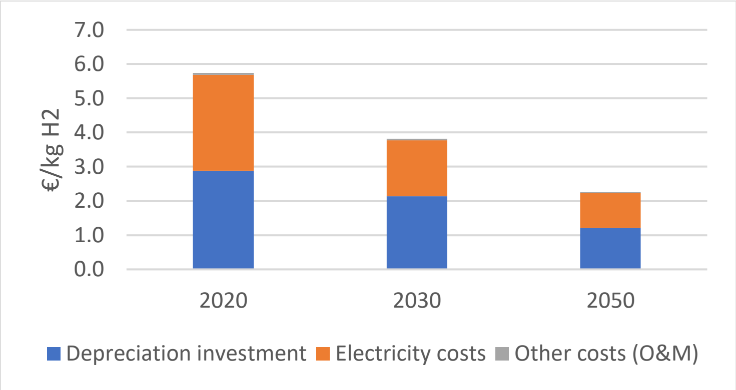

Figure 45. Production costs of hydrogen from water electrolysis powered by stand-alone wind power - Georgia high projection.

As for stand-alone production from hydro, shown in Figure 46, it is currently cheaper than solar and in par with wind-powered production at 5.3 €/kgH2. Long term, though, since there is no significant either increase in average load hours or decrease in generation costs expected for the future of hydropower, its costs do not decline as sharply as solar and wind stand-alone configurations. Nevertheless, by 2050 green hydrogen from hydro has a good chance of being more economic than from PV unless strong cost reductions occur for electrolyser systems.

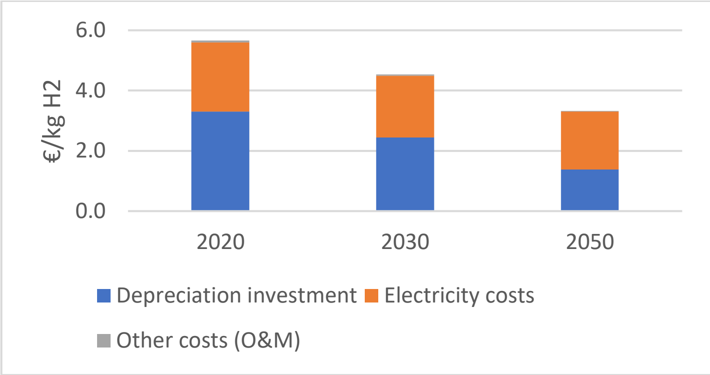

Figure 46. Production costs of hydrogen from water electrolysis powered by stand-alone hydropower - Georgia high projection.

4.2.2. Spain

Figure 47, Figure 48, and Figure 49 present the costs results for hydrogen production from SMR in Spain. In Spain, gas prices are currently high, so conventional SMR production of hydrogen is not as cheap as in other countries, standing at 1.6 €/kgH2. Incorporating carbon pricing into the mix increases that to 2.2 €/kgH2, which means that under this scenario blue hydrogen could already be competitive in the country with a production cost of 2.1 €/kgH2. By 2030 blue hydrogen is clearly a more economic option at 1.5 €/kgH2, a trend that continues long-term. However, without implementation of increasingly high carbon prices, it cannot compete with the decreasing cost of conventional SMR as gas prices are projected to stabilise at lower levels and be able to produce hydrogen at a cost between 1 and 1.2€/kgH2 in the next decades.

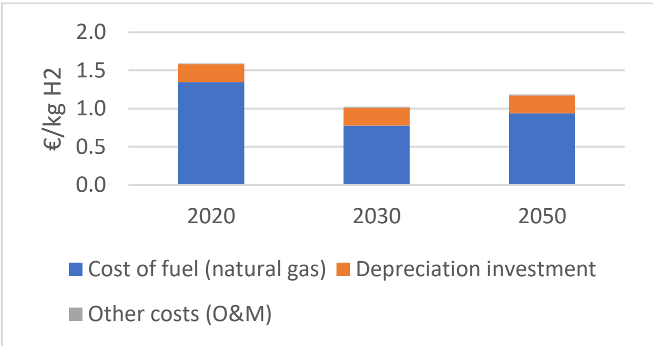

Figure 47. Production costs of hydrogen from SMR with natural gas and no carbon pricing in Spain

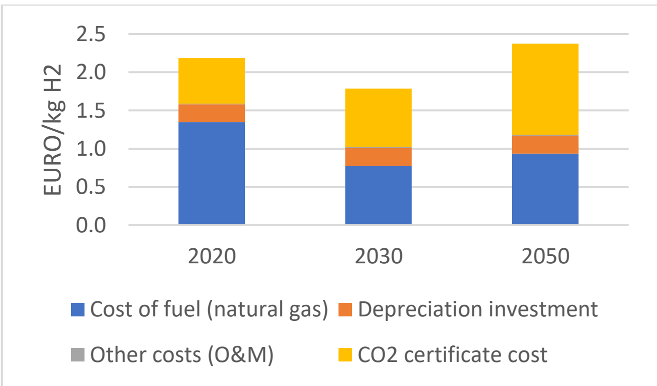

Figure 48. Production costs of hydrogen from SMR with natural gas and carbon pricing in Spain.

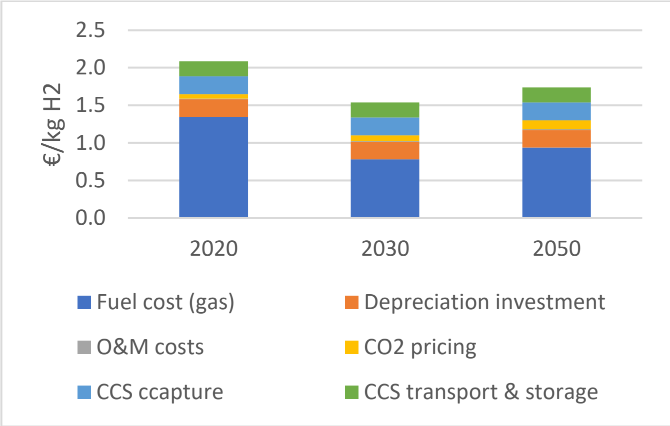

Figure 49. Production costs of hydrogen from SMR with natural gas and CCS, plus carbon pricing in Spain.

As an emerging technology, electrolysis cannot currently compete with conventional alternatives in Spain, no matter the configuration. Electricity prices have also been rather high in Spain in the last few years, which is why the grid-connected production route does not show good economic performance at the moment compared to Georgia. It is also why, together with high load hours making annualised investment less prominent, electricity costs represent almost 97% of total system costs. Even with a projected decline in grid electricity prices during the next decade in Spain, total costs would still sit at 3.9 €/kgH2 by 2030, as shown in Figure 50. However, further decline in costs as cheap wind and solar penetrate the national power mix make grid-connected production a potential competitive option by 2050 with a maximum cost estimate of 2 €/kgH2.

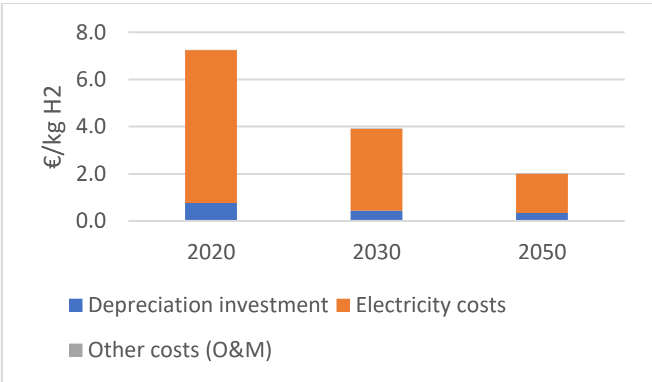

Figure 50. Production costs of hydrogen from water electrolysis powered by grid electricity – Spain high projection.

Stand-alone production powered by solar PV faces similar challenges to the Georgian case, as its low average load factor largely impacts CAPEX costs. Because of this, it is not cost competitive with conventional technologies neither now nor in the near future, as represented in Figure 51. However, as electrolyser costs keep declining with technological learning and scale up and PV keeps getting better and cheaper, hydrogen from stand-alone PV could produce hydrogen at a cost of 2.9 €/kgH2 by 2050 according to the higher estimate.

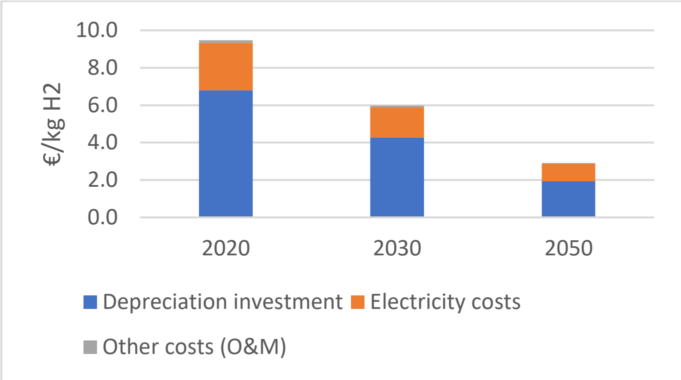

Figure 51. Production costs of hydrogen from water electrolysis powered by stand-alone solar PV - Spain high projection.

Wind-hydrogen coupled systems, albeit not competitive at the moment, fare better short-term in these projections than PV or hydro systems. However, they still cannot compete with grey hydrogen in that timeframe. Long term, wind-powered hydrogen is produced at a cost of 3 €/kgH2 (Figure 52).

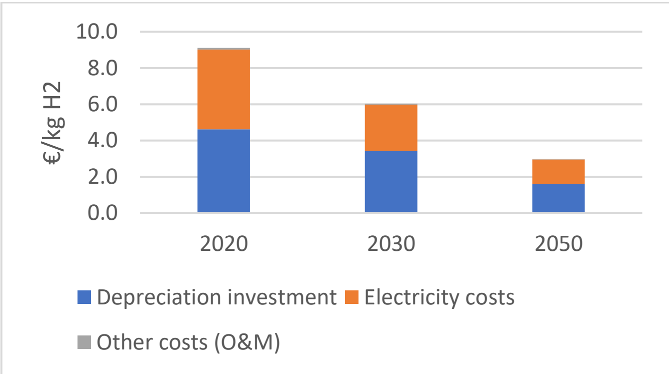

Figure 52. Production costs of hydrogen from water electrolysis powered by stand-alone wind power - Spain high projection.

