SHURA Energy Transition Center

İhsan Doğramacı Bilkent University Energy Policy Research Center

Techno-economic study of Turkey's production and export potential for green hydrogen

About SHURA Energy Transition Center

SHURA Energy Transition Center, founded by the European Climate Foundation (ECF), Agora Energiewende and Istanbul Policy Center (IPC) at Sabancı University, contributes to decarbonisation of the energy sector via an innovative energy transition platform. It caters to the need for a sustainable and broadly recognized platform for discussions on technological, economic, and policy aspects of Turkey's energy sector. SHURA supports the debate on the transition to a low-carbon energy system through energy efficiency and renewable energy by using fact-based analysis and the best available data. Taking into account all relevant perspectives by a multitude of stakeholders, it contributes to an enhanced understanding of the economic potential, technical feasibility, and the relevant policy tools for this transition.

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LIST OF ABBREVIATIONS

bcm	billion cubic meters
BMWi	German Federal Ministry for Economic Affairs and Energy
BOTAŞ	Petroleum Pipeline Company
CAPEX	capital expenditure
CCS	carbon capture and storage
CO_2	carbon dioxide
DOE	United States Department of Energy
EAF	electric arc furnace
EEG	Renewable Energy Sources Act
EMRA	Energy Market Regulatory Authority
ENTSO-E	European Network of Transmission System Operators for Electricity
EPC	engineering, procurement and construction
EU	European Union
FCHEA	Fuel Cell and Hydrogen Energy Association
FSRU	floating storage and regasification unit
GAZBIR	Turkey National Gas Distributor Association
GW	gigawatt
H_2	hydrogen
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
JODI	Joint Organisations Data Initiative
kg	kilogram
kV	kilovolt
kWh	kilowatt-hour
LCOE	levelized cost of electricity
m^2	meter squared
Mt	million tons
MVA	megavolt ampere
NH3	ammonia
OPEX	operational expense
PEM	Proton Exchange Membrane
PV	photovoltaic
R&D	research and development
RD&D	research, development and deployment
SOEC	Solid Oxide Electrolyzer Cell
TANAP	Trans-Anatolian gas pipeline
TWh	terawatt-hour


H2
Hydrogen
H2

Key messages

- A certain part of Turkey's renewable energy potential, supported by policies that enable cost-effective investments, may enable 3.4 million tonnes of green hydrogen production nationwide by 2050.

- Annual domestic demand for green hydrogen may reach 1.9 million tonnes for Turkey by 2050, substituting 10% of fossil fuel use with green hydrogen in the manufacturing industry, natural gas, and transport sectors.

- Turkey can export 1.5 to 1.9 million tonnes of green hydrogen to other countries in 2050, after covering part of its domestic needs.

- An annual investment of 3 to 4 billion dollars is required until 2050 to produce a total of 3.4 million tons of green hydrogen. On the other hand, taking into account possible costs and prices, green hydrogen would bring a total annual gross benefit of 6 to 8 billion dollars to the Turkish economy in 2050.

Executive Summary

The global energy transition from fossil fuels to zero-carbon technologies is currently underway and is fueled by a sense of urgency. Turkey has lit the fuse on its energy transition as the transformation of the Turkish power system is already underway. However, electricity demand still accounts for only 20% of Turkey's total final energy consumption, with the remaining energy used in buildings and the transport and manufacturing industries. Considering the recent ratification of the Paris Agreement, Turkey needs more ambitious climate and energy transition targets in 2030 and 2050. It is crucial to understand the role of hydrogen in reaching these targets. Many country-level as well as global net-zero pathways to 2050 emphasize the use of green hydrogen as a cross-cutting solution to decarbonize the energy system. In order to plan the role of hydrogen in the transformation of Turkey's energy system, it is important to understand the potential and the costs of the hydrogen supply in view of the available renewable energy supply and other resource potentials. In this context, this study aims to chart the potential of the total available green hydrogen for Turkey's own consumption and exports (including in other forms such as ammonia) by 2050 based on broad assumptions of how Turkey's energy demand could evolve across its 81 provinces. Within the scope of this study, only renewable electricity is considered for hydrogen production. In other words, only green hydrogen supply potential has been assessed in the study. Full decarbonization was not assumed in this report. The study yields two different scenarios for renewable energy deployment and three different scenarios for the hydrogen supply.

Assumptions

A brief assessment of hydrogen demand in Turkey has been carried out for the gas, manufacturing industry (including refineries) and transport as an end-use sector. Two cases are developed that assumes 10% and 5% substitution of the respective sectors' total energy demand with green hydrogen until 2050, after a stakeholder consultation process and a literature review in the Turkish context. This would mean a total domestic demand for green hydrogen between 1–2 Mt/year by 2050. The transport sector will account for half of domestic demand by 2050. According to 2050 hydrogen demand levels, manufacturing industry will account for a 25% share, with iron/steel a reaching 16% share, and the rest will be used for natural gas blending.

Hydrogen Demand Total	Unit	2030	2050
H5 (5% substitution)	Mt/year	0.24	0.94
H10 (10% substitution)	Mt/year	0.5	1.87

A regional approach was taken to compare hydrogen demand with supply assessments. Renewable electricity costs, capacity factors, and availabilities are assessed for each province in light of SHURA scenarios and official projections. Based on earlier SHURA studies ("Optimum electricity generation capacity mix for Turkey towards 2030" and "The most economical solution for Turkey's power system: Energy Efficiency and Business Models" (SHURA, 2020a, SHURA 2020b)), a capacity deployment analysis for the reference scenario was developed for 2030 assuming annual growth of around 3% for electricity demand between 2020 and 2030. For the period from 2030 to 2050, power generation capacities and electricity demand developments (average 2.5% per year from 2020 to 2050) were assumed based on general trends and other data from national and international studies.

Key Findings

Excess renewable power supply at the province level and unutilized available technical power capacity potential from wind and solar are considered as the key inputs for hydrogen production. In the reference scenario, total installed solar, wind, and hydropower capacity was assumed to increase from 44 GW today to 129 GW in 2050. The total annual electricity generation of 334 TWh from the renewable energy sources in the reference scenario covers 62% of the nationwide net electricity demand of 545 TWh in 2050. Technical potential implies an additional (compared to the reference case) 45 GW of wind and solar energy capacity with a total annual output of 124.4 TWh by 2050. Consequently, renewable energy sources can supply up to 84% of the total net electricity demand by 2050, with the remainder being covered predominantly by natural gas power plants. In the reference scenario total excess electricity supply from renewable power at the province level will be 50–55 TWh per year by 2030 and 2050, respectively. The potential excess supply of electricity generated from renewable energy and unutilized technical potentials could also be used for decarbonizing Turkey's power system.

Solar + Wind + Hydro Supply		2020	2030	2050
Reference Scenario				
Solar	TWh	11.26	63.23	101.28
Wind	TWh	24.7	75.9	99.95
Hydro	TWh	78.1	82.18	87.86
Enhanced Scenario				
Solar	TWh	11.26	73.64	147.29
Wind	TWh	24.7	96.59	178.31
Hydro	TWh	78.1	82.18	87.86

Three scenarios are used to assess the supply of green hydrogen:

- **Distributed Scenario 1/A** investigates green hydrogen production from excess renewable supply at the province level and is based on the expected capacity improvements by 2050. In this scenario, 0.6 Mt/year of hydrogen can be produced from the regional excess renewable power supply by 2050. This will require 6.6 GW of electrolyzer capacity.

- **Distributed Scenario 1/B** examines green hydrogen produced close to renewable power plants at the province level by utilizing the technical potential of solar and wind. Along with scenario 1/A, this scenario would require dedicated pipelines to increase green hydrogen trade or consumption. By utilizing the technical potential of wind and solar, an additional 2.8 Mt/year of green hydrogen can be produced by 2050. This implies an additional 28.7 GW of electrolyzer capacity compared to "Distributed Scenario A" to reach nationwide green hydrogen production of 3.4 Mt/year by 2050.

- **Centralized Scenario 2** considers the renewable electricity produced from the technical potential of solar and wind as well as the excess renewable supply (on province level) being transferred from each province to six designated key hubs to produce hydrogen. This scenario would require additional grid investments to transfer the electricity from renewable energy generation facilities around the country to these six designated key hubs.

Total Hydrogen Supply	Unit	2030	2050
Distributed Scenario 1/A	Mt/year	0.55	0.64
Distributed Scenario 1/B[1]	Mt/year	0.63	2.8
Centralized Scenario 2	Mt/year	1.17	3.4

The techno-economic assessment revealed that green hydrogen production costs could fall from 4.14–5.17 $USD_{real\ 2021}$/kg to 1.38–2.46 $USD_{real\ 2021}$/kg by 2050 for Alkaline and PEM technologies using wind- and solar-based electricity.

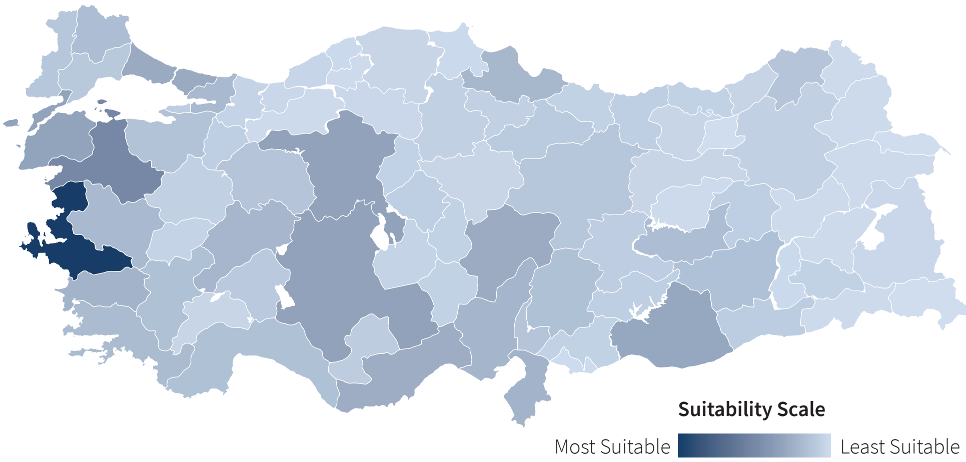
Hydrogen Production Cost[2] (Solar, Wind)	Unit	2030	2050
Alkaline	[USD/kg H_2]	4.14–4.45	1.39–2.47
PEM	[USD/kg H_2]	4.85–5.17	1.38–2.46
SOEC	[USD/kg H_2]	8.40–8.71	1.66–2.77

Along with favorable investments and policies, up to 3.4 Mt/year of green hydrogen production by 2050 can be achieved through utilizing excess electricity production from renewable energy sources and the technical potential of wind and solar. With respect to a maximum of 1.9 Mt/year of domestic hydrogen demand, Turkey will have a hydrogen export potential ranging from 1.5 to 1.9 Mt/year in 2050. Within the centralized scenario, there would be more green hydrogen to export after the hydrogen demand is met, since hydrogen use will be concentrated in six designated regions, not for the entire country. This would ensure the export potential of 1.9 Mt/year by 2050. This export potential could be utilized through blending into international pipelines such as the Trans-Anatolian Pipeline (TANAP) and through shipping by converting hydrogen to ammonia. A total of 85 to 119 billion USD will need to be invested into the power sector in order to create a hydrogen economy for local use and exports. On average, this would cost 3–4 billion USD per year between 2021 and 2050. In comparison, today, power sector investments in Turkey are around 7 billion USD annually. Accounting for estimated supply costs and avoided import fuel costs, this hydrogen economy would bring a total gross benefit around US$ 6-8 billion per year for the Turkish economy by 2050. The potential benefits of new job creation and economic activity from the hydrogen economy will potentially reduce the impacts of Carbon Border Adjustment Mechanism as well as Turkey's dependence on imported natural gas, oil and coal.

[1] Distributed scenario 1/B is complementary and additional to distributed scenario 1/A. Total hydrogen supply for the distributed scenarios (1/A + 1/B) reaches 3.4 Mt/year in 2050.
[2] The lower bound represents solar PV, while the upper bound represents wind-based hydrogen.

Export Potential	Unit	2050
Green H_2 Export Potential[3]	Mt/year	1.5–1.9
Injection to Pipelines	Mt/year	0.15–0.2
Ammonia Export[4]	Mt/year	1.35–1.7

This study offers two suitability indexes that prioritize the regions where green hydrogen projects may be initiated. The main reason for this differentiation is to underline different options for different strategic purposes, such as prioritizing hydrogen development potential to fulfill local demand or focusing on export. These evaluations combine all the factors considered in this study into a single number for each region. A colorful scale is used for the illustration purposes where darker blue represents better suitability score for that region (check table 14 for detailed results). The map below shows the “domestic suitability index” . It implies the provinces that would be more suitable for the first hydrogen projects that targets to fulfill local hydrogen demand.



[3] It is important to consider that these values can differ with strategic decisions to utilize renewable potentials differently.
[4] Based on stoichiometry of 0.178 t H_2/t NH3 and 1.7 Mt of green hydrogen, which would mean 9.5 Mt NH3/year.

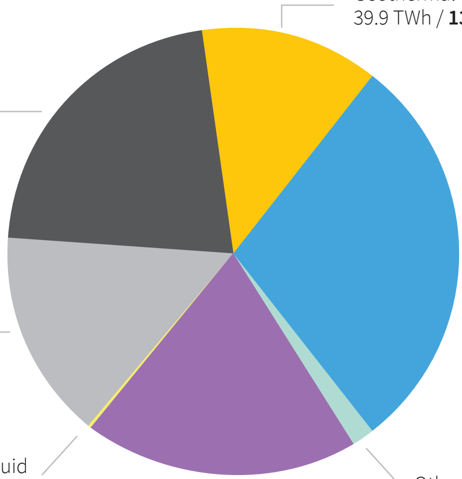
1. Introduction

1.1. Energy Transition Pathway: Turkey

The global transformation in the energy sector from fossil fuels to zero-carbon technologies is currently underway and is fueled by a sense of urgency. Turkey has lit the fuse on its own energy transition. The share of renewables in Turkey's total power supply reached 44% in 2019 (see Figure 1). Turkey's aim is to promote local energy sources. According to SHURA Energy Transition Center's "balanced policy action" scenario, the share of wind and solar energy in Turkey's power grid could reach 30% by 2030, with other renewables covering another 20% of total electricity output (SHURA, 2020).

The success of Turkey's power system transformation is indeed impressive. The sector is already on a low-carbon transition path. However, electricity accounts for only 20% of Turkey's total final energy consumption, with the majority of the rest of Turkey's energy consumption being used in buildings and the transport and manufacturing industries (Enerji ve Tabii Kaynaklar Bakanlığı, n.d). Turkey needs to take further actions on energy consumption in sectors other than the power sector in order to contribute to climate change mitigation and to sustain security of supply.

Figure 1: *Electricity generation in Turkey by source, 2019*



Source: TEİAŞ (2020)

Transport, industry, and buildings are considered as hard to decarbonize sectors. More specifically, some manufacturing sectors (such as iron/steel, cement, petrochemical, and fertilizer plants), the gas sector, and heavy-duty vehicles fall under this category and are often mentioned in the literature. Direct use of renewable energy and energy efficiency is at the heart of the electrification of these sectors. Thanks to this vision, renewable energy investments ramped up within the power sector and energy efficiency improvements back the reduction of electricity demand in hard to abate sectors. However, rapid decarbonization requires more ambitious solutions.

While not a panacea for achieving net-zero targets, hydrogen—when produced from renewable electricity and water—remains as a viable option to decarbonize hard to abate sectors. Other methods also exist, such as the conversion of biomass feedstock via gasification through steam reforming or methane pyrolysis with natural gas or coal gasification. In the literature an array of colors is used to describe the production methods of hydrogen that is derived from primary energy sources, such as gray for coal and blue for natural gas with carbon capture and storage. In this report neither of the primary energy sources used to derive hydrogen is considered to be compatible with long-term energy transition goals and thus neither of them is considered in this analysis. Considering global long-term energy transition goals, it is predicted that mostly green hydrogen will be traded among other forms (like gray or blue hydrogen). This analysis uses this as a starting point and considers Turkey's possible role in hydrogen trading in the future. Within this study the production of (green) hydrogen is considered only from renewable electricity, notably solar and wind energy.

While the use of hydrogen is context dependent and varies among countries' commitments, green hydrogen is viewed as a potential game changer around the globe (IRENA, 2020). With its versatility and cross-cutting technology in various sectors, green hydrogen could be an important auxiliary component of the energy transition. The development of the hydrogen economy will require a holistic approach that includes all sectors with a well-constructed regulatory system.

Numerous national strategies and initiatives concerning hydrogen policies have emerged as hydrogen is one of the most popular topics in the global energy sector. In parallel, hydrogen mobility began to be an important part of the discussion in Turkey in 2020. Hydrogen has become an important part of Turkey's energy transition strategy since the Ministry of Energy and Natural Resources initiated the kick-off meeting of the Hydrogen Quest Conference.

Within the framework of the conference, many areas for the study of hydrogen (such as the renewable energy-hydrogen link, the production of hydrogen from local coal, natural gas blending, transport and entrepreneurship opportunities) have been discussed. Turkey's Minister of Energy and Natural Resources Fatih Dönmez declared that Turkey will test blending hydrogen in the natural gas grid in 2021 and that the ministry will form Turkey's hydrogen strategy by considering sector and public opinion in 2021 (Turkish Ministry of Energy and Natural Resources, 2021).