Similar to Georgia, in Spain stand-alone production of hydrogen from hydropower is not cost competitive at the moment, and not projected to be in the future. With stable hydropower prices, the only cost reduction comes from electrolyser systems improvement. Figure 53 shows that electrolysis powered by stand-alone hydro could produce green hydrogen at a cost of 4.4 €/kgH2 by 2050, which is far from competing options. Accordingly, this is not yet contemplated in the National Hydrogen Strategy, which focus solely on wind and solar as the motors of the green hydrogen transition (Ministerio para la transición ecológica y el reto demográfico, 2020b).

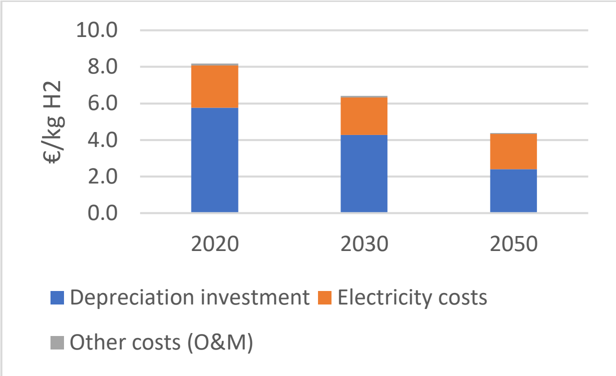

Figure 53. Production costs of hydrogen from water electrolysis powered by stand-alone hydropower - Spain high projection.

So far, the higher cost projections for green hydrogen have been analysed in detail due to the uncertainties surrounding the more optimistic assumptions of the lower estimate. However, in the hypothesis that both electrolysers and renewables experience a massive cost reduction from technological learning in the future, green hydrogen produced in stand-alone configurations powered by either PV or wind in both countries could potentially become significantly cheaper than any other alternative assuming high CO2 prices (see Appendix B). In Figure 54 the results from the lower estimate cost projections are summarized and compared to grey and blue hydrogen under high carbon pricing assumptions. The cheapest options in both countries achieve a cost of only 1.1 €/kgH2, those being wind for Georgia and PV for Spain.

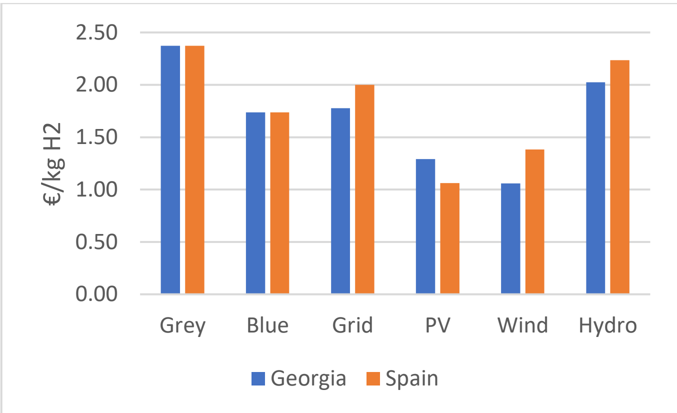

Figure 54. Summary of lower estimate projections of LCOH in 2050 for different production routes in Georgia and Spain

4.3. Sub-question 4: Production requirements and export potentials

In section 4.1 the potential use of hydrogen in the Georgian and Spanish energy systems was analysed, as well as its impacts and challenges. Here some further results derived from that analysis are presented.

First of all, total demand for hydrogen is gathered for both countries in 2030 and 2050. For Spain, this is the sum of current consumption, which sits at 500 ktonnes/year (Ministerio para la transición ecológica y el reto demográfico, 2020b), and the demand calculated in the LEAP energy model. For Georgia no specific data on hydrogen consumption is found, so the results from the LEAP energy model alone are used.

Table 12 presents, amongst others, the actual annual demand of hydrogen in order to decarbonise both energy systems as well as replace current hydrogen use.

Table 12. Hydrogen production requirements and export potentials in Georgia and Spain.

	Georgia		**Spain**	
	2030	*2050*	*2030*	*2050*
Demand (Mtonnes/year)	0.3	0.7	2.7	7.1
Installed electrolyser capacity requirements (GW)	0.4 - 2.2	3 - 13.8	4 - 18.4	31.7 - 144
Long term technical potential exports (Mtonnes/year)	-	3.9	-	25.7
Share of EU's hydrogen demand	-	5.7%	-	38.1%

Next, estimates are calculated for installed electrolyser capacity requirements. Uncertainty is quite high here because of the wide range of available load hours that electrolyser could have depending on the specific technology and place. Nevertheless, it is estimated that Georgia would need at least around 1 GW of total installed capacity to be built during the next decade, and up to ten times that by mid-century. In Spain, even assuming that at least half of hydrogen production up to 2030 is still covered by SMR, the lower estimate for electrolyser capacity required is around 7 GW to be built during the next decade. That is already almost double the 4GW target specified in the National Hydrogen Strategy, with higher estimates being as high as six times more than that target. By 2050, Spain could potentially need up to around 100GW of installed electrolyser to meet all demand with green hydrogen.

Finally, the export potential for both countries is estimated. Assuming no limitations for electrolyser capacity it is projected that after meeting own electricity and hydrogen demands, the remaining technical potential of renewables generation In Georgia could be used to produce almost 4 Mtonnes of hydrogen per year by 2050, which would represent almost 6% of EU's estimated annual hydrogen demand for the mid-century mark (Fuel Cells and Hydrogen Joint Undertaking (FCH), 2019). For Spain, that number could potentially be as high as 25.7 Mtonnes, which would represent 38% of the EU's demand (FCH, 2019). So together, Georgia and Spain could have the technical potential to provide around 44% of all EU's hydrogen needs.

4.4. Sub-question 5: Multi Criteria Analysis

In the MCA, the overall situation of both countries was analysed using a criteria framework develop based on literature on the subject, as described in the Theory section. The process behind each indicator and score calculation is described under the Methods section. Here the results of the analysis are presented, and briefly described. In the discussion section these results will be analysed and integrated with the other research results.

The criteria framework developed consisted of five main areas, of which four were analysed in this research, as explained in the Methods section. Below the specific scores for both Georgia and Spain for each indicator and criteria are grouped and presented for each of the general areas analysed. Scores, both on the criteria scale, for each general area and overall, range from 0-1, 1 being best possible situation for the development of a hydrogen economy and 0 worst possible situation.

4.4.1. Technical resources

The main technical resource required for green hydrogen production is availability of renewable energy resources. But for transition years, as has been previously established, natural gas could play a key role and therefore a country's capability to provide it could also have an impact, albeit maybe small. The results for the technical resources criteria are presented in Table 13. Both countries present good renewables resources, as previously described the Theory section and have a large share of them still untapped. Spain, nonetheless, has already deployed more of that potential than Georgia, which is why the eastern European country scores better on that criterion. They both score close to 0 on the natural gas criterion due to their almost negligent national production of gas, as they need to import almost all of their demand. Overall, Georgia has a score of 0.82 in this analysis area while Spain scores 0.72.

Table 13. Results for the criteria analysed in the technical resources area.

Criteria	Indicator	Value range	Score		Normalized score (0-1)	
			Georgia	*Spain*	*Georgia*	*Spain*
1A) Renewable energy resources	Untapped renewable energy technical potential	0-100%	95%	85%	**0.95**	**0.85**
1B) Natural gas supply	Share of own production in natural gas supply	0-100%	0.4%	0.2%	**0.004**	**0.002**

4.4.2. Economic framework

Here the country's economy for each country was analysed, as well as specific factors important for the development of a hydrogen value chain. Table 14 shows that overall Spain scores significantly better in this area than Georgia, being a more developed economy and part of the EU. Especially when it comes to existing and potential infrastructure, as well as the financing environment for new projects, there is a considerable gap. Spain also has some room for improvement, though, on all aspects but particularly in supporting research and innovation and also in developing trade possibilities for hydrogen-related sectors. Key industrial opportunities to boost hydrogen deployment in Spain are mainly in the oil and steel sector. Spain imports almost all of its crude oil needs (IEA, 2021), but it does have a sizable refining industry composed of 14 companies which generate an annual revenue of 47.2 billion € (Fernández, 2021). It also produces around 15Mtonnes of steel products per year (Spain Steel Production, n.d.). The fertilizer industry also provides opportunities for hydrogen but has been recently declining and currently Spain has to meet some of its demand with imports (Fertilizer Consumption, n.d.). However, recently the fertilizer producer Fertiberia and the energy firm

Iberdrola announced their plans to collaborate in the developing of a large green hydrogen plant for industrial production purposes, in this case, fertilizers, showing that there is interest within the country to deploy green hydrogen in this sector (Scott, 2020).

Table 14. Results from the analysed criteria in the economic framework area.

Criteria	Indicators	Value ranges	Score		Normalized score (0-1)		Criteria score	
			Georgia	*Spain*	*Georgia*	*Spain*	*Georgia*	*Spain*
2A) Synergy between economy and hydrogen value chain	Share of economic activities relevant to hydrogen economy	0-100%	30%	37%	0.30	0.37	**0.35**	**0.39**
	Share of exports relevant to hydrogen economy	0-100%	40%	41%	0.41	0.41		
2B) Infrastructure experience and potential	Quality of overall infrastructure index	1-7 (best)	3.92	5.51	0.56	0.79	**0.56**	**0.79**
2C) Access to finance	National credit rating	0-100	38.5	67.5	0.39	0.68	**0.39**	**0.58**
	Venture capital availability	1-7 (best)	2.71	3.42	0.39	0.49		
2D) Industrial clusters / niche markets	Presence of industrial centres for oil refining and/or production of steel, fertilizers	Existent/ Non-existent	Existent	Existent	1.00	1.00	**1.00**	**1.00**
	Presence of industrial port areas	Existent/ Non-existent	Existent	Existent	1.00	1.00		
2E) Research, develop-ment and innovation	Innovation aggregated indicator	1-7 (best)	2.80	3.70	0.40	0.53	**0.40**	**0.53**
2F) Interna-tional trade potential	Revealed comparative advantage	0-1	0.33	0.50	0.33	0.50	**0.33**	**0.50**

As for Georgia, albeit the limitations shown in some of the economic criteria, it still shows some potential as it also has a significant share of economic activity that could be linked to hydrogen demand, as well as specific key industrial niche markets mainly in the chemical sector.

Georgia has a large fertilizers industry, and its national production was enough to meet the country's requirements and export surplus for a value of 98.9 M€ in 2019, 2.34% of total exports value (The Observatory of Economic Complexity, n.d.). As for oil and steel, Georgia does not have significant industrial production (IEA, 2020a).

Finally, both countries have coastal areas in their territories with access to large ports (Dolbaia, 2016; González, 2012). This, as discussed in the Theory chapter, is important as these sites can be a starting point to boost both demand in the shipping sector and overall trade opportunities with other countries via marine transport. Specially in Georgia, with a prominent fertilizer industry and large production and exports of ammonia, this sector can be tied to shipping ports where it can be exported through the Black Sea, as hydrogen is usually required to be converted into other products to be transported by trucking or shipping anyway. This is due to the low energy density by volume of hydrogen (3 kWh/m^3). So hydrogen is commonly liquified or converted into ammonia, methanol, or synthetic fuels, which have higher energy density by volumes and therefore require less volumes of fuel to be moved in order to transport the same amount of energy (IRENA, 2021a).

Overall, Georgia has a score of 0.5 in this analysis area while Spain scores 0.63.

4.4.3. Policy framework

The results from the policy framework criteria are presented in Table 15 in the following page. Policy is where these two countries differ most in terms of being in good position to develop a hydrogen economy. Spain scores perfectly in its overall climate change policies, having clear and binding targets for both long term carbon neutral economy and renewable energy deployment. It also has support mechanisms for renewables in place and energy efficiency policies and targets. It can, however, improve specific policies to further support the implementation of hydrogen in the energy system, like setting firm targets or requiring stringent standards for emissions in heavy transport or specific industries. Overall it also has a good score in general political stability.

Georgia has a binding target for renewable energies and some energy efficiency measures in place and on their way to being implemented and has recently become part of the Energy Community. However, it does not have neither a long-term strategy for climate and energy or specific mentions of hydrogen in its current official national plans. Furthermore, political stability is an issue in the country due to concerns about some authoritarian tendencies of government as well as recent territorial disputes and conflicted relation with neighbouring Russia (Harris, 2018; Stronski, 2021).

Overall, Georgia has a score of 0.27 in this analysis area while Spain scores 0.68.

Table 15. Results from the criteria analysed in the policy framework area.

Criteria	Indicators	Value ranges	Score		Normalized score (0-1)		Criteria score	
			Georgia	*Spain*	*Georgia*	*Spain*	*Georgia*	*Spain*
3A) Climate change policy	Long term strategy	Existent/Non-existent	Non-existent	Existent	0	1	**0.5**	**1**
	Net-zero target	Existent/Non-existent	Non-existent	Existent	0	1		
	Liability of net-zero target	Binding/Non-binding	-	Binding	0	1		
	Renewable energy target	Existent/Non-existent	Existent	Existent	1	1		
	Liability of renewable energy target	Binding/Non-binding	Binding	Binding	1	1		
	Existence of clear and enforced renewable energy support scheme	Existent/Non-existent	Non-existent	Existent	0	1		
	Participation in global energy partnerships	Yes / No	Yes	Yes	1	1		
	Energy efficiency policies	Existent/Non-existent	Existent	Existent	1	1		
3B) Hydrogen development and hydrogen relevant policies	Existence of specific hydrogen roadmap/strategy	Existent/Non-existent	Non-existent	Existent	0	1	**0**	**0.4**
	Hydrogen target	Existent/Non-existent	Non-existent	Existent	0	1		
	Liability of hydrogen target	Binding/Non-binding	-	Non-binding	0	0		
	Are stringent emission standards set for heavy transport?	Yes / No	No	No	0	0		
	Existence of concrete policies for industrial decarbonization	Existent/Non-existent	Non-existent	Non-existent	0	0		
3E) General policy stability	Political stability index	-2,5 – 2,5	-0.45	0.32	0.32	0.63	**0.32**	**0.63**

4.4.4. Environmental context

The environmental context that could impact deployment of hydrogen production was analysed on two fronts for both countries. As results in Table 16 show, Georgia has close to a perfect score, meaning there is little to no concern that environmental factors could deter hydrogen deployment. Spain also has a good score but compared with Georgia there is factors that should be monitored. Although land requirements for a carbon neutral system are minimal in both countries, a large share of Spanish land is already under agricultural use, which is why further expansion of hydrogen production (for example for exports) could potentially result in land use conflicts in some regions or specific projects. Moreover, Spain, particularly its southern region, could experience some periods of water stress and scarcity in the future, which could in some regions tamper with hydrogen production.

Overall, Georgia has a score of 0.95 for this analysis area while Spain scores 0.7.

Table 16. Results from the criteria analysed in the environmental context area.

Criteria	Indicators	Value ranges	Score		Normalised score (0-1)		Criteria score	
			Georgia	*Spain*	*Georgia*	*Spain*	*Georgia*	*Spain*
4A) Water supply sustainability	Baseline water stress	0-100%	5.9%	42.6%	0.94	0.57	**0.94**	**0.57**
4B) Land use conflict	Estimate % of land needed for renewable power generation in carbon neutral system	0-100%	0.14%	0.27%	0.999	0.997	**0.97**	**0.83**
	% Of total country area cultivated	0-100%	6.4%	33.6%	0.94	0.66		

4.4.5. Social context

As explained in the Theory chapter, social acceptance of hydrogen is a determining factor for its success. Generally, studies have found that awareness of environmental disruption is at a high level and even in societies where modern energy technologies are not popular there is a motivation to apply changes that will foster the environment (Ingaldi & Klimecka-Tatar, 2020). However, knowledge about hydrogen as an energy source and related technologies is very low, and concerns exist about safety and availability issues with hydrogen use and technologies (Ingaldi & Klimecka-Tatar, 2020).

Recent results from the HYACINTH project by the FCH on European countries generally show a neutral to positive first opinion towards the use of hydrogen and fuel cell technologies, although only around 6% of respondents consider themselves to be familiar with the technology (Oltra, 2016). In Spain, particularly, awareness levels (i.e. having ever heard of hydrogen and/or fuel cell technologies in the context of energy production) are rather low at 29%, but acceptance upon being informed is high for residential fuel cell and hydrogen fuel cell electric vehicle (HFCEV) applications, as shown in Figure 55 and Figure 56 below (Oltra, Dütschke, Sala, Schneider, & Upham, 2017; Oltra et. al, 2017).

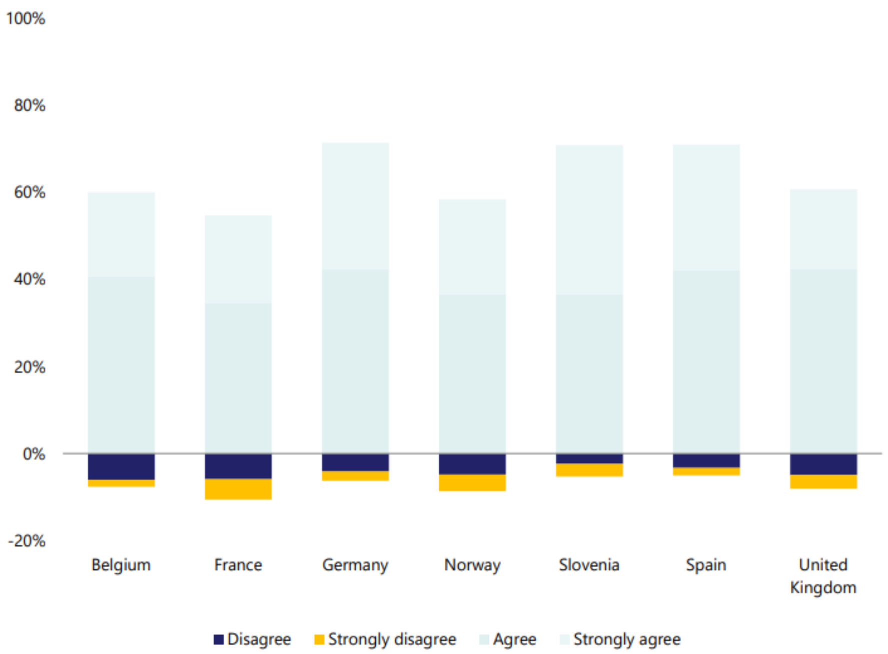

Figure 55. Social acceptance of residential hydrogen fuel cells (% of respondents that would like to have a hydrogen fuel cell system in their home) (Oltra, Dütschke, Sala, Schneider, & Upham, 2017).

Figure 56. Social acceptance of HFCEV (% of respondents that would like to have a HFCEV) (Oltra et al., 2017).

Unfortunately, no studies are available in Georgia neither on social acceptance of hydrogen nor on general attitudes towards renewables. Overall, studies and surveys analysed on public attitudes and views in the country did not mention renewable energy technologies or hydrogen at any point (National Democratic Institute, 2016; Sichinava, 2021; Woodward, 2012)

4.4.6. Overall results

Lastly, the results are integrated into a final score, as Figure 57 and Figure 58 show. Spain has a slightly better apparent situation for hydrogen development than Georgia. The former scored 0.72 overall in the MCA while the latter sits at 0.65. Both countries have good technical resources and Georgia gets the edge in potential environmental issues, but Spain economic and political context is significantly better positioned to start a hydrogen transition. Social context is left out of this final calculation because, as discussed in the Methods section, it is addressed only from a qualitative perspective.

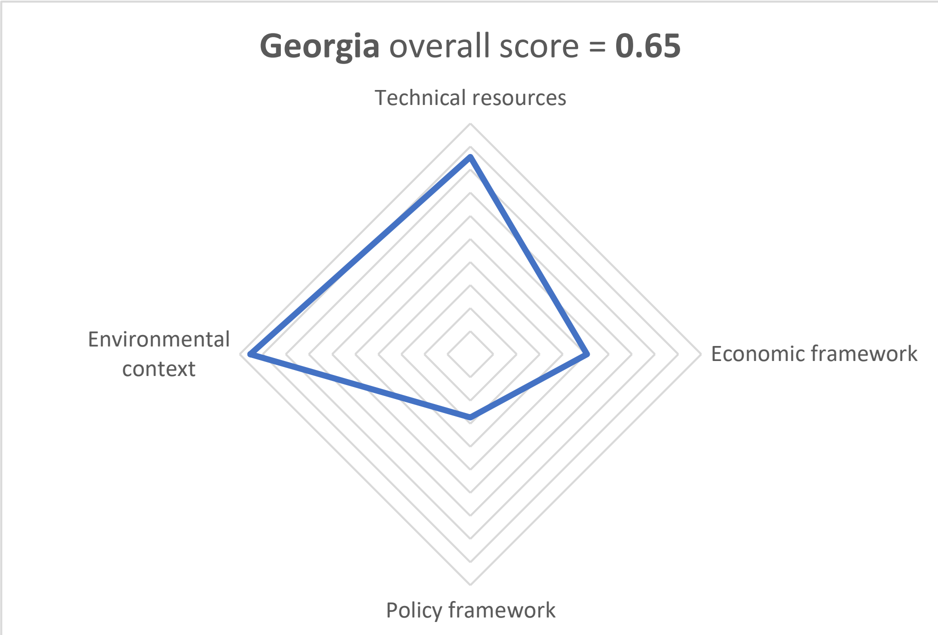

Figure 57. Final score of MCA and contributions from different framework analysis areas for Georgia.