In parallel, the Hydrogen Technology Association in Turkey has proposed a roadmap regarding the development of hydrogen technologies in Turkey. The roadmap proposes the start of studies to blend hydrogen in the natural gas grid from 2020 to 2025 in order to reach a minimum of 10% hydrogen in natural gas pipelines by 2025–2030, the development of the hydrogen economy and sector diversification for hydrogen use by 2030–2040, and expanding the use of hydrogen in various sectors by decreasing costs in its production by 2040–2050 (Hidrojen Teknolojileri Derneği, 2021). Similar targets are also available according to a report from Turkey's National Gas Distributor Association's (GAZBİR), including 10% blending of hydrogen and the start of governmental incentives to create Turkey's hydrogen market by 2030 (GAZBİR, 2021).

A recent analysis by SHURA Energy Transition Center suggests that a 5% substitution of fossil fuels with green hydrogen in Turkey's total final energy mix may require 36.3 GW of renewable capacity to be installed and a total of 45 billion USD in infrastructure investments. This excludes any potential role that Turkey could play as a country that can export green hydrogen to its neighboring regions such as the European Union in view of its large renewable energy resource potential.

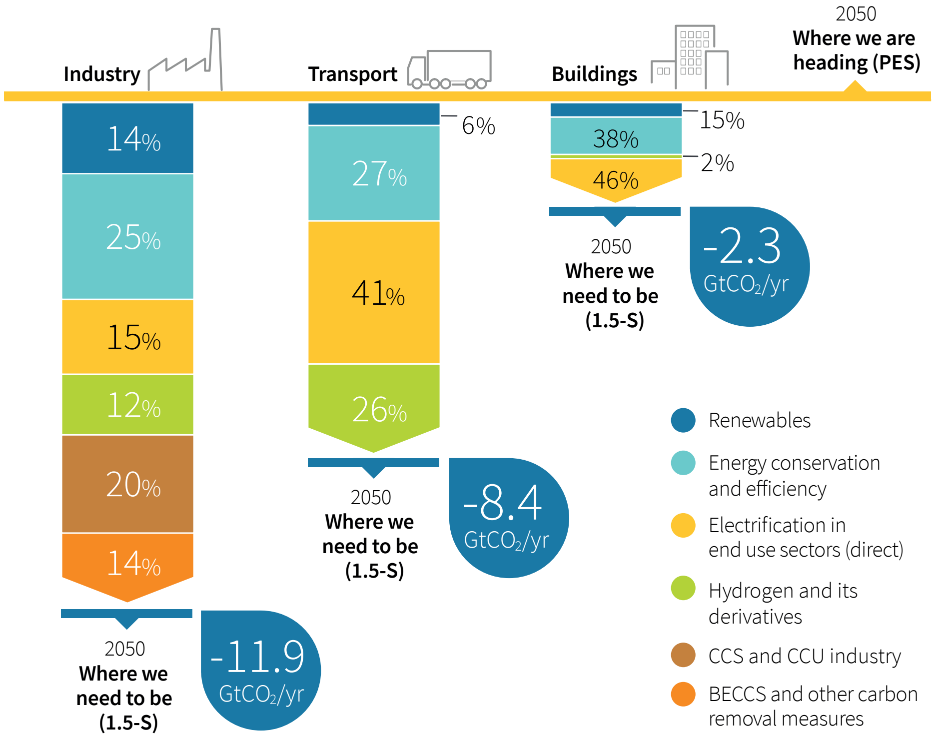
Recent tests to blend hydrogen into the natural gas infrastructure are being carried out by GAZBİR and its technical arm, GAZMER. The project received research grants from the Energy Market Regulatory Authority (EMRA). These tests include boiler and stove as well as security tests, which are essential for ordinary customers. Turkey is aiming for at least 5% hydrogen blending (i.e., blending) in its gas mix. When annual natural gas consumption is assumed to be 47 bcm, this would equate to 2.35 bcm of hydrogen replacing natural gas. This target can be exceeded with technical modifications and measures. In examples from other countries—such as in the United Kingdom, where initial trials have begun toward safety and the technical work of natural gas blending with hydrogen—there are targets of up to 20% (Isaac et al, 2021). According to a recent study in Turkey, a 20% share of hydrogen could be blended with natural gas (with the energy content by volume equivalent to 6%) without the need for a significant change in the current distribution infrastructure and consumer devices in Turkey (GAZBİR, 2021). Developments in green hydrogen costs will open the pathway for the larger use of renewable sources in transmission, distribution, and storage of gas infrastructure.

While it is expected that the national hydrogen strategy will determine the players of the hydrogen economy in Turkey, the public and private sector should cooperate to ensure the sustainability of investments. Providing a comprehensive regulatory framework will give the right signals for the private sector to invest in certainty.

1.2. Global Market Developments and Visions

The discourse on green hydrogen has cemented its role as a key energy vector in global net-zero emissions scenarios. The International Energy Agency's (IEA) most recent analysis puts significant emphasis on green hydrogen. Achieving 850 GW and 3,000 GW total installed electrolyzer capacity deployment by 2030 and 2050, respectively, have been included as two key milestones (IEA, 2021). Similarly, IRENA's (2021) analysis shows that 12% and 26% of the total emissions reductions in the industry and transport sectors could be achieved through increasing the capacity of green hydrogen and its derivatives, which requires almost 5,000 GW of water electrolysis by 2050 (see Figure 2).

Figure 2: *The role of green hydrogen in the decarbonization of end-use sectors*



Source: IRENA (2021)

Many countries are betting on hydrogen to accelerate their energy transition and to decarbonize sectors where solutions are limited. As hydrogen is an energy carrier, it can be produced from multiple sources including natural gas and electricity. These strategies vary in terms of technologies and the sources of hydrogen, such as blue, gray, and green hydrogen. For instance, green hydrogen is a key priority for the European Union in order to achieve its European Green Deal and its energy transition to a carbon-neutral system. As mentioned in the EU's strategic vision published in June 2021, the EU aims to achieve 40 GW of electrolyzer capacity and 10 million tons of green hydrogen production by 2030. Since this target will require a larger electrolyzer capacity than 40 GW, it implies greater import dependency on neighboring countries (IRENA, 2020). In order to support the implementation of investment plans and the creation of a hydrogen ecosystem, the European Clean Hydrogen Alliance was formed (European Commission, 2020). The EU's ambitious targets are backed by Germany, the Netherlands, France, Portugal, and Spain and their established national hydrogen strategies. Apart from the EU, Asian countries like Japan, China, and South Korea as well as Australia and the United States could be considered as the other frontrunners in the development of the global hydrogen economy. In order to meet their ambitious climate goals, multiple projects are being granted and incentivized by governments toward the advancement of clean hydrogen production.

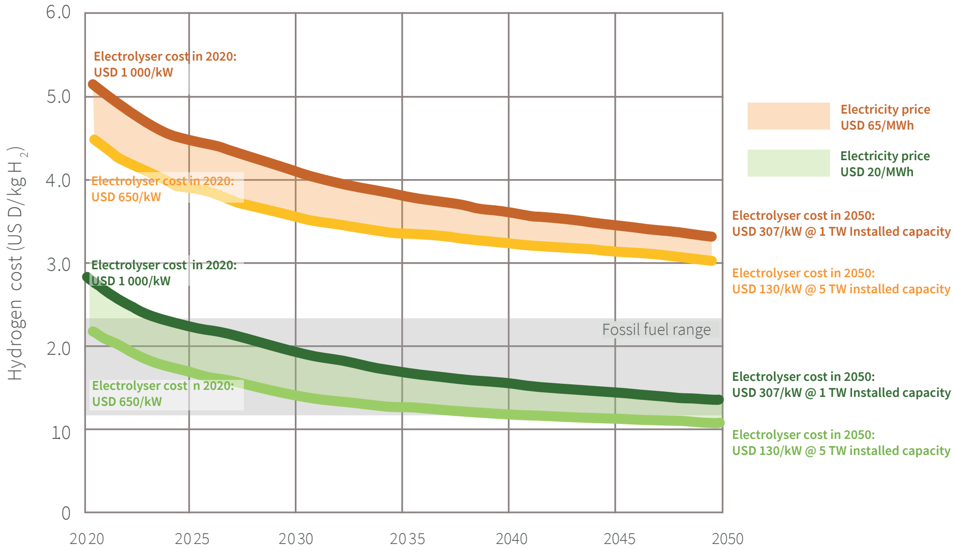
Along with international visions, market developments also need to be grasped. Private sector initiatives are growing globally while some are receiving various financial support from the government. Although the green hydrogen sector could be considered as nascent, new projects are announced almost in a daily basis. Investments in green hydrogen technologies vary among the type of electrolyzers because of the differences in their technical and economic performances. Alkaline and proton exchange membranes (PEM) are already being used commercially to produce hydrogen. PEM technology appears as being more efficient but more capital extensive than alkaline electrolyzers (SHURA, 2021).

According to IEA, 1,500 MW of additional electrolyzer capacity will be announced by 2023. For hydrogen use, blending into the gas grid and the decarbonization of refining and ammonia production make up a high share of the recently announced projects (IEA, n.d). To name a few, the HyDeal Ambition project plans to deliver 3.6 Mt per year of green hydrogen with 67 GW of electrolyzers in multiple locations across Europe, including Spain and Southwest France, with plans to extend to Eastern France and Germany by 2030. The Green Hydrogen Coalition, which consists of multiple U.S. solar firms and governmental organizations, aims to build 538 MW of renewable generation capacity to be used by electrolyzers in Utah by 2023. A recently announced project in Chile is expected to produce up to 1 million metric tons of green ammonia annually. A mega green ammonia/green hydrogen production facility will be located on a 2-GW wind farm and is expected to start operating within the next five years.

These initiatives are not limited to the construction of mega facilities to produce renewable hydrogen and its derivatives. For instance, the first hydrogen refueling station has begun to operate in Australia. The station aims to supply 100% renewable hydrogen for the new fleet of Hyundai Nexo hydrogen vehicles. Moreover, Swedish venture HYBRIT had made the first green steel delivery to a customer by replacing coking coal with green hydrogen in the production process. It is also important to note the European Union's "H2Ports" project, since hydrogen is seen as the fundamental component to decarbonize the transport and logistics sectors. Within the scope of this project, the port of Valencia will be the first port to use hydrogen in its operations with the aim of reducing environmental impact (H2 Ports EU, n.d).

However, for most regions green hydrogen is not yet cost competitive with fossil fuel-based hydrogen. The important factors that determine green hydrogen costs are renewable electricity prices, upfront investments costs of electrolyzers, electrolyzer efficiency, and capacity utilization actors. Renewable electricity has been considered as the largest cost component of green hydrogen. The increase in the renewable power demand for hydrogen production could contribute to further cost declines. The LCOE produced by utility-scale photovoltaics and on-shore wind fell by 82% and 39% respectively, in the last 10 years. (Agora Energiewende and Guidehouse, 2021). Along with more favorable regulations and aggressive headway to deploy electrolyzers, green hydrogen costs might fall to $\simeq$ 1 USD/kg, which is cheaper than fossil fuel-based alternatives (see Figure 3).

Figure 3: *Cost of hydrogen in different scenarios*



Source: IRENA (2020)

1.3. Hydrogen Trade

Within the scope of international strategies, many countries are looking for import opportunities, while some are planning to fulfill own their domestic demand and/or export. Ambitious decarbonization targets may not be fully achievable with local production alone for quite a few countries. In this context, hydrogen could be one of the main drivers of the energy trade in the future. The main drivers of hydrogen demand are the ambitions to meet climate goals and the lack of resources to mitigate this climate change. With the formation of the hydrogen economy, both hydrogen and its derivatives will be traded like any other energy commodity. In parallel, there are a growing number of mutual agreements between countries with high hydrogen demand and potential suppliers. The main aim of exporter countries, like Australia, is to transfer domestically produced green hydrogen to demand centers like Japan and the EU (ARENA, 2018). In particular, the EU is very much interested in clean hydrogen offers to advance its supply diversification and provide stable supply chains in line with their ambitious energy transformation targets (European Comission,2020). More specifically, the Federal Government of Germany has specified that its domestic generation will not be sufficient to cover their expected green hydrogen demand of 90–100 TWh by 2030 (BMWi, 2020). It is also important to understand that Germany will only support importing green hydrogen. This excess demand could be exported from Australia, Morocco, Ukraine, Turkey, and/or from other EU countries, like Denmark, Spain, Portugal, or Italy. Moreover, Australia could be considered as a key player in hydrogen exports, since it has already made agreements to supply hydrogen to Germany, Japan, South Korea, and Singapore. For instance, Australia has agreed with Japan to transfer the hydrogen produced from its lignite resources by capturing the carbon released during this process. The project is co-funded by both governments, and multiple private sector companies are involved.

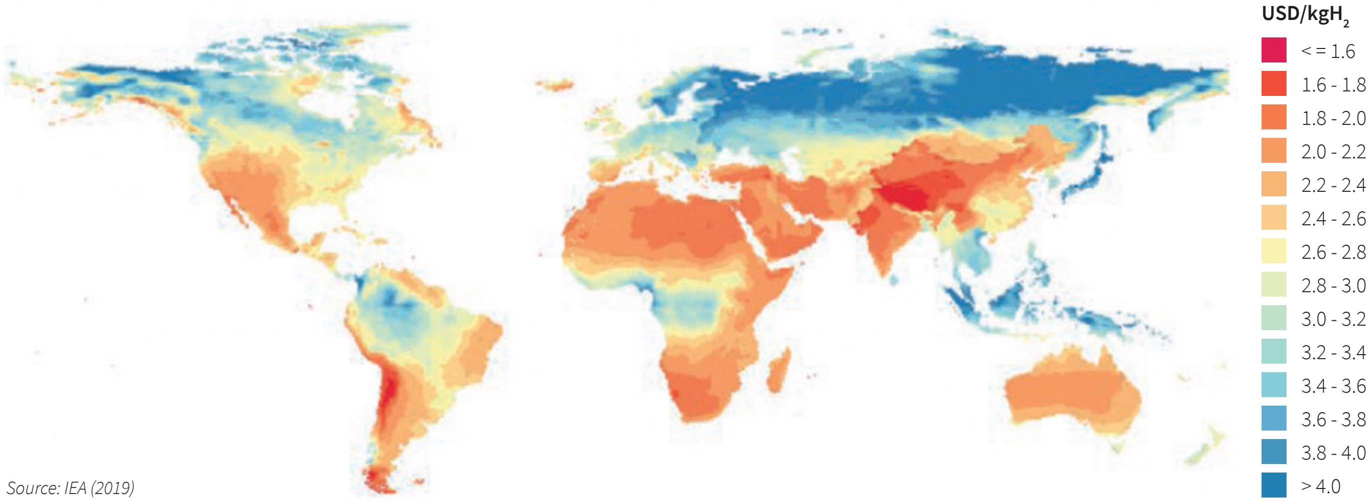
Furthermore, shipping hydrogen over long distances could provide flexibility. Instead of transporting hydrogen to a single destination via pipelines, hydrogen could be exported to various destinations through shipping. It is critical to determine which form of hydrogen will be shipped in view of its economic feasibility. Hydrogen could be shipped in liquid form or could be converted to methanol and ammonia. A recent study shows compressed hydrogen could also be an alternative for shipping, while being cost-competitive if shipped under a distance of 3,000 km as ammonia or liquified hydrogen (GEV, 2021). However, additional efficiency and boil-off losses need to be considered because of successive conversion processes.

A green hydrogen production strategy based on renewables will have to deal with intermittency and seasonality issues. Furthermore, the worldwide hydrogen economy in 2050 may look like the LNG or electricity markets today, meaning that regional integrations, cross-border hydrogen pipelines, and marine transport might be developed. Hydrogen as an energy carrier will not be immune to cyclical supply-demand issues as well as regional arbitration opportunities, which will create opportunities for international trade. Moreover, global trade flows will reduce the levelized cost of power fuels by up to 30% in some regions of the EU, which will result in considerable benefits for both producers and users (LUT University and DENA, 2020).

1.4. Road to the Hydrogen Economy and the Scope of this Report

As the global hydrogen economy is being formed, Turkey should take its place within this ecosystem in order to utilize its benefits and cover its further decarbonization needs. Turkey has significant resource availability for wind in the west and for solar throughout the country, especially in the center and south. Turkey also has rich hydropower to produce electricity and geothermal potential in the west. These resources would primarily be utilized to meet Turkey's domestic electricity needs in buildings, industry, or transport. According to SHURA's vision in 2030, a total minimum share of 50% renewables, including 30% wind and solar, can be realistically deployed (SHURA, 2020). However, to put the country on a low-carbon pathway to 2050, more solar and wind will be needed as hydropower resources are utilized. Therefore, there is a need to understand how Turkey can first meet its electricity needs with more renewables and subsequently use any remaining resources for green hydrogen production. Additionally, considering the high potential of renewables and land availability, it will also be important to understand whether the existence of any export potential for green hydrogen will create an additional value for the economy. According to Figure 4, Turkey could be one of the best regions globally to produce low-cost green hydrogen. The costs of renewable energy are decreasing rapidly, and significant developments are taking place in the electrolysis market driven by economies of scale. A recent solar PV tender in Turkey saw a bid of 0.022 USD/kWh in the southern part of the country. According to the scenarios outlined by the International Renewable Energy Agency (IRENA), electrolyzers could experience the same cost reductions as solar PV systems as their learning rate is similar (IRENA, 2020).

Figure 4: *Projected hydrogen costs from hybrid solar PV and onshore wind systems in the long term*



Source: IEA (2019)

Turkey has considerable advantages in future hydrogen markets. Its infrastructure for gas pipelines and available ports; existing industrial demand for hydrogen, which would imply potential new business opportunities; and its renewable resource availability might give Turkey a leg up in the development of its hydrogen market compared to other large emerging economies. Its integration into European gas and power networks and harmonized regulatory environment may also reduce the cost of doing business. With a cost-effective hydrogen strategy and cheap renewable deployment, these positive parameters can be translated into competitive vectors in the hydrogen ecosystem. As renewable energy investments accelerate, economies of scale will increase, and green hydrogen produced in Turkey might become competitive in other countries, especially in the Mediterranean and Black Sea rims.

In view of its own priorities, Turkey may want to utilize its green hydrogen potential to meet the growing energy demand of its end-use sectors for decarbonization. Alternatively, green hydrogen can be used for exports provided that other low-carbon solutions emerge to decarbonize Turkey's energy system. Considering the recent ratification of the Paris Agreement, Turkey needs more ambitious climate and energy transition targets toward 2030 and 2050, and it is crucial to understand the role of hydrogen for reaching these targets as well as different decarbonization perspectives. Considering these points SHURA Energy Transition Center's new study, conducted together with Bilkent Energy Policy Research Center through the support of the German Energy Agency (dena), aims to chart the potential of total hydrogen available for domestic use, Turkey's green hydrogen market development potential in particular locations by 2030 and 2050, and its potential to export hydrogen in the short- and medium-term.

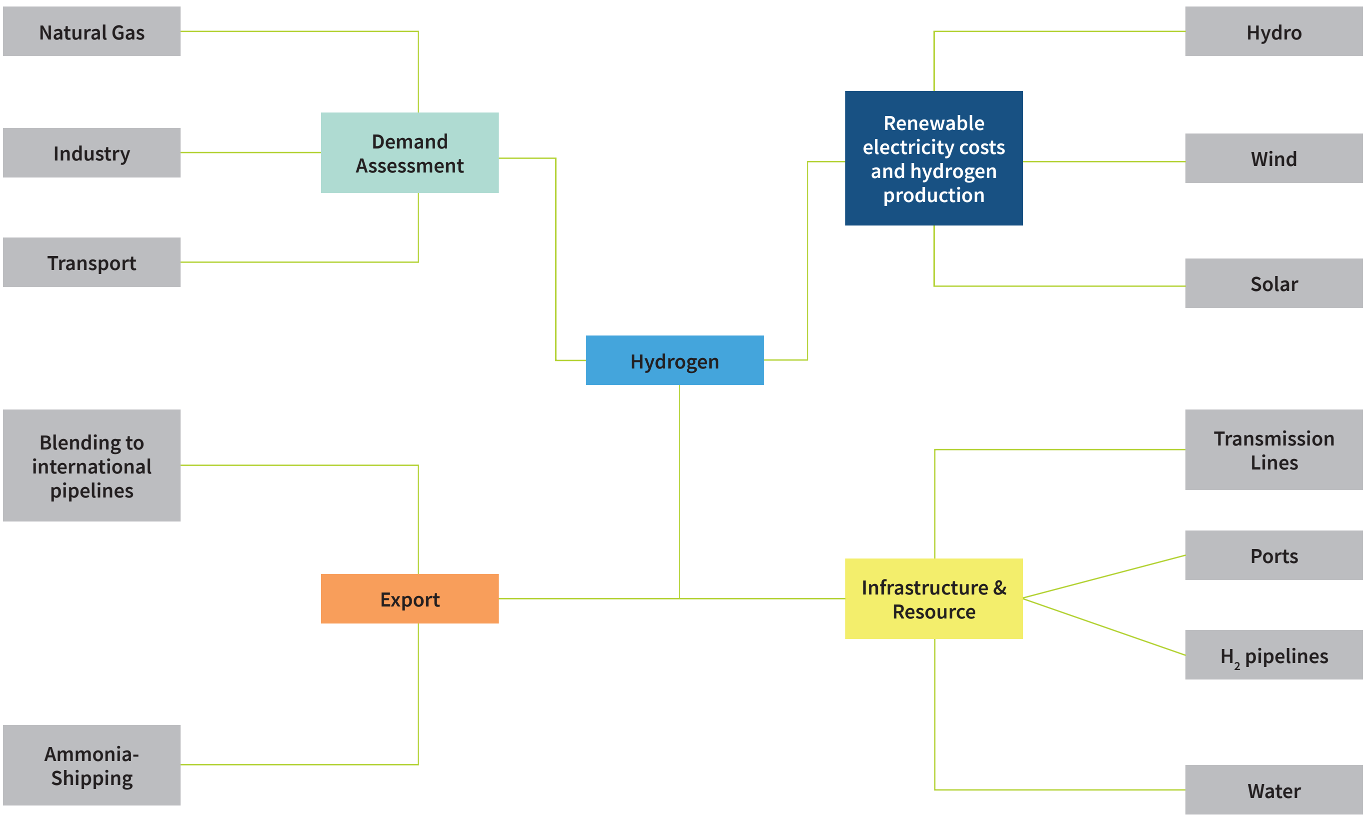
2. Methodology

This study uses available geographic data and the existing literature on Turkey to identify suitable locations for green hydrogen projects. As a first step, the geographical resolution is selected. Turkey is comprised of seven geographic regions (Thrace, Marmara, Aegean, Black Sea, Central Anatolia, Mediterranean, East Anatolia, Southeastern Anatolia) and 81 provinces. The methodology builds on four steps, and the geographical resolution is examined at as small a resolution (km^2) as possible from the available data (of public sources and earlier studies) across Turkey's geography. The analysis will cover the period between 2021 and 2050 regarding:

(i) A brief assessment of hydrogen demand in Turkey from the gas, industry (including refineries) and transport uses
(ii) The costs of renewable electricity and hydrogen production
(iii) The technical supply potential of green hydrogen in view of infrastructure and resource constraints
(iv) Identifying the export potential and suitable areas of green hydrogen through pipelines and in the form of end products such as ammonia to EU countries in order to identify "focus" regions in Turkey

The assessment develops a "Suitability Index," among other indicators, to rank regions that are suitable for low-cost production with abundant green hydrogen supply and export potential. A summary of the elements of the hydrogen ecosystem assessed in this study is shown in Figure 5.

Figure 5: *Elements of the Hydrogen Ecosystem*



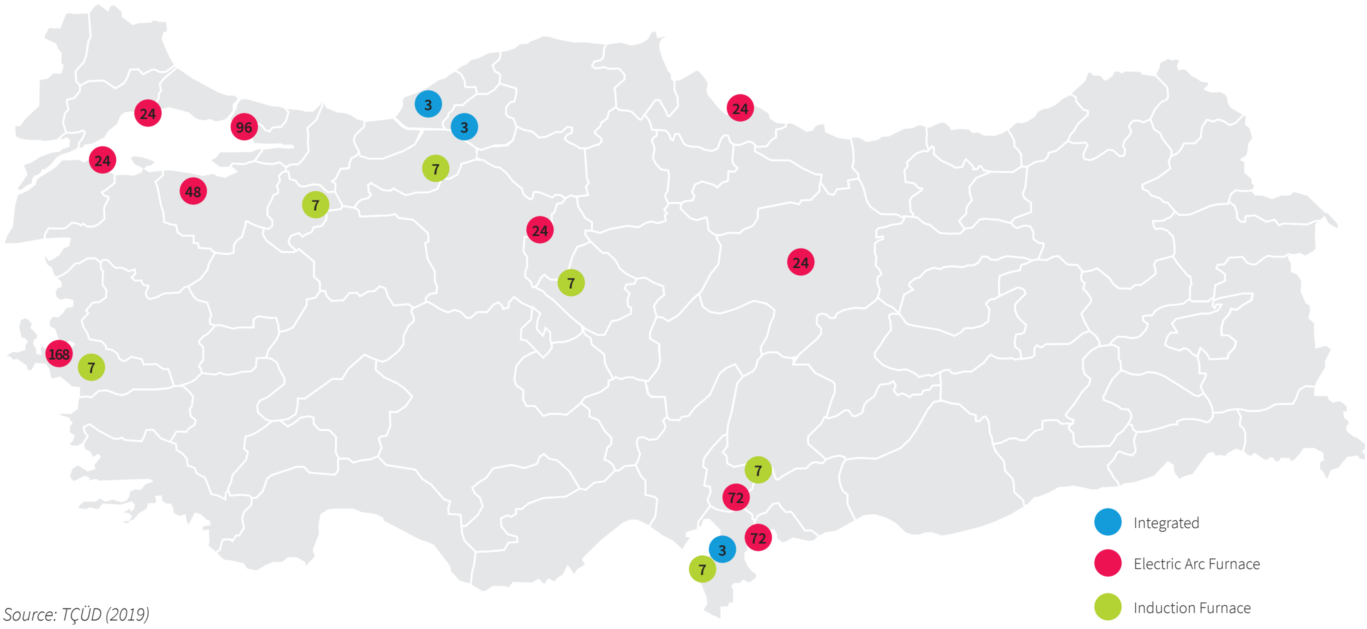
2.1. Hydrogen Demand

Green hydrogen demand is assessed in principle for the manufacturing industry (including refineries), transport, and natural gas blending as an end-use sector. An analysis of each sector is carried out in all 81 provinces. The location of each manufacturing industry plant is examined at the province level. For the transport and gas sectors, diesel and gas demand at the province level have been used as a proxy. Regarding the transition to hydrogen-based fuels, for the natural gas sector, hydrogen use is only considered for heating purposes in end-use sectors. It is considered as a substitute for diesel in the transport sector and for feedstock in industry, only for end-use applications.

There are three major energy-intensive industries in Turkey that are somewhat difficult to decarbonize: iron and steel production, of which two-thirds of all steel production is from the scrap-electric arc furnace (EAF) routes; the cement industry; and petrochemicals. Turkey’s iron and steel and cement sectors rank among the top-ten largest industries in their sector globally. Comparatively, the size of Turkey’s petrochemical industry is rather small. Nevertheless, the transition of petrochemical facilities is important. Petrochemical facilities already use hydrogen as fuel; hence, the petrochemical sector could be the starting point for using green hydrogen in major energy-intensive industries. With developing market conditions a wide supply chain has been established for fertilizers in Turkey, from the factory where production is carried out to the end user. However, Turkey mostly imports the raw materials used to produce ammonia, which is largely used in fertilizer production (Turkish Ministry of Technology and İndustry, 2018). This would be an early opportunity for hydrogen to take its place in the domestic market, since its already use in the production of fertilizers. Moreover, the operational characteristics of these petrochemical facilities and their temporal hydrogen demand is also an important factor to further consider in Turkey’s decarbonization plans. The locations of the production plants of these sectors are shown in Figure 6, Figure 7, and Figure 8. The growth of these industries in terms of their fuel and electricity demand in 2030 is based on industry and sector reports from academic sources from Sabancı University (e.g., Turkey Energy Outlook), government sources such as the Energy Market Regulatory Authority, and estimates from earlier SHURA studies.

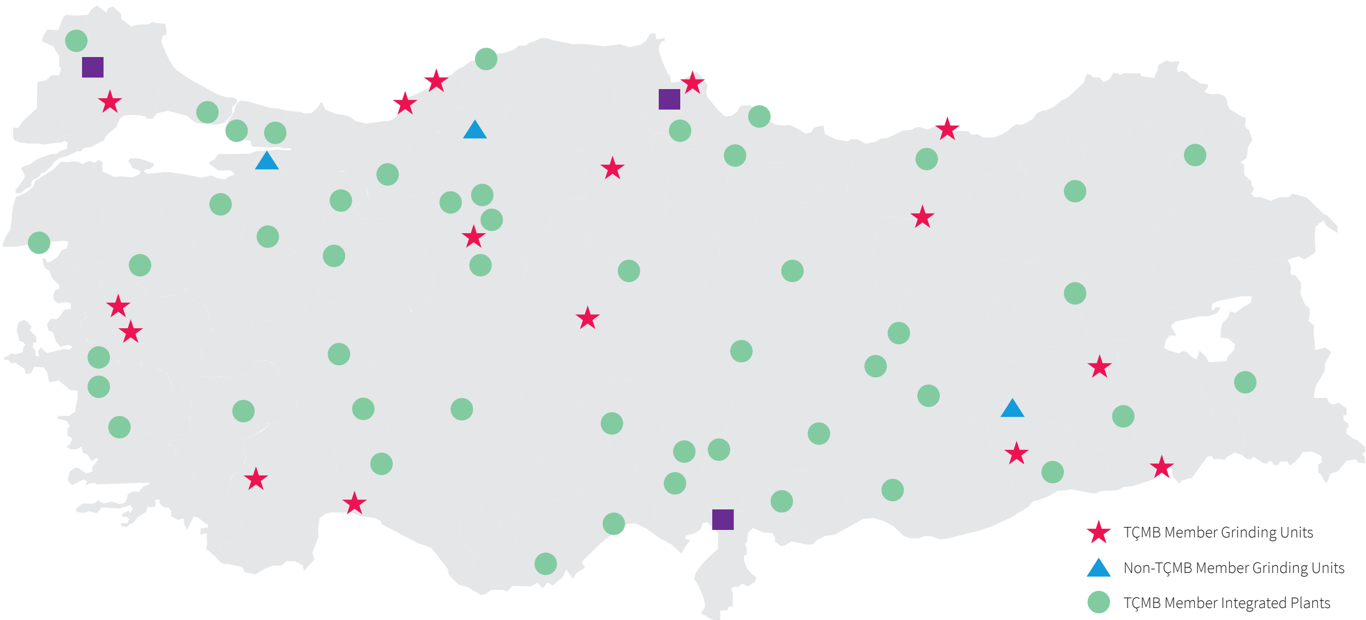
Two cases of potential fossil fuel substitution in 2050 have been developed, assessing a 5% and 10% share of green hydrogen in total final energy consumption, namely H5 and H10. H5 is an outcome of an earlier SHURA study (namely, “Priority areas for a national hydrogen strategy for Turkey”), whereas H10 is used to demonstrate a higher demand potential and its subsequent impact on export potential. Moreover, the 5% and 10% substitution estimations are based on the stakeholder consultation meeting that took place on May 6, 2021 (SHURA and Bilkent, 2021).

Figure 6: Steel map of Turkey



Source: TÇÜD (2019)

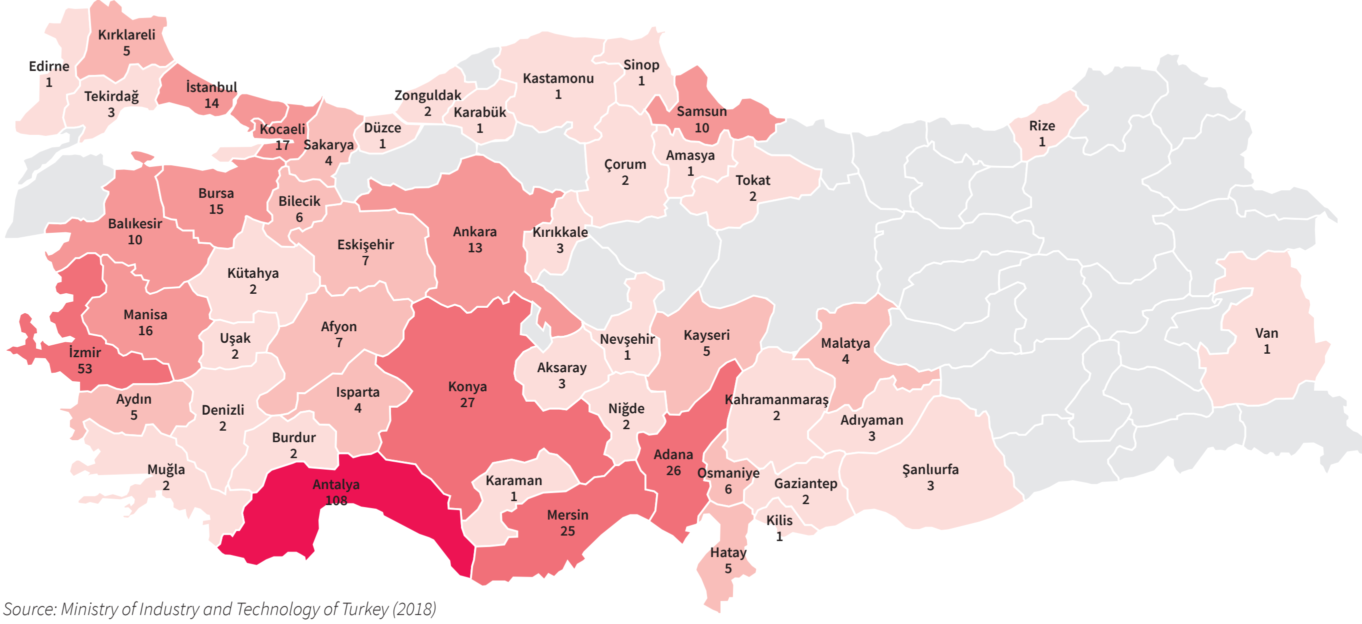
Figure 7: Cement factories in Turkey[5]



Source: TÇÜD (2019)

[5] TÇMB: Turkish Cement Manufacturers Association

Figure 8: *Map of chemical fertilizer factories in Turkey*



Source: Ministry of Industry and Technology of Turkey (2018)

Turkey's transport sector is comprised of nearly 20 million vehicles, of which around 12.5 million were passenger vehicles in 2019. There is a vision of Turkey to electrify passenger vehicles. Of the remaining vehicle stock, a notable share of energy is consumed by freight transport, which is composed of around 4 million vehicles. Estimated diesel demand growth is about 1% per year until 2030 and then around 0.5% per year until 2050. Turkey's road freight activity may also grow in parallel with its economic growth and with the emergence of new demand centers and trade (IICEC, 2020). It is expected that the number of electric vehicles (EV) will grow among passenger vehicles because of modal shifts in the sector and a slight increase in diesel demand due to increasing freight activity. In light of the developments concerning EVs, this analysis assumes a hydrogen strategy will substitute 5–10% of diesel use in road freight vehicles but assumes no role for hydrogen in passenger vehicles.