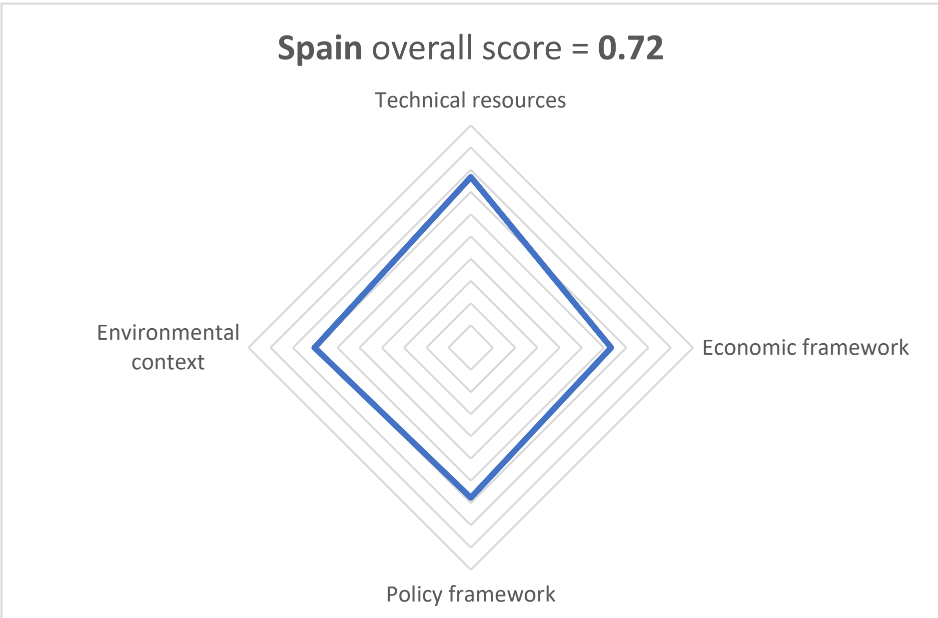

Figure 58. Final score of MCA and contributions from different framework analysis areas for Spain.

5. Discussion

This research aimed at expanding assessments of countries' potential to produce green hydrogen by combining techno-economic analysis with a broader framework based on interdisciplinary criteria from different areas of knowledge and testing that framework in case studies of Georgia and Spain. Here the results obtained and described in the previous chapter are further analysed and contextualized in order to answer the established research sub-questions. Next the limitations of the research process and potential improvements are discussed. Afterwards, the main research question is answered in the Conclusions.

5.1. Results discussion and answer to research sub-questions

5.1.1. Research sub-question 1: Hydrogen demand

The first research sub-question addresses the potential demand size for hydrogen in both countries via energy system modelling with the LEAP software. Results from the models establish that both countries could satisfy up to 40% of their final energy demand with hydrogen and derived products by 2050 in a carbon neutral economy. It has to be noted that final energy demand has decreased then by 37.6% in Spain and increased by 18.6% in Georgia as compared to the present. The 40% of final energy by hydrogen result is an unexpectedly high value compared to other existing projections by the EU and related agencies. As explained in the Results section, this can be attributed to several identifiable factors, mainly: discrepancies in assumptions regarding degree of electrification in road transport vehicles; increased hydrogen demand in industry in this research in order to reach zero emissions; and not considering in this research the potential use of other renewable fuels like hydrogen downstream products (i.e. ammonia, synthetic hydrocarbons) or biofuels . Nevertheless, the model provides an upper estimate value that is useful to assess whether these countries could provide the levels of green hydrogen and derived products a carbon neutral energy system might end up requiring. The models developed, albeit limited by simplifications and assumptions that will be addressed in the coming sections, manages to predict future energy consumption developments, as seen by comparing results from Spain with official governmental projections in its climate neutrality scenario (Ministerio para la transición ecologica y reto demográfico, 2020a).

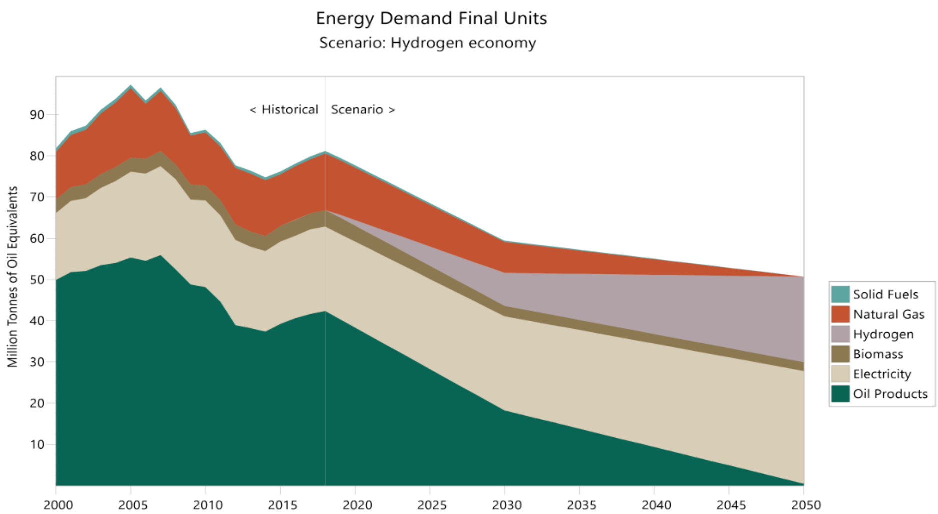

Figure 59. Final energy demand projected with the LEAP energy model in Spain (own calculation).

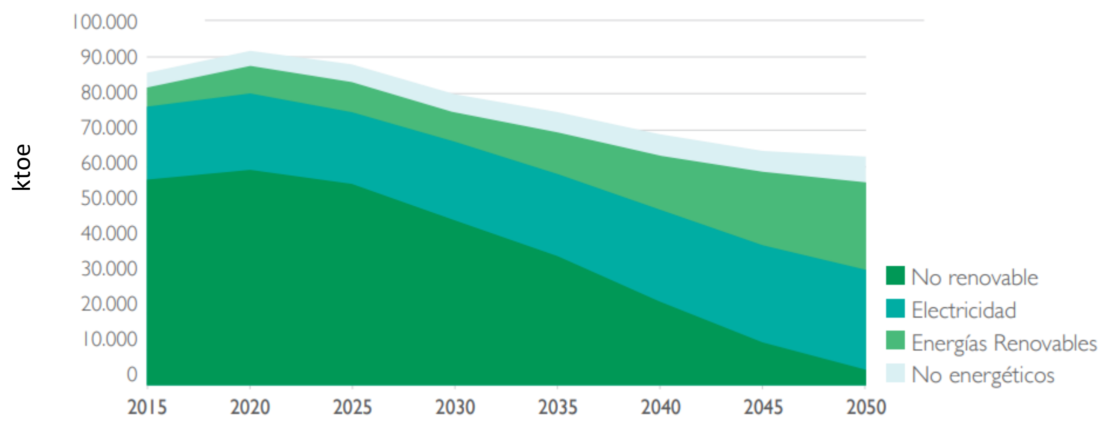

Figure 60. Final energy demand in Spain in ktoe according to a government climate neutrality scenario (Ministerio para la transición ecológica y el reto demográfico, 2020a).

Final consumption sits at 50 Mtoe in 2050 in this research projections (Figure 59) while in the official Spanish report is expected to be around 60 Mtoe (Figure 60) (Ministerio para la transición ecológica y el reto demográfico, 2020a). Moreover, the shares of electricity and direct renewable fuels (i.e. hydrogen, biomass, etc.) are on the same ranges similar as well. Unfortunately, no such projections exist yet for Georgia, so no comparison can be made. However, the proof of concept for the model seems to work for the purposes of this research framework, which is to provide a good overview of potential developments in the energy system that can later be used to make a more informed analysis on hydrogen deployment potentials.

Overall the models project that Spain could need up to 7 Mtonnes of green hydrogen annually to achieve climate neutrality in 2050 and Georgia 0.7 Mtonnes per year. Compared to current consumption levels (e.g. 500 ktonnes/year in Spain), this is a sizeable increase which would drastically impact the structure of the energy system in any country.

5.1.2. Research sub-question 2: Energy system impacts and challenges

As addressed in sub-question 2, the most important effect of scaling up green hydrogen production requirements to this extend is the consequential need for renewable electricity to power it. As seen in the Results section, electricity demand in Georgia already doubles in 2030 and is almost five times higher than 2018 levels by mid-century under this scenario. This obliges wind and hydro resources to be pushed close to their maximum potentials and requires solar PV in the country to expand from the planned 520 MW of installed capacity for 2030 to a massive 14 GW capacity deployment by 2050. In Spain, similar results are found. Producing all required hydrogen from electrolysis causes electricity demand to more than double between now and 2050 and forces wind and PV, the largest renewable resources in the country, to be expanded from 23.4 GW and 4.8 GW respectively in 2018 to around 140 GW each by mid-century. Moreover, and even though this is not quantitatively incorporated in the research framework, this kind of electricity generation deployment would require significant additions to the power system infrastructure and grid capabilities, which further challenges this transition.

But, although renewables requirements is the most important direct impact from it by far, developing a hydrogen economy also poses other challenges to both Georgia and Spain. As explained in the Theory chapter, various reports point at the importance of blue hydrogen to assist the development of hydrogen infrastructure and value chains during the coming years while electrolyser technologies keep developing ad scaling up. Since neither Georgia nor Spain produce significant amounts of natural gas, this could potentially deepen their dependence on imports for their energy demands and challenge their energy self-sufficiency and security in the coming years, especially up to 2030, as seen in the Results chapter.