Turkey is already testing the blending of hydrogen in its gas grids, with a target of a 5% share for hydrogen in the coming years. Although the current test results are positive, long-term tests are required to see the effects on the overall system, and it is necessary to determine the acceptable hydrogen concentration for each consumer device and equipment. Moreover, producers recommend a range of 1–5% of hydrogen concentration on gas turbines; however, turbines can operate up to 10% with technical modifications (GAZBİR, 2021). Blending hydrogen into the natural gas grid may require an extensive overhaul of the whole grid. This will include metering systems for steel joints in buildings. Most importantly, the volumetric replacement of natural gas with hydrogen will decrease the energy content of the final mix. In parallel, as the share of hydrogen increases, compressors must operate at higher or different levels to transport the same energy level. Higher concentrations (>20%) of hydrogen by volume could require changes to existing infrastructure and end-use applications.

[5] TÇMB: Turkish Cement Manufacturers Association

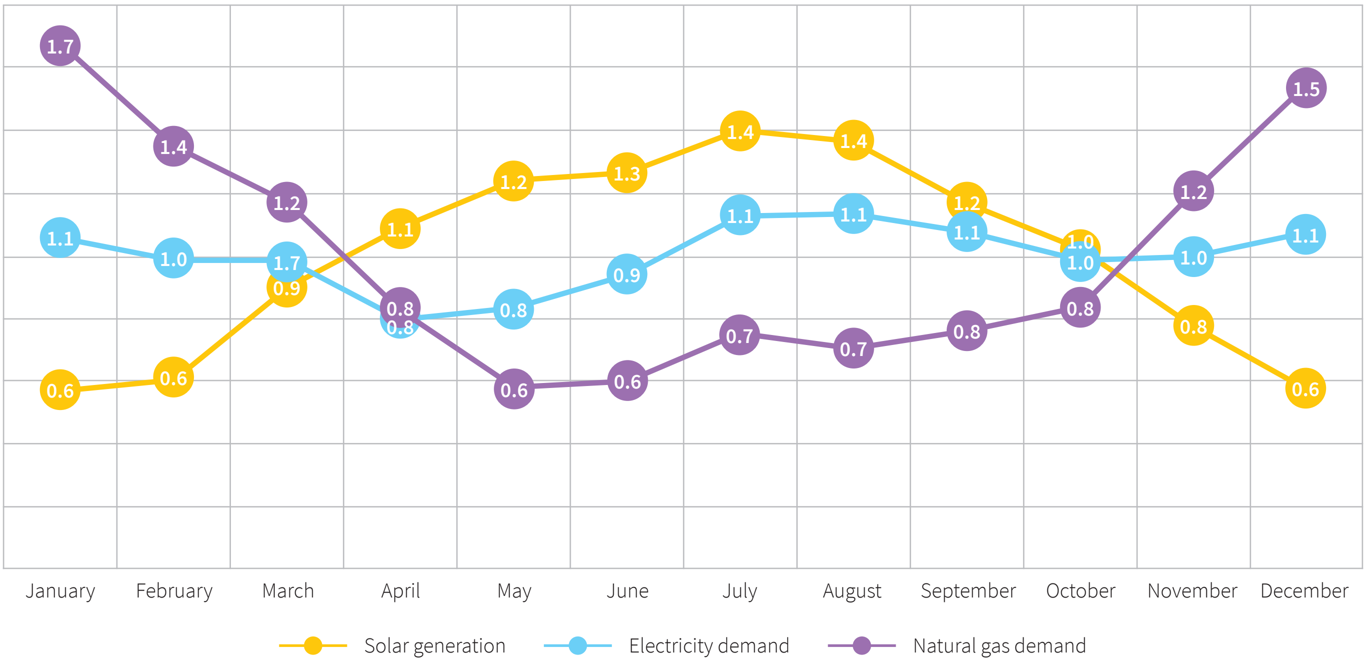
This analysis uses this as a starting point and subsequent assumptions for 2050 are made for 5% and 10% blending in gas grids. Gas use remains at around 47 billion m3 throughout the entire period assessed for this study. For hydrogen to be introduced into the gas grids, proximity to hydrogen supplies is necessary. The use of gas infrastructure for hydrogen could allow for scaling up production levels by using the existing supply chain of gas pipelines. The strategic decision to convert natural gas infrastructure to hydrogen blended gas infrastructure might be a win-win transition strategy. If not, separate infrastructure planning for a 100% hydrogen infrastructure remains costly. In the case that the pipeline infrastructure is gradually converted, BOTAŞ and EMRA's blending ratio targets will be important.

In a final step, the potential use of hydrogen as a flexibility option (i.e., storage) for grid integration of renewables is evaluated as a qualitative case study rather than a separate demand category. In the Turkish energy system, it is estimated that hydrogen may first take its place as a feedstock in the sectors mentioned above. When green hydrogen is produced and converted back to electricity after the storage process, it may not be cost efficient (compared to its end-use as feedstock) initially due to storage facility investments and conversion losses. However, hydrogen storage may take a vital part in power system flexibility for higher integration of renewable energy in the future.

Seasonal variations for solar demand are important and more predictable, whereas for wind there are some uncertainties. While increasing the share of solar among the power system does seem to be a panacea for summer demand, the bulk of Turkish natural gas demand is realized in the winter months, where solar generation is lowest. This may create discrepancies in the electricity market design unless excess solar is stored and reused in winter (see Figure 10). At this point, green hydrogen production and storage may be combined with power generation equipment such as fuel cells, reciprocating engines, combustion turbines, and steam turbines, which makes hydrogen a possible storage and demand response that may support intermittent renewable generation (Eichman, Harison and Peters, 2014). Therefore, green hydrogen could be a way to flatten seasonal differences and move excess solar generation to winter. However, the potential use of hydrogen as a flexibility option (storage) has not been considered in this study. The importance of seasonality is evaluated in Figure 9, where sources from EMRA and the Joint Organisations Data Initiative (JODI) are used to obtain data for electricity and natural gas demand. Seasonal storage of hydrogen can be solved through storage in salt caverns.

Figure 9: *Assessment of Seasonality for Turkish Solar Generation, Electricity and Natural Gas Demand*

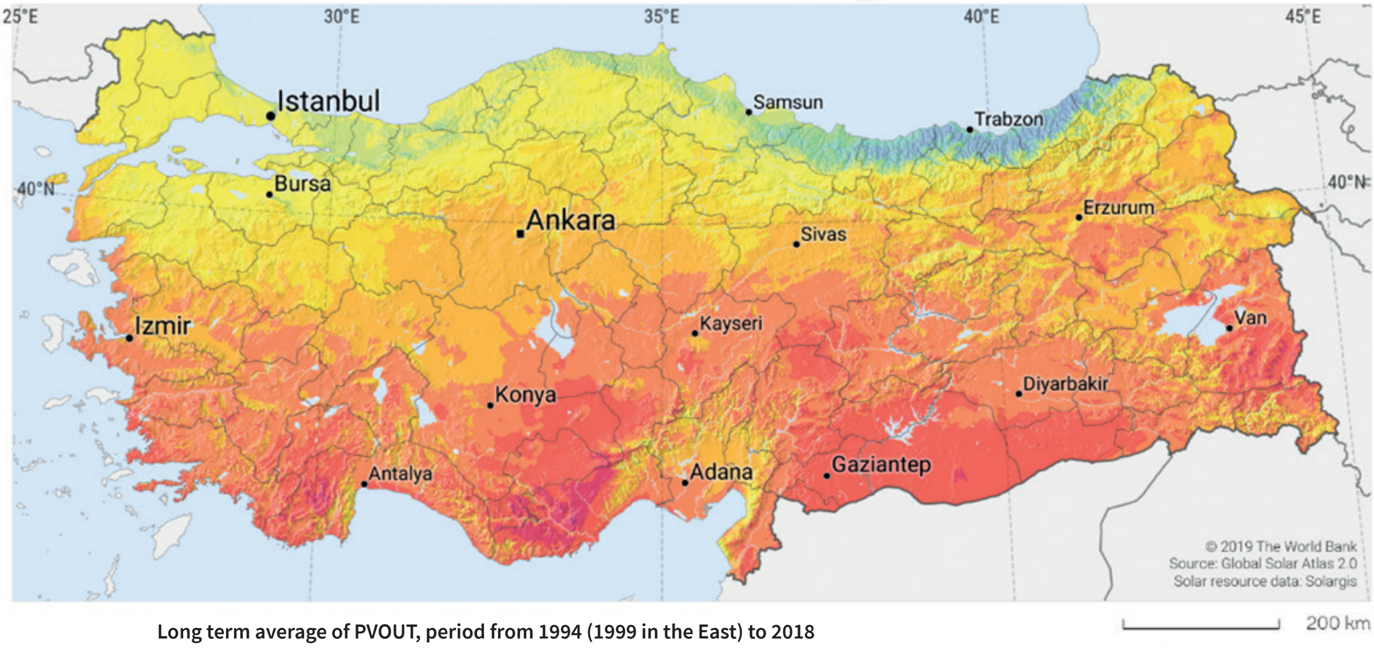
(Monthly average = 1)



2.2. Technical Supply Potential of Green Hydrogen

Renewable energy is used as a feedstock to produce green hydrogen. Turkey has significant resource availability for renewable energy. Maps of Turkey's renewable resources are shown below, in which the quality of wind and solar power by region is provided. Figure 10 depicts the long-term yearly average (1994 to 2018) of solar PV output. Darker red implies higher kWh/kWp for that specific region. There is higher potential for provinces in the south, such as Mersin and Konya. Figure 11 illustrates wind quality per region, where darker red implies higher speeds of wind in m/s. Wind speed reaches the highest value in Western and Central Anatolia, especially in western provinces such as Balıkesir.

Figure 10: *Turkey Solar Quality Map*

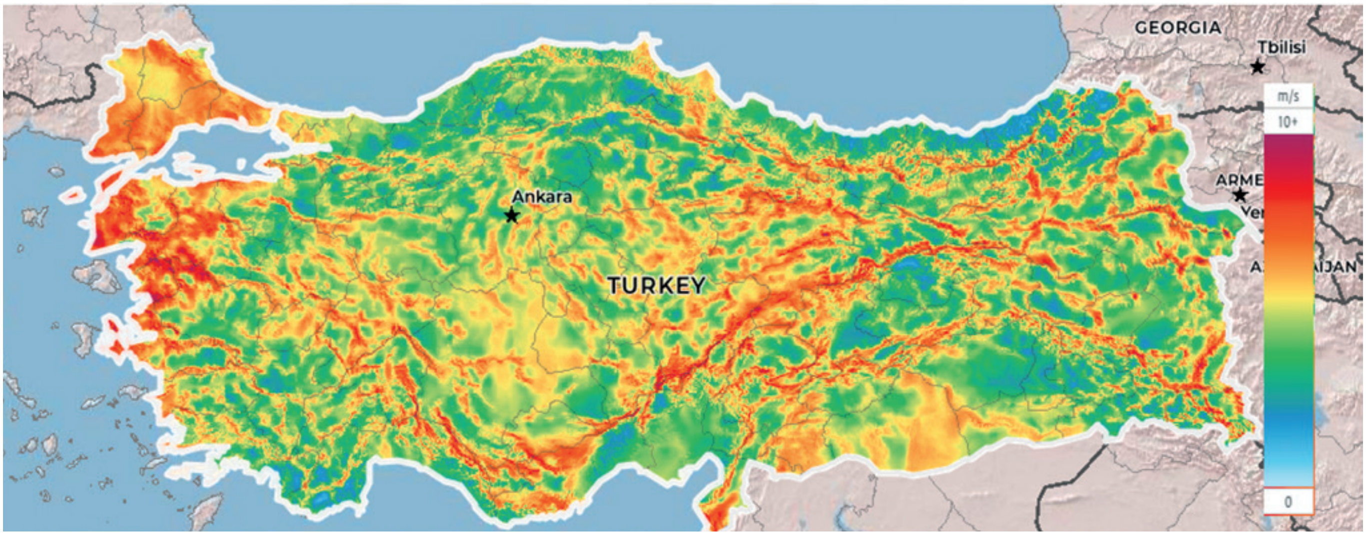


Long term average of PVOUT, period from 1994 (1999 in the East) to 2018

Daily totals:	3.0	3.4	3.8	4.2	4.6	5.0	**kWh/kWp**
Yearly totals:	1095	1241	1387	1534	1680	1826	

Source: Global Solar Atlas, SolarGIS (2019)

Figure 11: *Turkey Wind Quality Map*



Source: Global Wind Atlas (Mapped) (2021)

It is assumed that capacity factors range from 16% to 25% for solar energy and 25% to 34% for wind energy (SHURA, 2020). Unsuitable sites with altitudes higher than 2,000 meters and restricted land areas (e.g., urban areas, airports, nature protection areas) are excluded to determine the potential zones for electricity generation.

The capacity factors are subsequently combined with capital, operation, and maintenance costs of wind and solar photovoltaic (PV) technologies to estimate the levelized costs of electricity generation in Turkey.

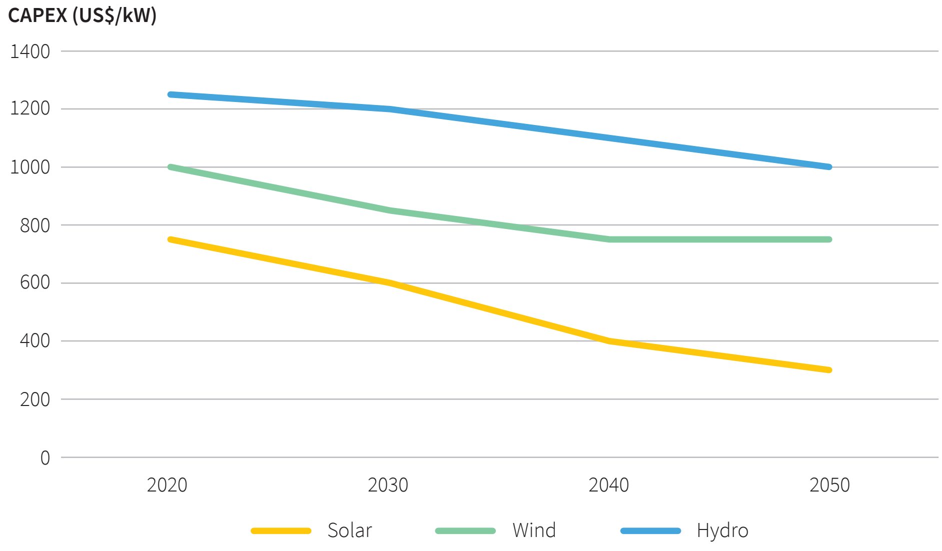
$$\mathbf{LCOE} = \frac{(\alpha * I + OM)}{E}$$

where

α: capital recovery factor (or annuity) as a function of lifetime and discount rate (10%) (in %/year)
I: initial investment (in USD) ⟶ (based on IRENA, BloombergNEF and real EPC cost data in Turkey)
OM: annual costs of operation and maintenance (in USD/year) (2–4%)
E: annual electricity production (in kWh/year)
LCOE: levelized cost of generating electricity (in USD/kWh = USD/year divided by kWh/year)

The development of the capital costs of renewable power technologies is crucial to estimate the LCOE. The assumptions for solar PV and onshore wind along with hydropower are shown in Figure 12.

Figure 12: *Development of capital cost assumptions for renewable energy technologies in Turkey, 2020–2050*

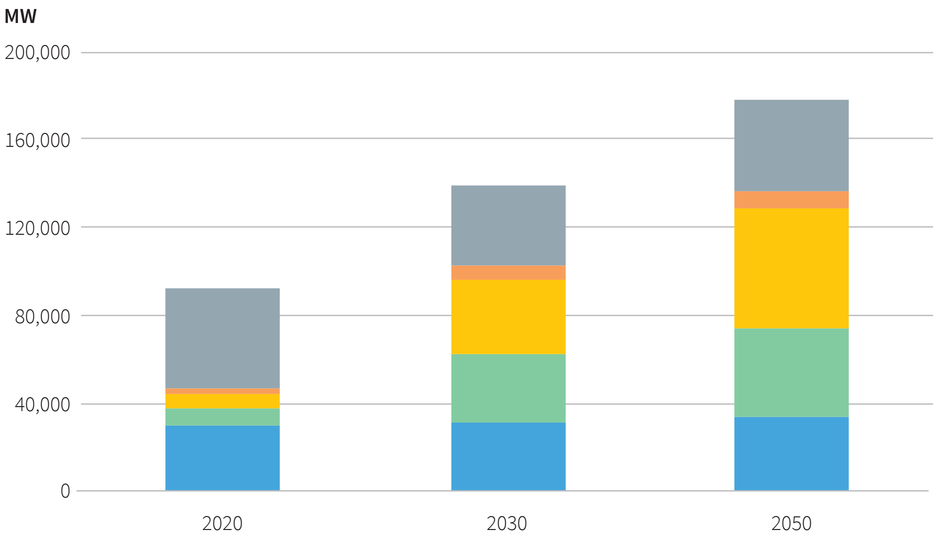


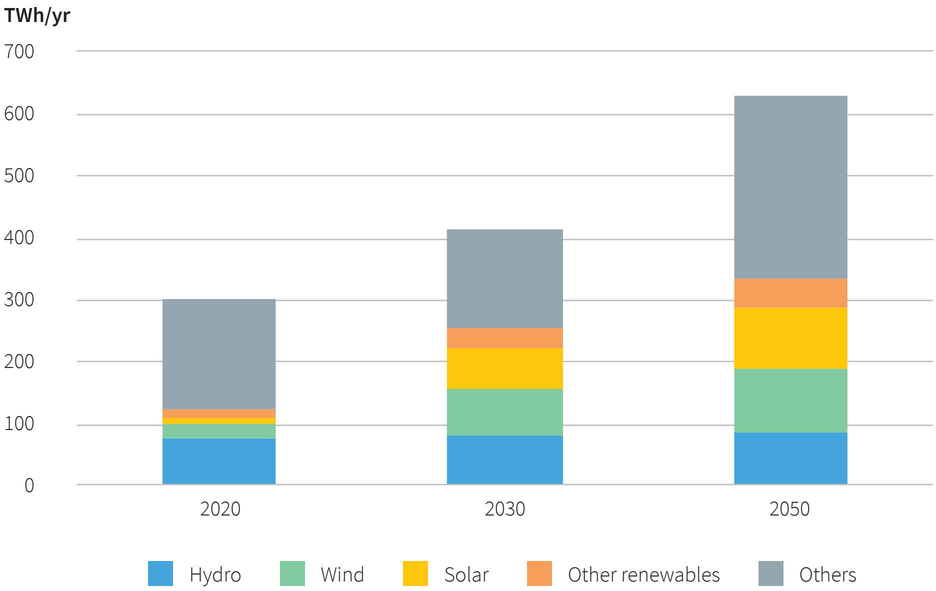
Source: SHURA Energy Transition Center (2020a)

In the next step, the total electricity available for green hydrogen production is assessed—i.e., the available technical electricity generation and capacity potential from wind and solar energy beyond what can be utilized in 2030 and 2050 (currently, total installed capacity exceeds 7 GW for solar PV and nearly 10 GW for onshore wind). Based on earlier SHURA studies ("Optimum electricity generation capacity mix for Turkey towards 2030" and "The most economical solution for Turkey's power system: Energy Efficiency and Business Models" (SHURA, 2020a, SHURA 2020b)), a capacity deployment analysis for the reference scenario is developed for 2030 assuming an annual growth of around 3% for electricity demand between 2020 and 2030. For the period from 2030 to 2050, power generation capacity and electricity demand developments were roughly assumed considering market trends and other data from national and international studies. It should be considered that these projections are not a net-zero emission scenario nor a target for Turkey, but rather they are reference and enhanced scenarios that follow the current trends and technical potentials for solar PV and wind sources. Technical potentials are estimated while taking topographic limitations into account.

According to the reference scenario, the share of renewables could reach at 62%, with wind and solar gaining a share of 36% for covering the assumed national electricity demand of 545 TWh in 2050 . As a result, a total of 40 GW and 55 GW of onshore wind and solar PV capacity, respectively, will be installed by 2050 (see Figure 13). This can be compared to the enhanced scenario, with a technical capacity potential of 60 GW onshore wind and 80 GW solar PV.

Figure 13: *Installed capacity and electricity supply projections for Turkey's power system, 2020–2050 (reference scenario)*





Potential renewable energy capacity across Turkey as well as the estimated developments resulting from this are presented above. Carrying out a renewable energy analysis across 81 provinces enabled us to investigate the hydrogen supply on a distributed level. Three scenarios for hydrogen supply are investigated in this study. Distributed scenario 1/A aims to find possible regions to produce hydrogen in light of the reference scenario. Accordingly, distributed scenario 1/B aims to harness the technical potential of wind and solar (enhanced scenario) to maximize the hydrogen supply. Regions with higher potential for renewable sources and water availabilities led us to examine the centralized scenario, which aims to discover the effects of limiting geographical choices on the hydrogen supply.

Hereby, the three scenarios for hydrogen supply are as follows:

- **Distributed Scenario 1/A:** On-site production of hydrogen from the expected potential of solar and wind by utilizing excess renewable supply at the province level after accounting for national demand in 2050
- **Distributed Scenario 1/B:** Producing hydrogen at the province level next to renewable power plants based on utilizing the technical potential of solar and wind in 2050
- **Centralized Scenario 2:** Transferring renewable power and produce to strategic regions according to the technical potential of solar and wind and excess renewable supply, although this implies additional grid investments

In distributed scenario 1/A, excess renewable power supply from each province is used to produce hydrogen at the province level. This is based on expected trends in 2050. This scenario will require improvements in gas grids in each province as well as better grid distribution and management, since renewables face seasonality effects. For instance, in Ankara, while solar generation is around 3 MWh in summer, it may drop to 1–1.5 MWh in winter. In contrast, heating demand in Turkey is highest in winter. There should be an interaction between storage and the grid to manage this demand and supply seasonality.

Distributed scenario 1/B examines producing green hydrogen next to areas with higher renewable energy capacity and utilizing the unused technical potential of wind and solar. Utilizing renewable capacities at the local level may further reduce wire and pipeline requirements if this energy is locally consumed.

In the centralized scenario, the key hubs for hydrogen exports are studied according to their future energy needs, proximity to resources, and port and water availability. This will require the reallocation of electrolyzer capacity, which is needed for the production of hydrogen in these key regions. Electricity produced from solar, wind, and hydro needs to be transferred to these regions, which would imply additional grid investments. Economies of scale and water issues should be improved under this scenario. Just like centralized electricity generation, the gas and power grid infrastructure will evolve around these hydrogen generation plants.

Distributed scenarios require the deployment of hydrogen infrastructure, namely dedicated hydrogen pipelines, compressors, and pressure reduction units for hydrogen consumption/trade/further processing. Furthermore, the centralized scenario requires additional electricity transmission grids. The costs of new hydrogen infrastructure for the EU are shown in Table 1. Although these costs may be slightly different for Turkey, they are assumed to be the same as the EU in this study. The capital costs of power transformer stations are assumed to be 8 million EUR for 1,000 MVA capacity. The capital costs of electricity transmission lines are 300,000 EUR per km (400 kV line) (SHURA, 2018). A lifetime of 50 years has been assumed for hydrogen pipelines and 30 years for electricity infrastructure. For infrastructure investments a discount rate of 2% has been assumed, which is close to social discount rates.

Table 1: *Costs of hydrogen infrastructure*[6]

	Unit	Low	Medium	High
Hydrogen pipeline	billion EUR/km	19	21	26
RM-A station needed	billion EUR/km	0.081	0.1215	0.162
Compressors needed	billion EUR/km	0.1782	0.2754	0.5427
Depreciation period (pipelines)	years		30–55	

Source: Guidehouse (2020)

For the centralized production of hydrogen, the key regions have been studied according to their port availability, marine safety, infrastructure availability, the presence of industrial facilities and demand centers, and the availability of renewable sources and water. Although a weighted analysis is not carried out, these parameters are both studied quantitatively (renewable potential, water availability, hydrogen demand, number of facilities) and qualitatively (marine safety).

1. Port availability: Practically speaking, the first approach to centralizing hydrogen production is the availability of port infrastructure. If the hydrogen must be exported by sea, an existing port infrastructure can be advantageous.
2. Industrial facilities: The presence of industrial facilities is an important parameter. While refineries are already using hydrogen as a feedstock, the transition to low-carbon fuels is expected in other sectors such as steel and cement. The proximity to an already existing market can be cost effective.
3. Renewable resources: Ports should be close to renewable electricity production plants as well as industrial facilities. The proximity of renewable resources will reduce infrastructure costs.
4. Water resources: Water scarcity will be an important parameter by 2030 and 2050. Estuary points (where a river meets the sea) are crucial for water-friendly hydrogen projects.
5. Demand centers: The hydrogen produced in Turkey will also be used for domestic consumption. Therefore, consumption centers are a bonus in such decisions, especially if a blending strategy is to be pursued.
6. Infrastructure: High voltage electricity and high-pressure grid infrastructure can decrease operating costs. Export and import lines and proximity to these lines are also key factors.
7. Marine safety: Exporting hydrogen and its derivatives is a dangerous operation, and marine operations may not allow ships to pass through the Turkish Straits.

[6] RM-A for pressure reduction for consuming from intercity lines

The relative merits of each scenario are variable (see Table 2). For instance, by standardizing the hydrogen supply chain in a centralized area, economies of scale could be rapidly achievable compared to decentralized production. It should be considered that the planning of the hydrogen economy needs to be in parallel with infrastructure planning and demand development for each region. Centralized production will shift hydrogen production into industrial zones where hydrogen can be used as feedstock for end-use sectors. Moreover, the freshwater requirements of hydrogen production could be better handled with centralized production, since some regions are less stressed compared to other regions of Turkey.

Table 2: *Comparison of the advantages and disadvantages of distributed and centralized production of hydrogen in Turkey*

	Distributed	Centralized
Economies of scale	+	+++
Hydrogen infrastructure	+	+++
Safety concerns	+	+
Power transmission system needs	+++	+
Water availability	+	++
Local benefits	+++	+

(+ indicates more advantages)

In addition to renewable power, water is needed for hydrogen production. While this does not add much to the final cost of hydrogen production, theoretically, about 9 liters of water are needed per kilogram of hydrogen (IEA, 2019). In reality, considering the inefficiencies in the processes of hydrogen production, the ratio can reach up to 18–24 kg of water per kilo of hydrogen (IRENA, 2020). Therefore, in our analysis we assumed a more realistic volume of 15 liters sourced from freshwater resources. To put this in comparison, the process of steam-methane reforming requires a minimum of 4.5 kg H_2O/kgH_2 of water in the reaction process, which increases up to 6.4–32.2 kg H_2O/kgH_2 when all processes and cooling are considered (Lampert et al., 2015, 2016).
While using seawater could become an alternative in coastal areas, this would cost around 0.7–2.5 USD per m^3 of water for desalination (Tractebel 2018, Caldera et al. 2018). Turkey is a water stressed region, and this “stress” is expected to increase in the coming years. While this study excludes a quantitative assessment of the water constraints on the hydrogen supply, its potential impacts are qualitatively discussed in the results section, and no additional water infrastructure is assumed to supply water to electrolyzers.

2.3. Costs of Green Hydrogen Production

Once suitable renewable power sources, available surplus electricity, and water resource rich areas are identified, supply potential (in million tons per year) and the generation costs of hydrogen (in USD/kg H_2) are estimated. In suitable areas with land availability, additional electrolyzer capacity will be installed. The decision on where to locate electrolyzers, whether next to power plants, potential storage facilities, or close to demand centers, is determined in the scenarios. Stakeholder consultation provided inputs on this decision as there is no established methodology available for doing so in past studies or the literature. The assumed technical and economic performance characteristics of hydrogen production technologies are provided in Table 3.

One crucial issue that determines the costs of hydrogen production is the capacity utilization factor of electrolysis units. From a business perspective, high-capacity factors are ideal, but this raises the cost of investments on the electricity supply side. With a low capacity factor, it becomes challenging for green hydrogen to compete with fossil fuel routes unless there are carbon incentives. The capacity factor will be dependent on the available wind and solar energy mix and the extent to which curtailed and surplus electricity could be used. The hybrid availability of wind and solar energy in Turkey yields a 50% capacity factor on average.

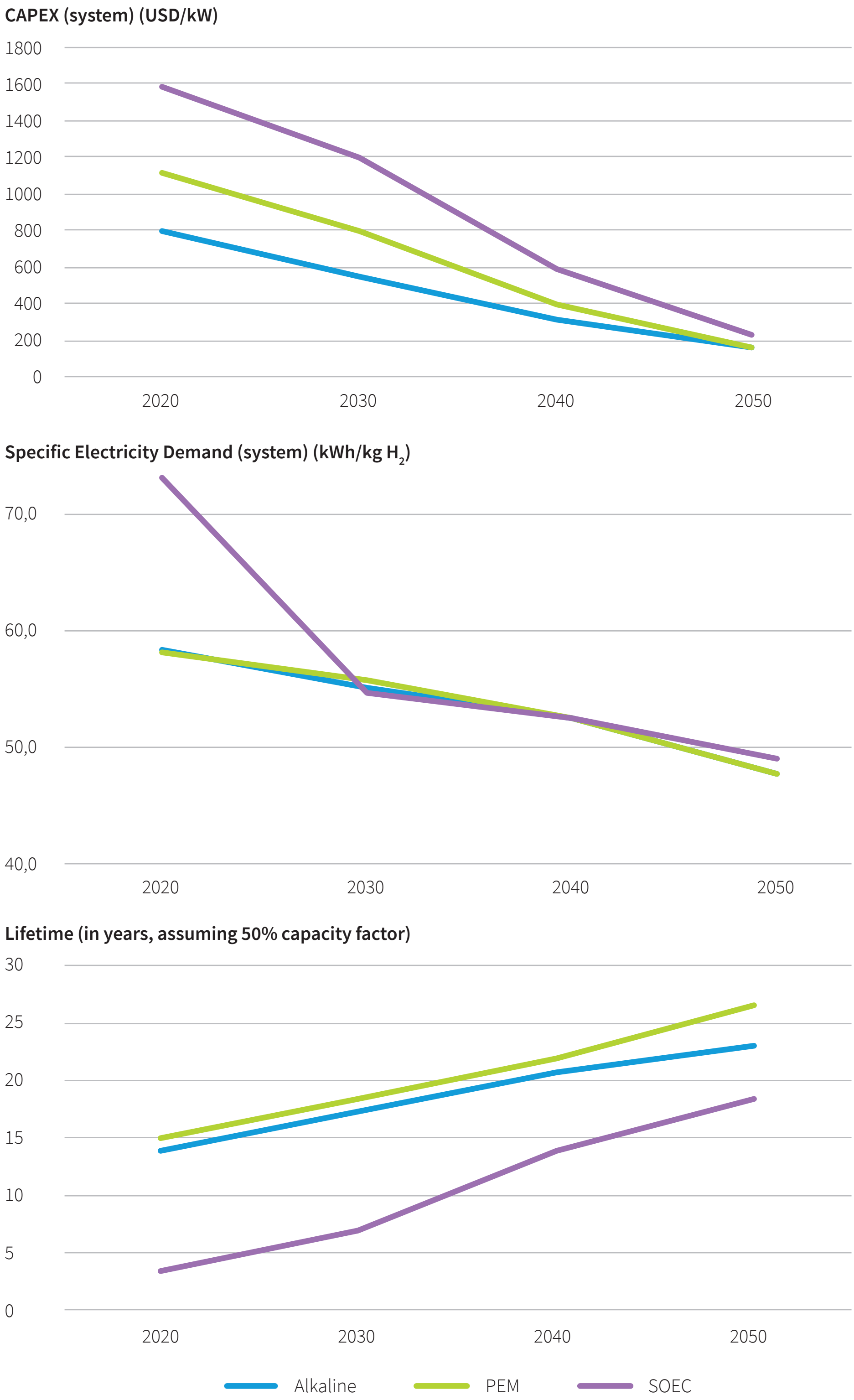
The analysis of technical and economic performance characteristics of hydrogen production technologies provided the baseline for future hydrogen costs in Turkey.

Table 3: *Technical and economic performance characteristics of electrolyzers*

Parameter	Unit	Reference	Alkaline		PEM		SOEC	
			2020	2050	2020	2050	2020	2050
Reference electrolysis capacity (system)	[MW]	Christensen (2020)	1	10	1	10	0.05	0.2
Reference CAPEX (system)	[USD/kW]	Christensen (2020)	1000	200	1400	200	2000	300
Analyzed electrolysis capacity (system)	[MW]	Analyzed	2	20	2	20	0.1	0.4
Analyzed CAPEX (system)	[USD/kW]	Analyzed	794	159	1111	159	1587	238
Scaling factor	[-]	Christensen (2020)	0.7	0.7	0.7	0.7	0.7	0.7
OPEX share of CAPEX	[%]	Christensen (2020)	1.5	1.5	1.5	1.5	1.5	1.5
OPEX	[USD/kW/yr]	Christensen (2020)	11.9	2.4	16.7	2.4	23.8	3.6
Capacity factor	[%/yr]	Analyzed	50	50	50	50	50	50
Efficiency (stack)	[%]	Christensen (2020)	64	75	66.5	75	50	75
Lower heating value H_2	[GJ/t]	Christensen (2020)	120	120	120	120	120	120
Specific electricity demand (system)	[kWh/kg H_2]	Christensen (2020)	58.5	47.6	58.2	47.6	73.3	48.9
Specific water demand	[liter/kg H_2]	Christensen (2020)	15	9	9	9	9	9
Discount rate	[%]	Analyzed	10	10	10	10	10	10
Lifetime	[years]	Christensen (2020)	13.8	23	15	26.5	3.5	18.4

As aforementioned, the costs and performances between the different types of electrolyzers vary. For instance, alkaline electrolyzers have the lowest capital costs today compared to PEM and solid oxide electrolyzers. However, PEM electrolyzers have a smaller carbon footprint, higher density, and output pressure in the production processes. Solid oxide electrolyzers (SOEC) have the highest installed costs, but the system could reach the highest efficiency levels among other types of electrolyzers. With scaling up investments and future technological innovation, it is expected that gaps in technical and economic performances of different types of electrolyzers will narrow over time (IRENA, 2020). Moreover, SOEC electrolyzers could be operated in reverse as a fuel cell to produce electricity, unlike Alkaline and PEM electrolyzers. This would mean SOEC type electrolyzers could provide balancing services for the grid (IEA, 2019). A common feature of all electrolyzer types is their capacity utilization factors. Higher rates of utilization will bring lower costs for the hydrogen being produced, which makes the continuous supply of renewable power essential. Figure 14 summarizes the expected developments in alkaline, PEM, and solid oxide by 2050.