5.1.3. Research sub-question 3: Hydrogen production costs

Next, in sub-question 3 the economic component of hydrogen development is introduced to the research as the cost of production for the main involved technologies are assessed. Results from this sub-question show that first of all, it is very unlikely that any alternative technologies would be able to economically compete with grey hydrogen without the immediate implementation of very stringent carbon pricing that increases even further in the future. On the other hand, if the required CO2 prices are imposed, blue hydrogen could already be competitive today in both Georgia and Spain at 1.6 €/kg H2 and 2.1 €/kg H2 respectively which strengthens its case as a transition fuel during the next decade for the deployment of hydrogen infrastructures and creation of demand. Nevertheless, careful analysis on the future impacts of largely deploying blue hydrogen is needed. Due to the investments and payback periods, focusing now on blue hydrogen could lead to unexpected rebound effects as industries and governments might find themselves locked into fossil fuel technologies long-term like natural gas production and distribution infrastructure. Therefore the right balance between rapid overall adoption of hydrogen use by deploying blue hydrogen and long-term focus on the development of green hydrogen must be studied and discussed.

As for costs of hydrogen produced from electrolysis, the results show that stand-alone RES/electrolyser systems are limited, both at the moment in the short-term future, by low annual load hours which amplify the impact of electrolysers' high CAPEX on total cost of production. In Spain, grid-powered electrolysis does not fare much better due to historically high electricity prices in recent years. In Georgia, however, thanks to its vast hydropower resources, cheap electricity makes grid-connected hydrogen production the best economic option for green hydrogen in the country short term at cost ranges of 2.5-3.3 €/kg H2 at the moment and 2.3-2.8 €/kg H2 in 2030 and could be a starting point for deployment of electrolysis in the country. Long term, the uncertainties regarding both cost of renewables (specially wind and PV) and costs of electrolyser make it difficult to predict the developments for green hydrogen production costs. However, some overall trends can be extracted from the results. In Georgia, electrolysis powered by solar PV is the most uncertain technology, with higher estimates caping its development at 3.6 €/kg H2 by 2050 while lower estimates see it decreasing as much as to 1.3 €/kg H2. Consequently, there could be higher risks associated with focusing on this technology and it might be a good option for Georgia to await future developments to commit policies and/or resources and begin the deployment of stand-alone hydrogen plants with wind-powered electrolysis instead, which in these projections appears to have a more certain future with higher cost estimates of only 2.3 €/kg H2 in 2050 and potentially as low as 1.1 €/kg H2 in the lower estimates. Regarding stand-alone production from hydropower, the limited expected developments in hydropower technology and price narrow the margin for cost reduction of hydrogen production. However, since Georgia's electricity production already consists mostly of hydropower, it could be a better option to produce hydrogen close to existing hydropower plants but in a grid-connected configuration that would allow for increased load hours in periods with low hydro production. This could benefit from decreased costs of grid-connected production by 2050, ranging from 1.8 to 2.3 €/kg H2.

In Spain, the use of hydropower for green hydrogen production is not considered a real option so far, as demonstrated by its lack of mention in the national hydrogen strategy. The costs projected in the results range 2.2-4.4 €/kg H2 long-term and considering Spain has already allocated much of its hydro resources to electricity generation, it seems unlikely that the country would opt for this technology. PV and wind stand-alone configurations project to be better long-term options, albeit the uncertainties, with costs of 1.1-2.9 €/kg H2 and 1.4-3 €/kg H2 respectively. If the most optimistic technological assumptions are realised, Spain could potentially produce green hydrogen both from wind and from solar PV at considerably cheap costs. Moreover, as its power system converts to 100% renewables by 2050 causing electricity prices to decrease, grid-connected production also becomes a competitive option (costs of 1.4-2 €/kg H2) to not only produce hydrogen but also help integrate large shares of VRES in the system.

5.1.4. Research sub-question 4: Electrolyser requirements and export potentials

In sub-question 4 further impacts and possibilities from a hydrogen-based energy system in Georgia and Spain are assessed. It is found, as expected, that producing all the green hydrogen required in long-term carbon neutral scenarios would result in large installed capacities of electrolysers. In Spain, fulfilling the national target of 4 GW installed by 2030 would only cover the lowest estimate needed in this model, and requirements could end up being as high as 18 GW. By 2050, those values increase to 32-144 GW. Again, this very wide ranges are a result from technological uncertainty, in this case regarding load hours of hydrogen production plants. In Georgia there is no comparison to be made because there are not either targets or current installed electrolysers in the country but transitioning from that to the required 0.4-2.2 GW by 2030 in just ten years might prove challenging.

Additionally, sub-question 4 looked at potential exports from both these countries. Assuming no limitations for installed electrolysers and renewables except for the country's technical resources, it is calculated that Georgia could export almost 4 Mtonnes of green hydrogen annually by 2050 and Spain up to 25.7 Mtonnes/year. Together this would be enough to meet around 44% of the projected hydrogen demand of the EU. This, however, would require the right policies to be implemented, sufficient investments and resources expended, the necessary infrastructure developed, not to conflict with the environmental sustainability of the countries and not face strong opposition from the general population.

5.1.5. Research sub-question 5: Multi Criteria Analysis

Consequently, in sub-question 5 all the aforementioned issues are addressed by broadening the scope of the research to include a wide variety of qualitative aspects which are assessed in an MCA. The results from this analysis indicate that overall both countries have positive conditions for hydrogen development but with room for improvement in particular areas, as the scores of 0.65 for Georgia and 0.72 for Spain in a scale of 0 to 1 demonstrate. It is established establish that, notwithstanding some differences in favour of Georgia, both countries should not be limited by technical or environmental factors in the transition to a hydrogen-based energy system, albeit some minor risks regarding land use and water supply in Spain. However, they could benefit from improvements in their economic environments, particularly regarding access to finance for new projects, overall innovation and research support and international trade possibilities. Spain should also begin to establish specific policies to facilitate hydrogen penetration in key sectors like freight transport and some industries. As for Georgian policy, it seems to be the most likely factor to limit or derail hydrogen development in the country, as no long-term strategy for carbon neutrality is in place and policy stability is a worrisome issue in the country.

5.2. Research framework and process limitations

Overall, the aim of the research to develop a framework that allowed evaluation of countries potential beyond technical capabilities is considered achieved, as is the goal to use this framework to study Georgia and Spain as potential hydrogen producers. However, the implementation of such a framework with a diverse arrange of methods and areas of analysis has some limitations, particularly under the scope of a Master Thesis research project. Generally, there is a trade-off between expanding the number of methods and areas of analysis and the depth at which these areas can be analysed. In this case, this has consequences in several aspects of the methodology used which have to be considered when analysing the results and could be improved upon in further research. In the following paragraphs, these limitations are discussed for the different parts of the research.

5.2.1. LEAP energy models

The models built for the Georgian and Spanish energy systems were projected using a simple top-down approach based on energy intensities and GDP/population data. This approach, although able to provide a general picture of overall developments in a specific country, fails to capture accurate information for each specific sector. When building the Energy Transition scenario, the same energy efficiency targets are applied to all sectors of the economy. This is clearly not realistic since some sectors and end-uses have more potential for energy savings than others. This could be improved upon with a more detailed approach per economic activity, maybe even bottom up in some cases such as road vehicle transport for passengers. Furthermore, energy savings are not applied to non-energy uses. Although this is no part of direct energy efficiency measures, other sustainability developments like a boost of circular economy activities could decrease the demand for feedstock in industries like plastic or manufacturing (Sen, Meini, Napoli, & Foundation, 2021). This impacts the results for total consumption in non-energy uses, which is significant since under the hydrogen economy scenario, is the only economic activity which still uses fossil fuels in 2050.

Another limitation is that when expanding to the hydrogen economy scenario, only the use and production of pure hydrogen is incorporated into the model. This is one of the reasons why the model developed tends to overshoot on hydrogen demand in Georgia and Spain, reaching around 40% of final consumption by 2050 in both cases. Other motives for this are analysed in pages 46 and 47 under the Results chapter and mainly consist of discrepancy of results and assumptions regarding electrification of freight road transport and degree of decarbonisation in industry. For a different research approach more detailed into individual sectors might be more limited by these simplifications, but for research looking at the potential overall role of hydrogen to achieve net-zero emissions, it provides interesting results.

Lastly, a simplification included in this model is that it does not account for transportation and distribution losses in energy supply. This is obviously unrealistic and would increase the size of primary energy demand for the countries by a not insignificant margin. Also, due to time limitations the model was reserved to energy analysis only, and therefore does not include calculations for greenhouse gas emissions. Instead, fossil fuel supply is used in the results to show the impact of the different scenarios in reducing energy-related emissions. Both these factors could be improved upon in the future and would definitely provide both more accuracy on existing results as well as new, interesting results regarding mitigation.

5.2.2. Costs and export calculations

When calculating the costs of hydrogen production, several factors affect the reliability and accuracy of results. In the first place, the fact that electrolysers are not a widely deployed technology results in very large uncertainties regarding its cost in the future. Even within literature, projections vary significantly when it comes to assessing potential future CAPEX costs of electrolysers. For example, while the IEA (2019) estimates the lower possible costs in 2030 to be around 400 US$/kW, the Hydrogen Council (2021b) projects costs to potentially be as low as 130 US$/kW in 2030. Furthermore, each specific projection generally has wide ranges of values. This heavily impacts the calculations for stand-alone green hydrogen production routes, which result in large differences between higher and lower cost estimates, as explained during the Results chapter.

Secondly, electricity prices also play a role in cost developments, particularly in grid-connected production (see Figure 43 and Figure 50). Therefore, the assumptions and uncertainties surrounding the LCOE calculations used in this research make an impact on final costs results. For instance CAPEX costs of VRES, albeit not as much as electrolyser, also present uncertainties as regards to future developments, and different ranges of values can be found, as explained in Appendix B. Additionally, the assumptions made for interest rates of renewables projects are not either country or technology specific, which is a simplification that could vary the results as well. Likewise, these interest rates, as well as economic lifetimes, are assumed static in the future. This is also the case in the assumptions for electrolysers. These factors will probably change in the future, though, and that is not captured accurately in this research.

Another very important assumption for these results is the values for CO2 certificates prices and the implementation of carbon pricing. In this research, for results introducing carbon pricing, it is assumed that no free allocations exist and that the EU's Emission Trading System (ETS) covers all emissions derived from hydrogen production. Price values for CO2 assumed are rather high starting at 68 €/t CO2 for both countries. During 2021, however, the daily price of CO2 in the EU's ETS increased from around 30 €/t CO2 in the beginning of the year to peaks of almost 60 €/t CO2 (Daily Carbon Prices, n.d.). Furthermore, Georgia, not being a part of the EU, is not currently subject to any carbon pricing measures, contrarily to the assumptions made here. Although a deviation from reality, these assumptions are made in order to assess required developments for blue and green hydrogen to potentially be competitive with grey hydrogen.