Figure 14: *Summary of estimated developments in the key technical and economic characteristics of electrolyzer technologies, 2020–2050*



2.4. Export Potential of Hydrogen Production

Estimated hydrogen demand is assessed against supply potential in order to forecast Turkey's available hydrogen supply that can be exported (in million tons H_2/year). Ideally, Turkey's low-cost hydrogen supplies would be utilized for domestic use, and more expensive supplies would be exported. This balance could change depending on how international market dynamics evolve. The amount of green hydrogen that will be exported is dependent on the strategy decision, separate from renewable energy availability.

Turkey's natural gas infrastructure is quite young, and it is considered as a sunk cost. Following a cost-effective strategy, it is expected that Turkey will retrofit this infrastructure rather than building a new one. Hence, the existing pipelines can be used for both domestic and export purposes. There are currently enabling technologies in development such as membrane technologies that may be key to reaching Turkey's export potential. Membrane technologies separate different materials at the outlet of the infrastructure, meaning a mix of methane and hydrogen gas can be separated to achieve the desired level of hydrogen concentration. In order to realize this export potential, three possible means of hydrogen transportation are considered:

1. Road freight
2. Marine transit
    a. Hydrogen (Cryogenic)
    b. Ammonia
        i. Along the Black Sea rim
        ii. Along the Mediterranean rim
3. Pipeline
    a. Existing Pipelines
        i. TANAP
        ii. Interconnectors
    b. Dedicated Hydrogen Pipelines

Road freight is the most straightforward way of exporting cryogenic hydrogen; however, this is the most energy-intensive option. Currently, Turkey is considering using trucks to transfer LNG exports from LNG terminals in Turkey to Europe. Hydrogen is also transported cryogenically in certain cases. With road freight transport, export options are limited by volume. Since this option is expected to cover a maximum of 5% of all export potential, its overall effect is not qualitatively assessed. The destination of these exports is likely Bulgaria or Greece, with a small possibility of exporting to Georgia depending on cost effectiveness.

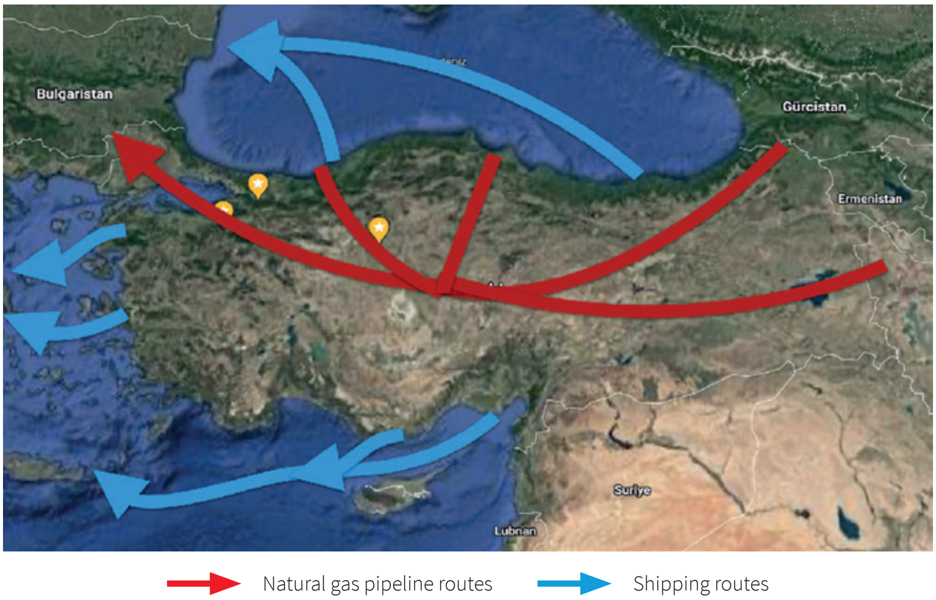
A qualitative assessment has been carried out for two potential export opportunities. The amount of hydrogen gas that can be blended into international pipelines (i.e., TANAP) in Edirne and Eskişehir provinces is 20% according to TANAP officials. To assess the remaining export potential, seaport routes are considered, in which case hydrogen would be converted into ammonia for shipping. While additional costs will accrue due to this conversion process, the cost efficiency of ammonia production highly depends on the feedstock cost, namely green hydrogen (Benner et al, 2012). While electrolyzers account for more than half of capital costs, expenditures on construction facilities are only around 10% for green ammonia production (Sustainable Process Technology, 2017). An extensive review of the literature estimates ammonia production costs from green hydrogen vary between 400 USD/t NH3 and 700 USD/t NH3. This can be reduced to around 300 USD/t NH3 in 2050 (see Table 4).

Table 4: *Literature Review of Ammonia Production Costs*

	Armijo and Philibert (2020)	Ikaheimo et al. (2018)	Rivarolo et al. (2018)	Laval (2020)
Green ammonia production cost	480–700 USD/t NH3	475–525 EUR/t NH3	366 EUR/t NH3	2025–2030: 400–850 USD/t 2040–2050: 270–450 USD/t
Region	Argentina and Chile	North Europe	Brazil-Paraguay	N.A.

Technical limitations as well as maritime traffic and route limitations are discussed while considering export potential in the following chapters. The possible export routes are observable in Figure 15.

Figure 15: *Illustration of Turkey's possible export routes*



2.5 Suitability Index

Based on the supply and export assessment, this study aims to help policy makers and industry sectors select regions that are best suited to the establishment of the hydrogen business. This study identifies these regions through the creation of suitability indexes in order to provide optimum choices for investors and policy makers.

In this report, suitability indexes are assessed in two parts. The main reason for this differentiation is to underline different options for different strategic purposes, such as prioritizing hydrogen development potential to fulfill local demand.

One option to be considered by Turkish policy makers is suitability for domestic supply and demand. This option is labelled as the "domestic suitability index." The domestic suitability index is a weighted index that forecasts the renewable energy supply, water availability, and hydrogen demand of Turkey's 81 provinces until 2050.

The domestic suitability index formula is as follows:

$$(0.3 * \text{Water Availability}) * (0.5 * \text{Renewable Electricity Supply}) * (0.2 * \text{Local } H_2 \text{ Demand})$$

The parameters of this index take into account:

- **Water availability:** This parameter represents the extent to which a province can provide water for the production of hydrogen. Moving forward to 2050, desalination might be an alternative in coastal areas. This is calculated using water balance figures from 2018 and water demand projections in 2050 for each province.
- **Renewable electricity supply:** With the highest coefficient of 0.5, renewable electricity supply is calculated using the total maximum renewable energy supply (including technical potential) for each province. Lower renewable potential would mean no green hydrogen supply, which makes this parameter the most important of the three.
- **Local H_2 Demand:** This parameter reflects the extent to which the hydrogen supply may be used in a specific province. Investors may also take this parameter into account when prioritizing their investments. A coefficient of 0.2 is used. Local hydrogen demand is calculated based on the H10 case.

The suitability index for exports provides a basis from which to analyze the capability of each province to export hydrogen. The index is developed while considering the renewable energy supply, water availability, industrial zones (local hydrogen demand), and the port infrastructure at the province level.The major determinant in the selection of these regions is each region's existing port and trade infrastructure. In Turkey's future hydrogen trade, security or diplomatic concerns may arise; for instance, shipping hydrogen through the Turkish Straits will carry major risks for the regions that have higher populations due to hydrogen's flammability. Therefore, the safety regulations of the trade must be carefully observed. In a similar vein, ammonia is not as flammable as hydrogen, and it is less likely to explode (ARENA Ocean Hyway Cluster, 2020).

The export suitability index formula is as follows:

$$\frac{(\text{Water availability} * \text{Renewable Electricity Supply} * \text{Proximity to Infrastructure}^2)}{(\text{Local } H_2 \text{ Demand})}$$

The parameters of this index are as follows:

- **Water availability:** This parameter is calculated using the water balance from 2018 and water demand projections for hydrogen in 2050.
- **Renewable electricity supply:** This parameter assesses the total maximum renewable energy supply (including technical potential) for each province.
- **Proximity to infrastructure:** This parameter is a major bottleneck for the export potential of each region; thus, this value is squared in the assessment. The closer the province to the seaside, the higher proximity value (on a scale of one to five, with five being the highest) is given to that province. Provinces are also ranked according to the availability of their ports. This is calculated using the absolute distance to the seaside and the availability of ports. This methodology is presented below:

Absolute Distance to Seaside	Points
Seaside with port availability	5
Less than 100 km	4
100–150 km	3
150–250 km	2
More than 250 km	1

- **Local hydrogen demand:** This is calculated according to the H10 case (see chapter 3) for each province. Since higher demand would mean lower export potential, this indicator is used in the denominator.

In both suitability indexes, all values are converted to z-score[7] for the purpose of standardization, apart from the “proximity to infrastructure” indicator. In the second phase, these z-scores are all increased by the lowest amount to avoid negative values. Higher values indicate more water availability, more electricity supply, closer proximity to infrastructure (in our case the seaside), and higher hydrogen demand. One of the aims of the report is to survey export opportunities, where having a seashore is a major advantage for a province. For instance, six regions were specifically studied considering their proximity to major estuary points. It also should be considered that 2050 water demand forecasts for every province are not available in Turkey. Additionally, after considering the statement from TANAP officials on a 20% blending opportunity for hydrogen and declaring that blending into international pipelines will be dependent on international agreements, additional weight was given to the proximity to infrastructure parameter as well as port availability and a province’s absolute distance to the seaside.

[7] https://en.wikipedia.org/wiki/Standard_score

3. Hydrogen Demand

Turkey's energy policy is highly influenced by its relations with Europe and opportunities stemming from trade relations with the European Union (EU). However, unlike the EU's mega-package deals such as the Green Deal, Turkey's energy strategy has generally progressed in a gradual manner. Turkey's national hydrogen strategy might follow the same path. One of the most important pillars of this possible strategy is "creating demand and markets" for a national hydrogen ecosystem. Planning a hydrogen strategy in Turkey requires a solid assessment of future demand, areas of use, and production sites depending on the forecasted needs. An early demand market would allow suppliers to begin their journey with a steeper learning curve and lead to a decrease in the production costs of hydrogen. This would require a collaboration between private and public institutions.

In this study, the use of hydrogen is only focused on end-use applications in related sectors. This could enable a low-cost sustainable strategy for gradual market creation and demand growth. However, it is crucial to understand the structures of each sector in order to better integrate green hydrogen into their processes. It is assumed that natural gas will be blended with green hydrogen for the purpose of heating in end-use sectors. Moreover, current hydrogen consumers (like refineries) will be gradually switching to green hydrogen, while their feedstock needs are being replaced and existing assets will be gradually transformed with green hydrogen in Turkey.

This regional approach, coupled with supply and water requirement calculations, reveals the complementary nature of the future of hydrogen in Turkey. This analysis has been made based on the H5 Case (5% substitution) and H10 Case (10% substitution), which refer to swapping 5% or 10% of Turkey's total final energy consumption with green hydrogen. In both cases, the 2020–2030 period will see a slow take off due to learning and technical safety regulations that need to be prepared. Hydrogen safety is a major concern among policy makers and regulators and may hinder the acceleration of hydrogen development. In the H5 case, a more gradual approach is assumed. The technical tests as well as changing boilers and meters are carried out after 2025, at which point pilot projects are prioritized in the industry sector. Transport, especially road freight, is a major area for development in both cases, followed by natural gas blending. In the accelerated case of H10, hydrogen use is developed through additional support tools and incentives. The main factor in this case is the decline of the cost of electrolyzers and renewable technologies, especially solar. According to the analysis, a maximum of 5% (minimum 1%) of total energy demand in the relevant sectors will be substituted with green hydrogen in 2030. This will increase up to 10% (minimum 5%) in 2050. This implies a total hydrogen demand of 1–2 Mt/year by 2050 for the relevant sectors in Turkey.

3.1 Industry

The industrial and manufacturing sector is considered one of the hardest areas to decarbonize. The manufacturing sector, which is dominated by chemical and petrochemical industries that use fossil fuel as a feedstock, accounts for 39% of Turkey's total final energy consumption when non-energy use is being included. Nearly half of this sector's energy consumption is supplied from imported hard coal, natural gas, and oil (Turkish Ministry of Energy and Natural Resources, 2018). The industrial sector is expected to face carbon taxes on exports in accordance with the

European Green Deal. Thus, in order to sustain the competitiveness of this sector, decarbonization with locally produced and converted energy sources has become an urgent priority for this sector. Green hydrogen could play a vital role in the decarbonization of the manufacturing industry.

3.1.1 Refineries and Petrochemicals

There are two major players in Turkey's refinery sector, namely Star[8] and Tüpraş. Star refinery is in İzmir. Tüpraş[9] has refineries in Batman, Kırıkkale, İzmir, and İzmit. Star refinery was constructed to also provide feedstock to Petkim petrochemical plant. Therefore, Petkim[10] is closely coupled with Star refinery's production. The oil production capacities of the abovementioned refineries are shown in Table 5.

Table 5: *Refineries and Production Capacities*

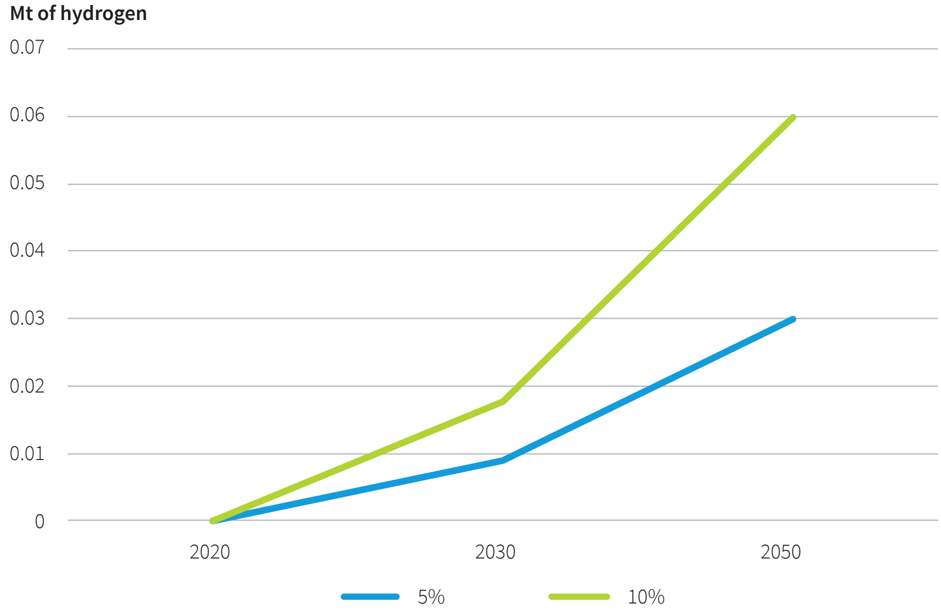
Refinery	Production Capacity (Mt of oil)
Tüpraş İzmit	11.3
Tüpraş İzmir	11.9
Tüpraş Kırıkkale	5.4
Tüpraş Batman	1.4
Star-İzmir	10
Petkim	3.2-3.4

From the demand-side perspective, hydrogen is one of the main components of the petrochemical sector (including petroleum refining) as well as ammonia production, which is mostly used in fertilizer production. By considering the sector's current hydrogen use, the petrochemical sector may be the first sector in which hydrogen replaces natural gas as a feedstock in its processes.

Within this analysis it is assumed that refineries and petrochemical plants will commission greater green hydrogen production after 2025. Hydrogen demand for the petrochemical sector is assessed as 0.06 Mt/year by 2050 in the 10% substitution case. This estimate also includes refineries. A considerably lower demand of 0.03 Mt/year for green hydrogen is assumed in the 5% substitution case (see Figure 16).

[8] http://www.socar.com.tr/star-rafineri.html
[9] https://www.tupras.com.tr/rafineriler
[10] https://www.petkim.com.tr/Sayfa/1/8/KURUMSAL-KURUM-PROFILI.aspx

Figure 16: *Green hydrogen demand for the petrochemical sector in Turkey*



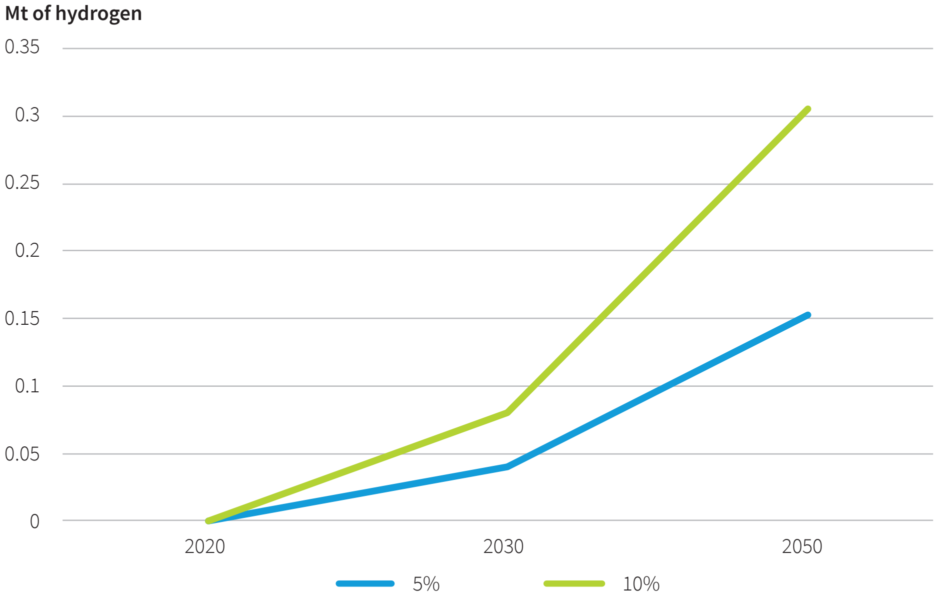
3.1.2 Iron and Steel

In the iron and steel industry, increasing attention is paid to switching from traditional thermal processes to electricity-based alternatives. For iron/steel production the existing electric arc furnaces can be coupled with direct reduced iron (DRI) technology, which relies on hydrogen. Per ton of DRI, about 65 kg (HHV) or 750 Nm^3 of hydrogen is required (Schöffel, 2021). This presents a pathway to decarbonize the process of producing iron from steel, if the logistics and production infrastructure of steel scrap would be altered to drive its commercialization. Turkey ranks in the top ten countries worldwide in iron/steel production capacity. This ranking makes green steel important for the competitiveness of the Turkish steel sector. Currently, there are three major plants in Turkey that can produce iron and steel from ore: Kardemir, İsdemir, and Ereğli. DRI technology is also used in other provinces in Turkey.

Along with the cement sector, the iron and steel sector in Turkey will most likely be effected by the Carbon Border Adjustment Mechanism, because its main trading partner is the European Union. Although switching from traditional processes (i.e., those that use coal as a feedstock) to DRI (i.e., those that use green hydrogen as a feedstock) may increase production costs, the costs saved from the reduced carbon prices may compensate for the initial increase in production costs.

Hydrogen demand in the steel sector is estimated to reach 0.3 million Mt/year by 2050 in the H10 case. In the much more conservative H5 case, hydrogen demand is 0.15 Mt/year by 2050. According to the analysis, the iron/steel sector will account for 16% of total hydrogen demand by 2050 (see Figure 17).

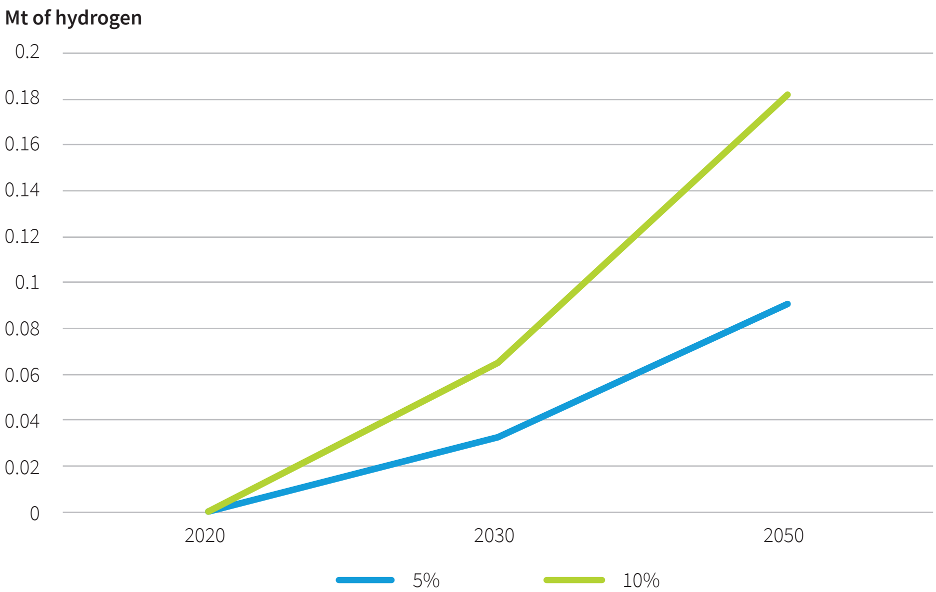
Figure 17: *Green hydrogen demand for the steel sector in Turkey*



3.1.3 Cement

The Turkish cement sector has the capacity to produce approximately 150 million tons/year of cement and is considered as a major exporter to Europe. The greening of cement production is a major issue for the long-term competitiveness of Turkey's cement industry. Compared to steel, the cement industry is geographically much more dispersed in Turkey. This factor may be an advantage if a distributed hydrogen production scenario is followed. The evolution of hydrogen demand is similar in the iron/steel and cement sectors. However, in terms of the total consumption of hydrogen, hydrogen consumption in the cement sector is estimated to be nearly half that of the steel industry. The regionally distributed structure of the cement industry also makes regional hydrogen development a viable option. Within this analysis green hydrogen substitution has been considered as a feedstock to replace the use of coal in production processes in the cement sector. Green hydrogen demand for the cement sector reaches 0.18 Mt/year in the H10 case and 0.09 Mt/year in the H5 case by 2050 (see Figure 18).

Figure 18: *Green hydrogen demand for the cement sector in Turkey*



3.2 Transport

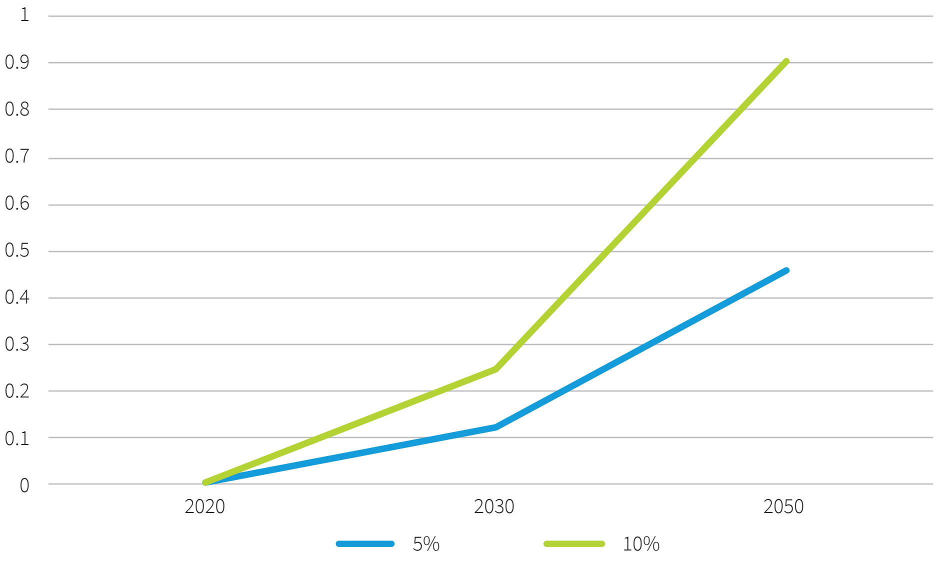
Turkey has a vision to deploy at least 1 million EVs and 1 million charging points by 2030. The charging of EVs will create 4 billion kWh of additional electricity demand, which would increase the country-wide electricity demand about 1% (Saygin et al., 2021). However, road freight is another growing transport mode in which commercial solutions are limited. As the sector emits 23.6 Mt CO_2/year in Turkey, reducing the use of diesel in transport could be a priority area for Turkey (SHURA, 2021). As green hydrogen might replace diesel fuel in certain applications, Turkey can use this opportunity to reduce its energy imports and sustain its energy security.

In transport, hydrogen is assumed to play a sizeable role in road freight. However, EVs are still far from being commercialized as the required infrastructure for charging and battery storage poses a barrier for long-distance freight transport. In the future, it is also possible to see increased opportunities for hydrogen in the aviation and maritime sectors. The major initiators of these developments will be European policies and market dynamics. In the light vehicles sector, electrification will likely be the dominant technology. For long-distance trucks, which consume huge amounts of diesel according to their power and size, electrification is generally less efficient for fuel use when compared to lightweight passenger vehicles. While there is no universal solution for decarbonizing long-haul truck transport, battery-electric and fuel cell electric trucks (FCEV) could be part of the solution.

Hydrogen produced in electrolyzer plants can be transported via trucks (gaseous or liquefied) or via pipelines to hydrogen fueling stations to be used in FCEVs. On-site production of hydrogen (near refueling stations) is another alternative that would eliminate the need for trucks or pipelines. This option will require the storage of hydrogen in tanks. From the decarbonization perspective of the transport sector, FCEVs will require fueling stations and hydrogen infrastructure, while EVs require grid expansion and charging stations.

Our analysis shows that the transport sector will account for around 50% of Turkey's hydrogen demand by 2050 compared to other hydrogen use areas assessed in this study. This implies that the hydrogen demand of the transport sector will reach 0.90 Mt/year if 10% of diesel use is replaced with green hydrogen (see Figure 19).

Figure 19: Green hydrogen demand for the transport sector in Turkey



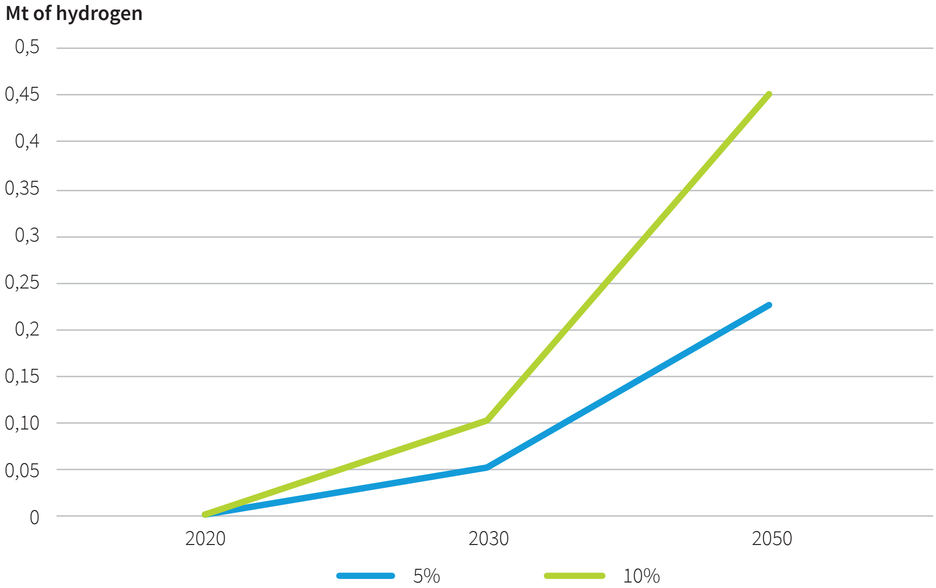
The regional demand for transport matches the regional demand for oil. The demand is highest in Istanbul, followed by Ankara and İzmir. In contrast to the regional distribution of the cement industry, transport demand is concentrated at major hubs. This is also valid for the electrification of mobility. Historically, LPG demand as an alternative fuel for mobility in Turkey boomed in Istanbul and Ankara. Companies have targeted vehicle fleets and taxis for LPG use in transport. In road freight most of the major logistics companies are headquartered in these cities. The results of this study reflect these dynamics.

3.3 Natural Gas Blending

As aforementioned, blending hydrogen into the natural gas grid might be a pillar of Turkey's hydrogen strategy and a priority for Turkish policy makers. This may provide several benefits for the development of the hydrogen economy and reduce import dependency if the opportunities are well understood. According to an earlier SHURA report, even 5% blending in the gas grid will eliminate the need for 2.5 billion m^3/year of imported gas. This would reduce spending on natural gas by around 0.6 billion USD (SHURA, 2021). Blending natural gas with hydrogen is also crucial for the development of hydrogen costs in Turkey in terms of cost reductions. Blending will improve the nationwide utilization of green hydrogen. Turkey has recently expanded its natural gas infrastructure to all villages and purchased floating storage and regasification units (FSRUs). Additionally, recent findings of over 500 billion m^3 of Black Sea mega gas reserves support a strong future for natural gas in Turkey.

Hydrogen demand for natural gas blending for the purpose of heating in end-use sectors is assessed as 0.45 Mt/year in the 10% substitution case and 0.22 Mt/year in the 5% substitution case by 2050. This impies that a quarter of the total demand of 1–2 Mt/year by 2050 will be generated through blending (see Figure 20). It should be considered that the blending of hydrogen into the natural gas grid may be used for different purposes in each sector, especially in the manufacturing industry. This will provide greater substitution in this sector. In this study, it is assumed that the blending of hydrogen into the gas grid is used for the purpose of heating in end-use sectors in order to avoid double counting in the calculations.

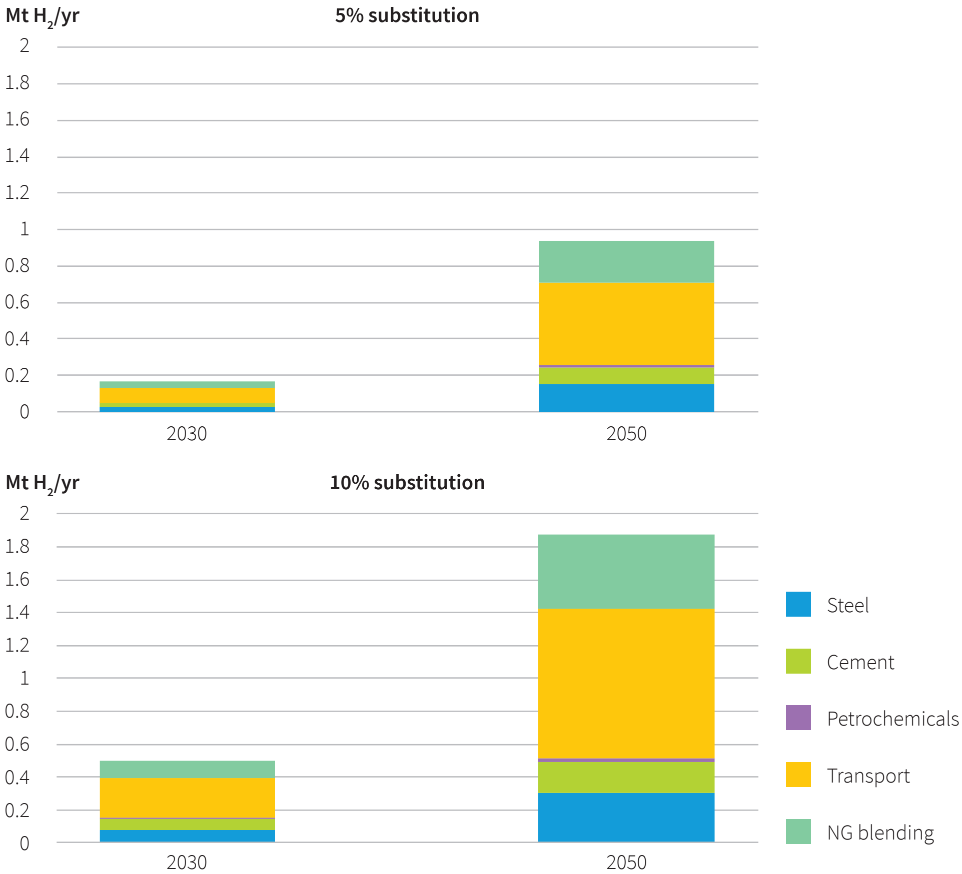
Figure 20: *Green hydrogen demand for natural gas blending in Turkey*



3.4 Total Demand

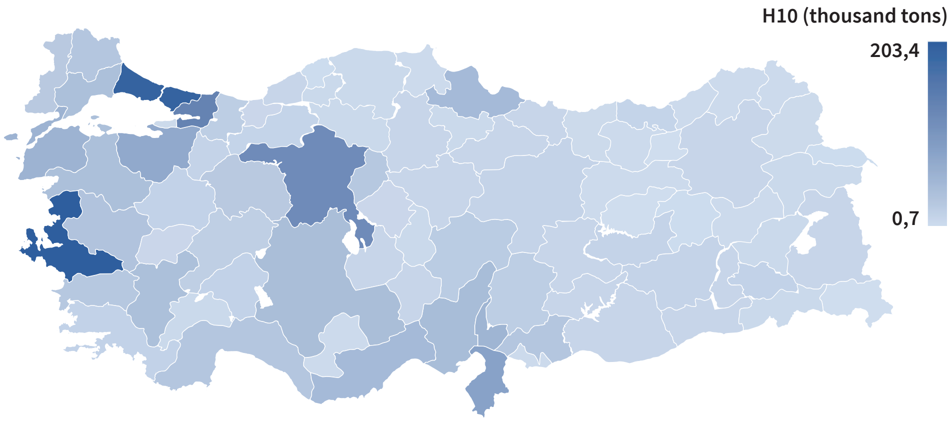
According to the H10 case, total domestic demand for hydrogen will reach 1.9 Mt/year in 2050, if hydrogen is well integrated in the processes of the manufacturing industry (e.g., iron/steel, petrochemicals, cement, fertilizer), transport sector (freight), and natural gas networks. Demand estimates in the H5 scenario, 0.93 Mt/year, are roughly half of those in the H10 case. Detailed results for each sector can be seen in Figure 21.