Finally, in this research costs calculations are limited to exclusively hydrogen production. However, for complete analysis on region-specific hydrogen costs, storage, transport, and distribution costs should also be incorporated into the discussion. This is important not only for overall costs results but for the assessments of specific countries, since their location and conditions could impact how hydrogen it is transported and potentially exported and the impacts of these differences on final costs. The Hydrogen Council (2021b) has shown, for example, that pipelines transport is the most economic option but is not fitted for very long distances transport, where more expensive shipping transport would need to be deployed.

As for the calculations of potential exports from Georgia and Spain, the main limitation comes from assuming that technical renewable energy resources in these countries are fully exploited, which is not realistic. Furthermore, since it is assumed that for the countries to export green hydrogen, they first need to meet own demands for a carbon neutral system, uncertainties and limitations in the LEAP energy models used to find these demands are also carried into these calculations.

5.2.3. Criteria framework and Multi Criteria Analysis

In part of this research a criteria framework is developed to evaluate countries' potential to develop green hydrogen from a wide range of influencing factors. Due to the scope and time constraints of the research, this framework shows some limitations and areas where it can be expanded upon and improved, which are addressed below.

In the technical resources, more indicators could be developed to evaluate energy resources. For example having different indicators for each renewable technology and weighting them so good resources in technologies that produce green hydrogen at lower costs carry more value. Moreover, existing surplus of electricity could be added as an indicator by assessing the countries imports or exports of electricity.

In the economic area of the analysis it should be discussed whether potential redundancies exist between criterion 2D (key industrial clusters) and indicators for criteria 2A and 2B (hydrogen infrastructure and value chain). In this research an argument is made that while there might be some overlapping, it is important to single out the specific importance of these key industrial sectors to scale through the hydrogen equipment value chain (Hydrogen Council, 2021b). Nonetheless, further analysis of this matter is needed to improve the framework.

For the policy analysis, the main limitation in this research is that when implementing the MCA, almost all indicators under this area are converted into binary (i.e. existence or not of specific policies or targets). Further work should be done to develop indicators and scoring systems that can better capture gradual differences between existing policies, targets, and their implementation.

The analysis of the environmental context is limited to potential land use and water supply issues, but it could also expand to analyse impacts on biodiversity in the sites where hydrogen plants are constructed and also in the areas where the renewable technologies required are installed.

As for the social context, it is the main limitation of the MCA since its criteria are not incorporated in the quantitative analysis. Therefore the first step to improve the framework in this regard is to develop indicators that can quantitatively capture the information under the social acceptance criteria in the countries. The need to combine qualitative and quantitative approaches in this regard has already been mentioned in literature (Heras-Saizarbitoria, Cilleruelo, & Zamanillo, 2011).

Furthermore, weighting of criteria should be established not only for the technical resources and then the final score calculation, but for each criterion in all the framework areas of analysis. This would add value to the results and better account for the importance of the different factors influencing hydrogen potential. Similarly to the costs part of the research, a limitation here is the lack of focus on hydrogen transport and distribution. As previously mentioned, the location and transport and distribution possibilities for each country is relevant to the overall interest in developing green hydrogen in a particular country. Therefore another way to improve this framework could be to add more specific criteria addressing these factors.

Finally, the dynamic nature of all these criteria also limit the framework's ability to predict whether a country could be successful in developing a green hydrogen value chain. Therefore it should be studies how to account for that when possible, using for example existing future projections for some of the indicators used.

6. Conclusions

The aim of this research was to develop a framework that could combine technical analysis and the inclusion of determining factors for deployment of green hydrogen in particular countries and use that framework to evaluate the possibilities for Georgia and Spain to develop large scale production of green hydrogen and potentially exports to the EU.

To achieve this goal, in the Introduction the following main research question was posed:

How well are Spain and Georgia positioned to transition into a hydrogen economy and become large scale producers of green hydrogen and potential exporters to the EU?

To answer it, several sub-questions were addressed using a variety of methods and areas of analysis, as explained through the Results and Discussion chapters. The research results have shown that for Georgia and Spain to achieve climate neutrality in 2050, hydrogen and derived products could be required to provide around 40% of their respective final energy demand. To do so, 0.7 Mtonnes of hydrogen must be produced annually from renewable sources in Georgia, and 7.1 Mtonnes in Spain. This would correspond to having installed electrolyser capacities between 3 GW and 14 GW in the case of Georgia, and between 32 GW and 144 GW for Spain. Consequently, a massive deployment of renewable power generation is also required. Even by achieving, in the case of Spain, national targets for installed electrolyser capacity and renewables, there is not sufficient green hydrogen production to meet the required demand by 2030. So, blue hydrogen could play a prominent role in the coming decade to develop the hydrogen infrastructure and value chain needed to eventually have a green hydrogen-based, carbon neutral energy system by 2050. However, it is very important that this is done carefully in order to not cause any lock-in effects for natural gas and related technologies. For instance, by retrofitting gas networks and distribution infrastructures and building SMR plants, investment depreciation might force this these technologies to extend their lifetimes and the use of natural gas beyond what climate strategies establish. The potential need for blue hydrogen as a transition fuel mostly stems from economic competitive factors. In spite of the promising renewables resource potentials in both countries, projections made do not see any scenario in which green hydrogen can be produced at costs below 2 €/kgH2 either now or in the short-term future, and costs for some technologies are significantly high in the coming years. On the other hand, blue hydrogen is able to compete with grey hydrogen in both countries within the next decade at costs close to 1.5 €/kgH2, as long as stringent carbon pricing measures are implemented. Long-term, albeit uncertainties are considerable, green hydrogen could become competitive in both countries and be produced at a cost of 1.1 €/kgH2 in the best-case scenarios.

Both countries have the sufficient renewable energy resources to support this expansion of green hydrogen, but it will also require the confluence of the right policies and economic environments as well as social acceptance from the population. Results from the Multi-Criteria Analysis have shown that Spain has a well-balanced situation across determining factors, with a score of 0.72 out of 1, but would benefit from creating binding policies specifically designed to support green hydrogen, as well as from facilitating innovation and access to finance. On the other hand, Georgia has glaring limitations to address in terms of strategic energy policies and access to financing for new projects.

On the whole, Georgia is assessed to have an average to good starting position for green hydrogen development but easily improvable by policy support and continued economic development. Meanwhile, Spain is assessed to have a good to great starting position, with concrete issues regarding policies and economic environment for innovation which, if addressed, could make it a leading European country in green hydrogen and related technologies.

From the EU's point of view, Spain would seem like the better and safer choice at the moment to invest resources and create both production and demand centres within the EU. Results have shown that at its maximum deployment, Spain could supply close to 38% of hydrogen demand in Europe by 2050. Not only that, but Spain could be integrated in the middle of a green hydrogen import route from North African countries with vast solar resources, a possibility already analysed in literature. At the same time, though, Georgia does present promising signs and has shown interest in green hydrogen recently. Moreover, thanks to its strategic location, it could play a role similar to mentioned for Spain as a distribution hub at the end of a green hydrogen import route, in this case from Middle Eastern and Central Asian countries.

Both countries are therefore encouraging to be studied further in future research, especially within the European imports context and expanding analysis to include transportation and distribution costs and possibilities. Furthermore, the general research framework developed here could also be expanded and improved upon by addressing the limitations and recommendations discussed in section 5.2.

Overall, even with the limitations and constraints that applied to this research, the developed framework is considered successful in being able to provide a good overview of the potential for green hydrogen developments in different countries. Despite the limitations and simplifications in the process the specific case studies of Spain and Georgia have provided useful insight into the country's general estate and the impacts and challenges of producing green hydrogen there. Finally, this is a good starting point for more detailed research both on the countries analysed and also by improving the framework and applying it to other regions

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Appendix A

Energy Models Assumptions and Input Data

Input data and assumptions for electricity generation modules

- Efficiency of renewable technologies (PV, CSP, wind, and hydro) is assumed 100% as is typically done in energy statistics, except for generation from biomass and waste, established at 30% from current working plants data (Bain & Overend, 2015).
- Efficiency of nuclear is assumed to be 33% (Andrews & Jelley, 2017).
- Average efficiency for oil and coal power plants is assumed at 38% (Who has most efficient power plant, 2017).
- Efficiency for combined cycle gas plants is assumed at 60% (Natural gas power plant, n.d.).
- Average capacity factors are calculated for each country based on recent years generation and installed capacity data (Potencia Instalada (MW), n.d.; Georgia Energy Balances 2000-2019, n.d.). They are assumed to remain constant for all technologies except wind, solar PV and CSP, where some improvements derived from technological developments are expected. Table 17 below shows the load factors used per energy source and country until 2050.

Table 17. Capacity factors used in this research for different technologies in Georgia and Spain.

Capacity factor (%)		**2020**	**2030**	**2050**
Georgia	Natural gas	31%	31%	31%
	Oil	50%	50%	50%
	Solar PV	15%	17%	20%
	Wind	40%	40%	40%
	Hydropower	35%	35%	35%
Spain	Nuclear	85%	85%	85%
	Solar PV	17%	20%	25%
	CSP	18%	20%	30%
	Wind	25%	25%	30%
	Hydropower	20%	20%	20%
	Waste, biomass, and other renewables	68%	68%	68%
	Natural gas	26%	26%	26%
	Oil	45%	45%	45%
	Coal	43%	43%	43%

Installed capacity data in Spain is retrieved up to 2021 from (Potencia Instalada (MW), n.d.). In the BAU scenario (Table 18), development for all technologies is assumed as planned by the government (Ministerio para la transición ecologica y reto demográfico, 2020c) until 2030 with the exception of all non-hydro renewables which are assumed to remain static. Since this installed capacity is sufficient to meet projected demand until 2050, no new additions are made in that time.

Table 18. Electricity generation installed capacity in Spain under BAU scenario.

Installed capacity (GW)	2021	2030	2050
Hydro	20.4	24.1	24.1
Nuclear	7.1	3.2	3
Coal	4.9	0	0
Oil	0.8	0	0
Gas	33.6	32.1	32
Wind	27.8	27.8	27.8
PV	13.1	13.1	13.1
Solar CSP	2.3	2.3	2.3
Waste and other renewables	1.7	0.4	0.4
Biogas	-	0	0
Biomass	-	0	0

In the Energy Transition scenario (Table 19) the plan for installed capacity by the government is applied in all technologies for 2030. By 2050, total capacity is increased to 200 GW to meet demand and the power system is assumed 100% renewable. All renewable technologies are assumed to keep the same share in production, except wind and solar PV which are assumed to expand further and replace phasing out gas and nuclear production.

Table 19. Electricity generation installed capacity in Spain under Energy Transition scenario.

Installed capacity (GW)	2021	2030	2050
Hydro	20.4	24.1	30.5
Nuclear	7.1	3.2	0
Coal	4.9	0	0
Oil	0.8	0	0
Gas	33.6	32.1	0
Wind	27.8	50.3	87.9
PV	13.1	39.2	69.8
Solar CSP	2.3	7.3	9.2
Waste and other renewables	1.7	0.4	0.5
Biogas	-	0.2	0.3
Biomass	-	1.4	1.8

In the Hydrogen Economy scenario (Table 20), same developments are assumed as the energy transition, but to cover the increasing demand in 2050 several assumptions are incorporated:

- Hydro is pushed to realize its technical potential in the country
- CSP doubles its capacity from 2030
- Wind and solar PV provide all the rest of the added requirements

Table 20. Electricity generation installed capacity in Spain under Hydrogen Economy scenario.

Installed capacity (GW)	2021	2030	2050
Hydro	20.4	24.1	33
Nuclear	7.1	3.2	0
Coal	4.9	0	0
Oil	0.8	0	0
Gas	33.6	32.1	0
Wind	27.8	50.3	138.3
PV	13.1	39.2	145.4
Solar CSP	2.3	7.3	15
Waste and other renewables	1.7	0.4	0.5
Biogas	-	0.2	0.3
Biomass	-	1.4	1.8

In Georgia, for the Energy Transition scenario (Table 22) the exact capacities planned by the government (GSE, 2021) are used until 2030. By 2050, phasing out of natural gas is assumed. In the BAU (Table 21) the same values are also utilised, but it is assumed that no future deployment of PV is developed in the country, and natural gas is kept long-term. In both cases, capacity installed by 2030 is sufficient to meet demand until mid-century so no new capacities are added.

Table 21. Electricity generation installed capacity in Georgia under BAU scenario.

Installed capacity (MW)	2021	2030	2050
Hydro	3323	7188	7188
Natural gas	1189	1358	1358
PV	0	0	0
Wind	21	1330	1330

Table 22. Electricity generation installed capacity in Georgia under Energy Transition scenario.

Installed capacity (MW)	2021	2030	2050
Hydro	3323	7188	7188
Natural gas	1189	1358	0
PV	0	520	520
Wind	21	1330	1330

In the Hydrogen Economy scenario (Table 23), hydro is assumed to meet its economic potential (Hydropower Development in Georgia, n.d.), wind to be increased to its technical potential (UNPD, 2012), and rest of the requirements to be met by expansion of solar PV.

Table 23. Electricity generation installed capacity in Georgia under Hydrogen Economy scenario.

Installed capacity (MW)	2021	2030	2050
Hydro	3323	7188	8806
Natural gas	1189	1358	0
PV	0	520	14000
Wind	21	1330	2300

Input data and assumptions for hydrogen generation.

Since only one hydrogen production module is established, the efficiency used is an average of the different lower and higher estimates for different technologies (i.e. alkaline and PEM) by the IEA (2019) (Table 24). Electrolysis is assumed to increasingly produce hydrogen up to 30% of demand in 2030 and 100% in 2050.

Table 24. Input data and assumptions for hydrogen generation in LEAP energy model.

	Process efficiency (%)		Process share (%)	
	SMR	Electrolysis	SMR	Electrolysis
2020	76%	62%	95%	5%
2030	76%	67%	70%	30%
2050	76%	73%	0%	100%

Input data and assumptions for heat generation in Georgia

For district heating in Georgia, geothermal resources are available and recently solar thermal energy has begun to be deployed. Continuing that trend, the shares in Table 25 below are assumed for heat generation in the country. In the BAU scenario there is less penetration of solar energy in heat generation as recent trends continue, while in the energy transition and hydrogen economy scenarios development of solar energy is pushed in this sector.

Table 25. Input data and assumptions for heat generation in Georgia in LEAP energy model under different scenarios.

	Geothermal		Solar thermal	
	BAU	ET/HE	BAU	ET/HE
2018	85%	85%	15%	15%
2030	83%	76%	17%	24%
2050	80%	60%	20%	40%

Input data and assumptions for energy demand

For 2030, national targets are utilised for both countries. In 2050, assumptions are made for Georgia to catch up with EU 2030 targets and for Spain to slightly improve on Europe's 41% target for 2050, as the cited report is almost a decade old.

Table 26. Final energy savings assumed as share of total consumption assumed for the energy transition and hydrogen economy scenarios.

	2030	2050	Sources
Georgia	11%	32.5%	(Government of Georgia, 2017)
Spain	32.5%	50%	(Ministerio para la transición ecologica y reto demográfico, 2020c; European Commission, 2012)

Levelized Costs of Electricity Inputs for Hydrogen Costs Calculations

When calculating LCOH to answer research sub-question 3, LCOE for renewable generation technologies is needed as input. Region-specific calculations are made in this research for cost of PV and wind in Georgia and Spain. Hydropower is assumed to have a cost of 36.67 €/MWh similar to world average costs in both countries (IRENA, 2020b).

For wind and PV, LCOE are calculated using the following formulas:

$$LCOE_{wind}\ (€/MWh) = \frac{\alpha * CAPEX\ (€/kW) + OPEX\ (€/kW)}{CF(\%) * 8760h} * 1000$$

$$LCOE_{PV}\ (€/MWh) = \frac{\alpha * CAPEX\ (€/kW_p) + OPEX\ (€/kW_p)}{PV_{OUT}\ (kWh/kW_p/day) * 365d} * 1000$$

Where α is the annuity factor

$$\alpha = \frac{r * (1+r)^t}{(1+r)^t - 1}$$

Below the input data for these calculations is shown, both at the technological level (Table 27 and Table 28) and for country specific conditions (Table 29).

Table 27. Technology data inputs for calculation of wind energy LCOE.

Wind	2020	2030	2050	Sources
CAPEX (US$/kW)	1400-2000	1100-1200	650-800	Own calculation
OPEX (% of CAPEX)	3%	3%	3%	(Stehly & Beiter, 2019)
Lifetime (years)	20	20	20	(Stehly & Beiter, 2019)
Interest rate (%)	4%	4%	4%	(Feldman et al., 2020)
Conversion US$/€	1.2	1.2	1.2	-

Table 28. Technology data inputs for calculation of solar photovoltaic energy LCOE.

PV	2020	2030	2050	Sources
CAPEX (US$/kW)	530-800	400-500	110-210	Own calculation
OPEX (US$/kW)	13.3	13.3	13.3	(Kost et. al, 2021)
Lifetime (years)	25	25	25	(IRENA, 2020b)
Interest rate (%)	4%	4%	4%	(Feldman et al., 2020)
Conversion US$/€	1.2	1.2	1.2	-

Table 29. Wind capacity factors and PV outputs used for LCOE calculations in Georgia and Spain.

	Georgia			Spain		
	2020	**2030**	**2050**	**2020**	**2030**	**2050**
Average wind energy capacity factor (%)	40%	40%	40%	25%	25%	30%
Specific PV power output (kWh/kWp/day)	3.56	3.56	3.56	4.35	4.35	4.35

Capacity factors for wind energy are the same as presented in Table 17 and average specific PV power output is retrieved from (Global Solar Atlas, n.d.).

The CAPEX costs for wind and PV systems are projected using learning rates and historical developments. Data on cumulative installed capacity, annual market sizes and system costs developments is used from IRENA (2018). From annual market sizes (i.e. new capacity added each year) historic data, and using CAGR between 5% and 10%, a range of future annual built capacity is projected for each technology, using the calculation below:

$$Ending\ Value = \ log(CAGR + 1) \cdot years + \log\left(Starting\ Value\right)$$

Finally, by adding up these values to existing capacity for each year, cumulative total installed capacity ranges are calculated.

Based on historic data, learning rates (LR) derived for each technology using the following formulas:

$$C(x_t) = C(x_0) \cdot \left(\frac{x_t}{x_0}\right)^{-b}$$

$$LR = 1 - 2^b = 1 - PR$$

Once learning rates are established for both technologies, the first formula is used to project future costs for the different ranges of cumulative capacity, establishing a range for system costs as well.

For incorporation of these costs into LCOH calculations, connection costs are incorporated as follows:

- Grid-connected electricity is added a connection charge of 11 €/MWh for wind and hydro and 7.5 €/MWh for solar PV (Agora Energiwende, 2016).
- Stand-alone configurations are added a small charge of connection between electricity generation and hydrogen plant of 2 €/MWh.

As for the mix of power generation for grid electricity, in Spain is assumed the same as developed for the LEAP energy model under the energy transition scenario. Here, however, the less prominent technologies are grouped under one category which is assigned a static cost equal to the current price of electricity in Spain. The different shares are shown in Table 30 below.

Table 30. Spain simplified grid power generation mix projections for LCOH calculations.

	2020	2030	2050
Hydro	18%	15%	15%
Wind	25%	32%	44%
PV	12%	25%	35%
Others	45%	27%	5%

In Georgia, as hydropower already dominates production, it is assumed that grid-powered production of hydrogen can be deployed using only generation from renewables in the grid. At first this is just hydro, by 2030 the capacities planned by the government are assumed, and finally by 2050 static shares of wind and hydro in the overall system are assumed as PV expands to replace remaining generation from gas power plants. The different shares are shown in Table 31 below.

Table 31. Georgia grid RES power generation mix projections for LCOH calculations.

	2020	2030	2050
Hydro	100%	80%	69%
Wind	0%	15%	13%
PV	0%	6%	18%

Multi Criteria Analysis Data Inputs

For the calculation of the indicators under criteria 2A of the MCA, synergy between economy and hydrogen value chains, the groups of products in Table 32, Table 33, and Table 34 below are considered as relevant for the hydrogen value chain in Georgia and Spain. For the national activities analysis products are grouped differently since they come from the respective national datasets. The trade analysis considers the same group of products since data is retrieved from international trade databases.

Table 32. List of product groups in national economic production considered relevant for hydrogen value chain – Georgia.

Coke and refined petroleum products
Chemicals and chemical products
Rubber and plastics products, and other non-metallic mineral products
Basic metals and fabricated metal products, except machinery and equipment
Electrical equipment
Machinery and equipment n.e.c.
Transport equipment
Electricity, gas, steam, and air conditioning

Table 33. List of product groups national economic production considered relevant for hydrogen value chain - Spain.

Crude petroleum
Natural gas
Coke and refined petroleum products
Basic chemicals, fertilisers and nitrogen compounds, plastics, and synthetic rubber in primary forms; pesticides and other agrochemical products
Rest of agrochemical products
Rubber products
Plastic products
Basic metals
Fabricated metal products, except machinery and equipment
Electrical equipment, except domestic appliances
Machinery and equipment n.e.c.
Ships and boats
Air and spacecraft and related machinery

Table 34. List of product groups in international trade considered relevant for hydrogen value chain – Georgia and Spain.

Mineral fuels, mineral oils, and products of their distillation; bituminous substances; mineral waxes
Inorganic chemicals; organic and inorganic compounds of precious metals; of rare earth metals, of radio-active elements and of isotopes
Fertilizers
Stone, plaster, cement, asbestos, mica, or similar materials; articles thereof
Ceramic products
Glass and glassware
Iron and steel
Copper and articles thereof
Nickel and articles thereof
Aluminium and articles thereof
Lead and articles thereof
Zinc and articles thereof
Tin and articles thereof
Nuclear reactors, boilers, machinery, and mechanical appliances; parts thereof
Electrical machinery and equipment and parts thereof; sound recorders and reproducers; television image and sound recorders and reproducers, parts, and accessories of such articles
Vehicles; other than railway or tramway rolling stock, and parts and accessories thereof
Aircraft, spacecraft, and parts thereof

Appendix B

Levelized Cost of (green) Hydrogen results from lower estimate projection

Georgia

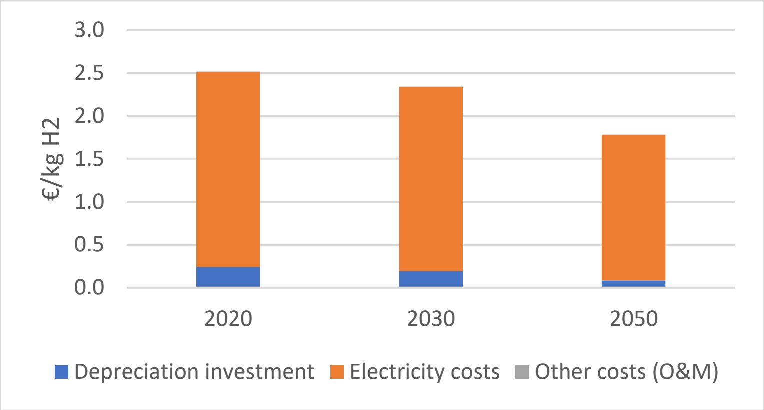

Figure 61. Lower estimate cost projections for green hydrogen from grid electricity in Georgia.

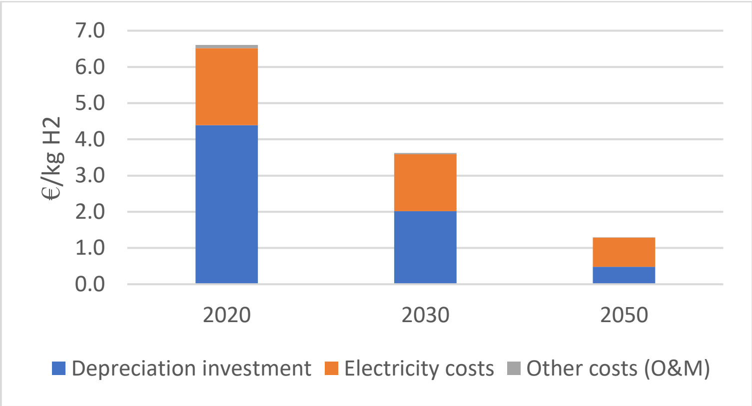

Figure 62. Lower estimate cost projections for green hydrogen from stand-alone PV in Georgia.

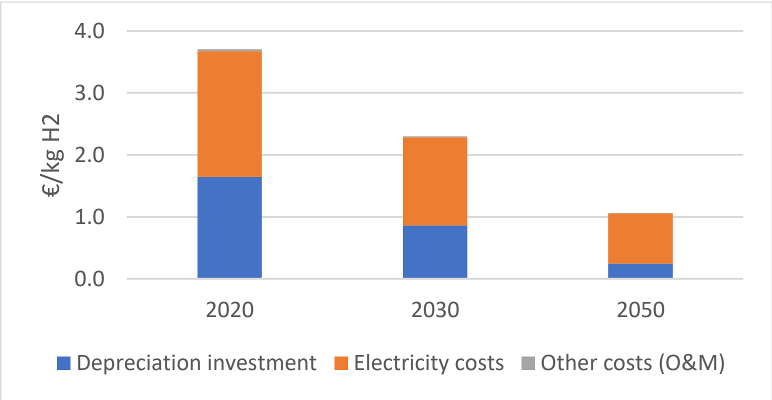

Figure 63. Lower estimate cost projections for green hydrogen from stand-alone wind in Georgia.

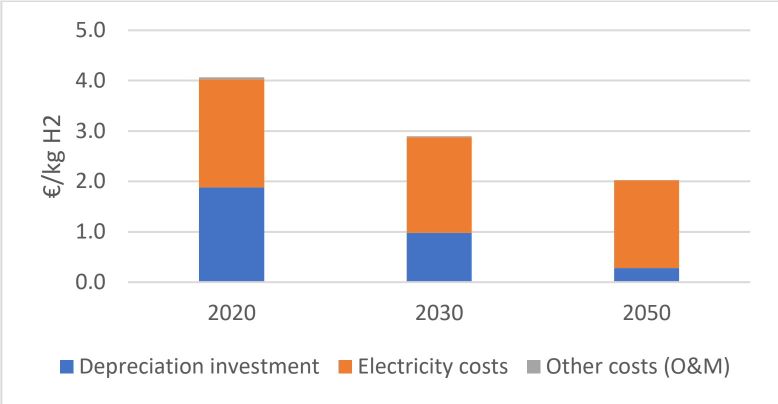

Figure 64. Lower estimate cost projections for green hydrogen from stand-alone hydro in Georgia.

Spain

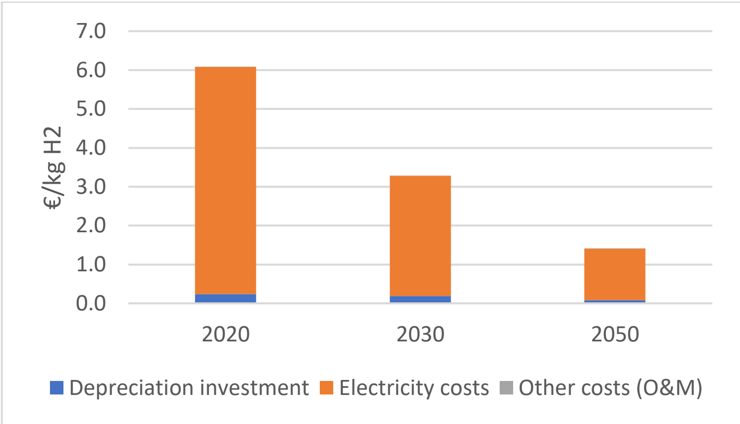

Figure 65. Lower estimate cost projections for green hydrogen from grid electricity in Spain.

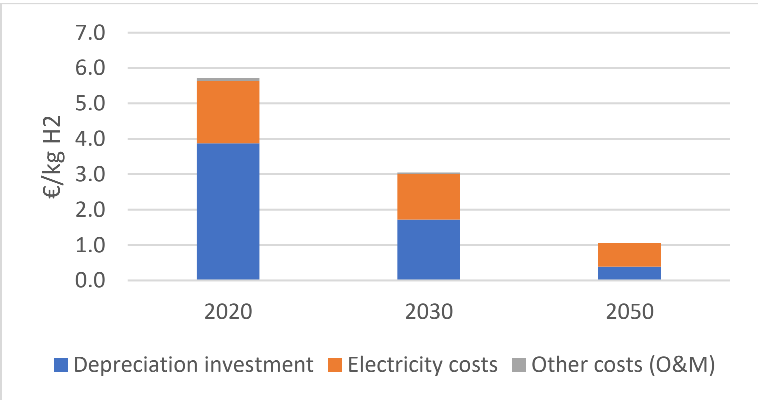

Figure 66. Lower estimate cost projections for green hydrogen from stand-alone PV in Spain.

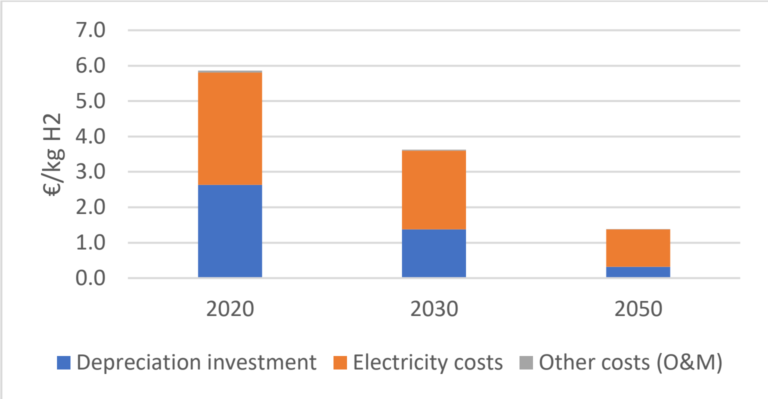

Figure 67. Lower estimate cost projections for green hydrogen from stand-alone wind in Spain.

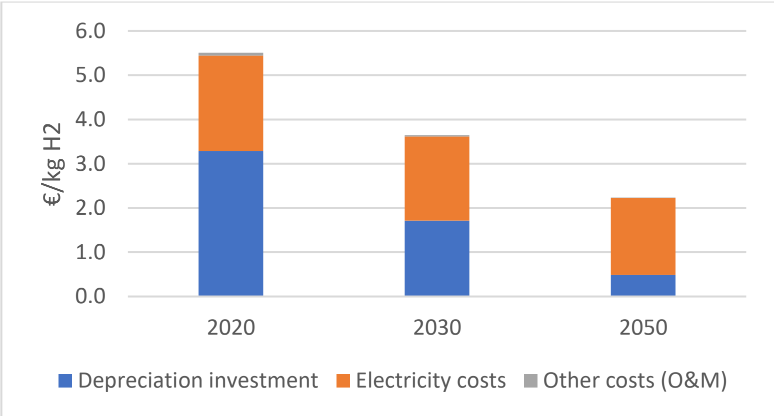

Figure 68. Lower estimate cost projections for green hydrogen from stand-alone hydro in Spain.

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