Figure 21: *5% and 10% substitution of energy demand with green hydrogen for hard to decarbonize sectors in Turkey*



Final regional distribution is not fundamentally different from regional electricity and natural gas consumption, since the assumptions are based on industrial plants, natural gas consumption, and road freight. However, İzmir surpasses Istanbul as the top hydrogen consuming region in Turkey. Several factors contribute to this result such as major petrochemical and refinery zones, port availability, and trade possibility. In the H10 case, Istanbul and İzmir together are expected to demand more than 1.1 Mt/year of hydrogen. İzmit and Ankara are the next biggest consumers of green hydrogen. The eastern part of Turkey is less industrialized, which leads to lower demand. This assessment is in parallel with energy demand trends in Turkey. More densely population regions are generally close to seashores or at lower altitudes. Therefore, regional hydrogen demand trends may not be too different than for other energy sources. Among these regions İzmir as well as the southern part of Turkey, where solar conditionals are favorable, could be considered as rich in renewable resources (Figure 22).

Figure 22: *Regional Hydrogen Demand in 2050 for Turkey (H10 Scenario)*



4. Costs and Supply of Green Hydrogen

4.1 Overview

The green hydrogen supply produced from the cost-effective renewable electricity arise as a common ground of consideration in the hydrogen strategies globally. The synergy between renewable energy sources, infrastructure, electrolyzers, and water costs is essential. This interplay between these parameters should progress in a sustainable way to support Turkey's own energy needs in the long term. For instance, the decision on where to locate electrolyzers will depend on the availability of renewable energy sources as well as infrastructure needs.

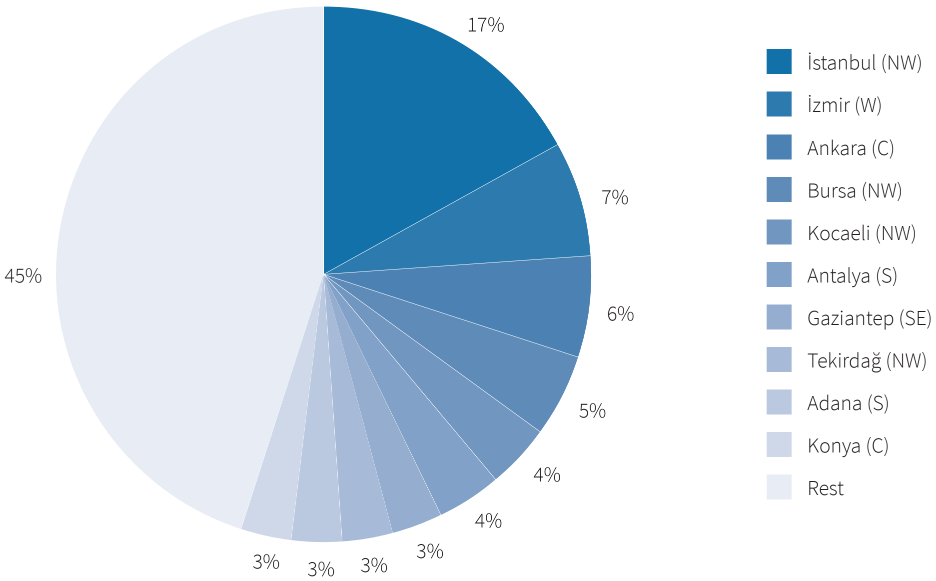
Over the next 30 years, Turkey aims to maximize its integration of low-cost renewable capacity in its grid. If costs and learning curves persist according to historical trends, electrification will have a major cost advantage. However, there are hard to decarbonize sectors and interseasonal (i.e., long-term) storage issues. Green hydrogen can be an alternative and may pave the way for a more resilient energy system, decarbonizing the industrial sector and benefiting from the cost advantages of renewable energy. For an import-dependent country like Turkey, this is an opportunity to both reduce import fuel costs and maintain electricity supply security.

Furthermore, although utilizing solar and wind resources certainly provides power supply security, grid integration needs to be planned considering all system implications. Higher grid integration of wind and solar requires a more flexible power system including demand flexibility, battery energy storage, and other flexibility solutions. Hydrogen, through blending, converting to ammonia, or intermediary energy carriers, may shift renewable peak periods to peak demand periods. The seasonality of Turkey's energy supply-demand dynamics also creates opportunities for exports as well as imports. Exporting electricity is limited to copper wires, but hydrogen and its derivatives may enjoy much more freedom through already existing natural gas pipelines and marine freight. This will also increase the economic utilization of resources.

4.2 Supply and Demand Projections for the Power System

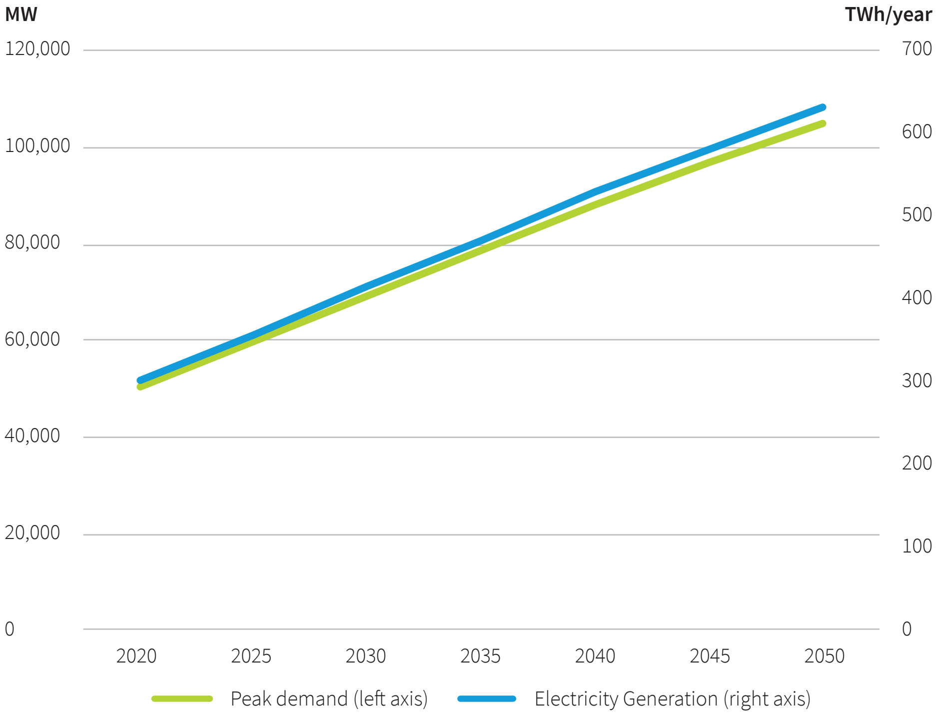
Under an ideal decarbonization strategy, low-cost renewable resources should be consumed within the locality of generation. Therefore, regions that have a higher electricity demand may play a key part in Turkey's future hydrogen strategy. This analysis shows that electricity is mainly used in the northwestern provinces of Turkey. More than half of Turkey's electricity is consumed in ten major cities including Istanbul, İzmir, Ankara, Bursa, Kocaeli, Antalya, and Gaziantep, the majority of which are in the Thracian and Aegean regions. This trend is expected to persist into the future (see Figure 23).

Figure 23: *Share of Electricity Demand by Region*[11]



Compared to 2020 figures, total electricity generation is expected to be more than double in 2050. Estimated annual supply for electricity will reach 631 TWh by 2050, and the growth rate of electricity demand will gradually slow from 3.3% in 2025 to 1.6% in 2050 while taking energy efficiency improvements into account (see Figure 24).

Figure 24: *Turkey's Estimated Electricity Generation and Peak Demand, 2020–2050*



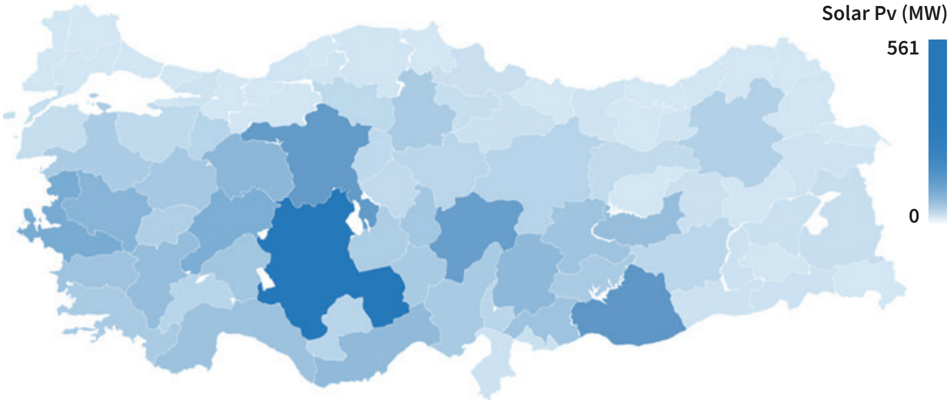
[11] Initials in the parenthesis represent the related geographical location of that province, e.g. "W" stands for West, C stands for Central

4.3 Renewable Power Supply and Costs

Solar

Current solar generation in Turkey is highly skewed in favor of Central Anatolia due to the location of a 1,000-MW Renewable Energy Resource Area (YEKA) tender (see Figure 25). Konya has the largest geographic area of any province, and it is home to the first solar YEKA in Turkey. Land availability, low population density, and proximity to electricity consumption centers and transmission lines are beneficial for such development. Konya is an optimal point when considering such parameters, setting aside water availability. However, the current distribution of solar capacity can also be read as the utilization of sweet spots for solar capacity development in Turkey. If technical limits permit, these provinces also have good grid connectivity. For cheaper green hydrogen production, the expansion of solar energy capacity should be carried out around these regions. From a business perspective, south part of Gaziantep (SE)-Çanakkale (NW) axis (provinces along Aegean/Mediterranean) is clearly visible.

Figure 25: *Estimated Geographic Distribution of Solar Capacity Development in Turkey (2020)*



Currently, the cost of generating electricity from solar PV points is 3 cents USD per kWh in most of Turkey's southern provinces. By 2050, the LCOE of solar PV is expected to drop to 1.8 cents USD per kWh. Figure 26 shows the provinces that could provide electricity for lower than 2 cents USD/kWh by 2050 from solar PV technology.

Figure 26: *Levelized costs of electricity supply from solar PV plants in Turkey, 2050*

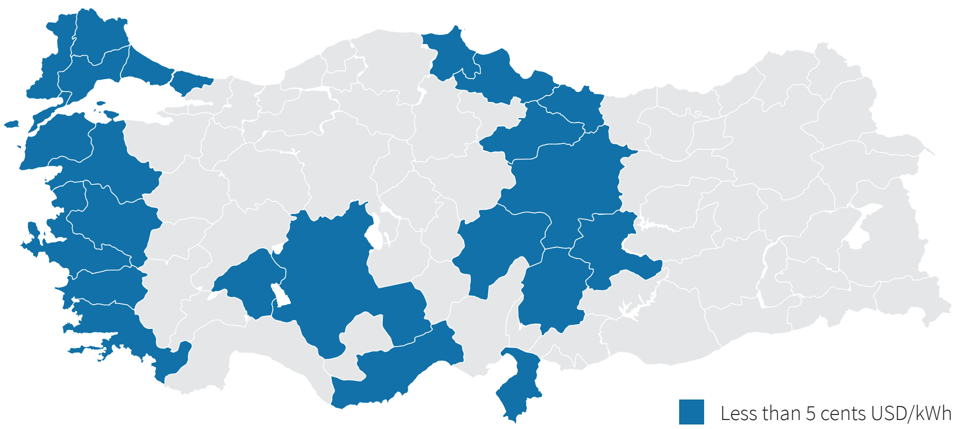
Wind

Wind capacity in Turkey is concentrated in Western Turkey (see Figure 29). This is advantageous, since İzmir is one of the major consumption centers, with a sizable petrochemical and industrial base. The availability of nearby transmission lines also decreases the capital costs to realize projects. Forecasting into the future, as bigger turbines will replace smaller ones, wind capacity in the region will have more room to expand.

Figure 27: *Estimated Geographic Distribution of Wind Capacity Development in Turkey (2020)*

Current tenders in Turkey have seen the lowest bids in Western provinces. By 2050, wind generation costs will range from 3.4 cents USD to 4.7 cents USD per kWh for most provinces. Figure 28 shows the provinces in which it is projected that electricity from wind turbines can be produced for lower than 5 cents USD per kWh in 2050.

Figure 28: *Levelized costs of electricity generation from onshore wind plants in Turkey, 2050*

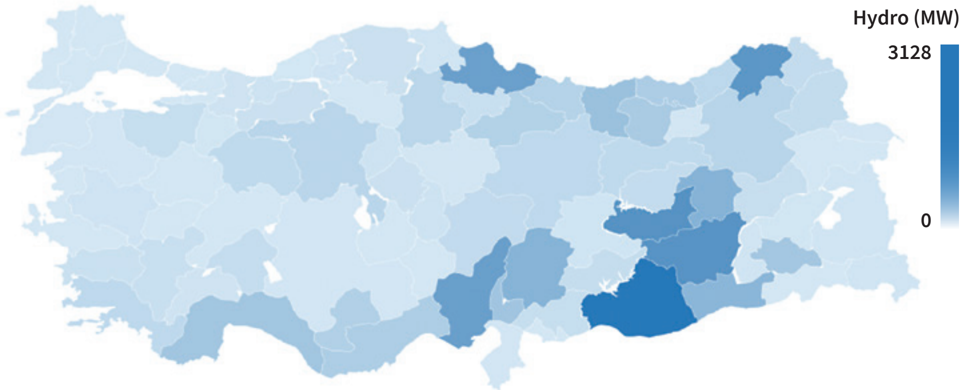


Hydroelectric

Historically, Turkey's major hydro reserves are in the southeastern part of Turkey. However, after the market liberalization of the Northern Black Sea, this region has also become an important hydro generation area (see Figure 29). Furthermore, hydroelectricity is reaching its potential limits. Possible droughts caused by climate change may be a limiting factor for water availability. Cross-border water issues can also constrain water usage.

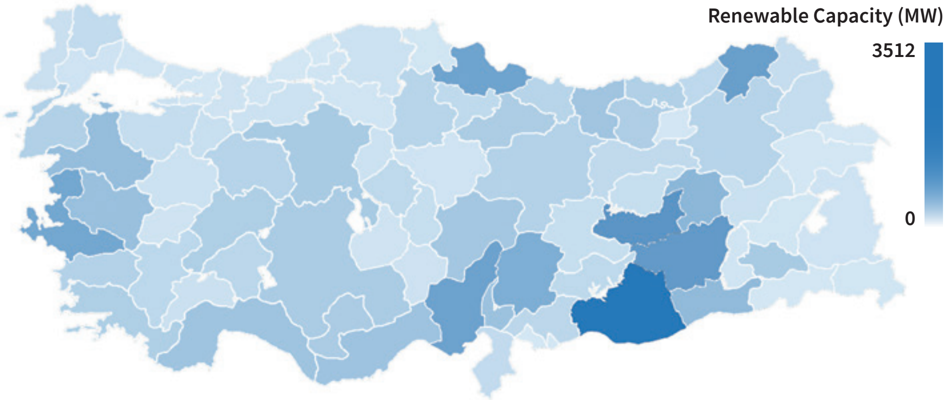
The Northeastern Black Sea region, with its interconnections to neighboring countries, is a low-demand region. The roughness of the terrain increases the connection costs. Therefore, the hydro capacity of this region can be utilized to produce green hydrogen.

Figure 29: *Geographic Distribution of Hydroelectric Capacity Development in Turkey (2020)*



Even if Turkey's current renewable energy capacities are located in separate regions, they are mostly concentrated in the eastern part of Turkey (see Figure 30). The majority of this capacity is from hydroelectric power plants. The highlands of Anatolia are the source of one of the largest hydro capacities in the region; however, hydro expansion is reaching its limits. The current capacity (as of 2020) of 29,790 MW of hydroelectric plants may only extend by 10,000 MW depending on economics and environmental rules. In the forecasted period to 2050, additional wind and solar capacity are expected to be significantly greater than hydro capacity. Given the current (as of 2020) 16 GW of solar and wind installed capacities, traditional East-West distribution has skewed in favor of the West-South axis.

Figure 30: *Estimated Geographic Distribution of Renewable Capacity in Turkey (2020)*



In the western parts of Turkey, there is abundant wind capacity. Hydro resources are located in the northern and eastern parts of the country. Solar resources are more cost effective in the southern part of Turkey. Historically, the availability of renewable energy sources has shifted from eastern parts to the southwest regions of the country. This also shifts the center of gravity of seasonal renewable electricity injections. This shift will also have positive effects in terms of grid development. The traditional east-west flows of renewable resources require huge overhead transmission grids. In parallel, solar PVs and wind turbines can be built close to major population centers, reducing the need for transmission lines.

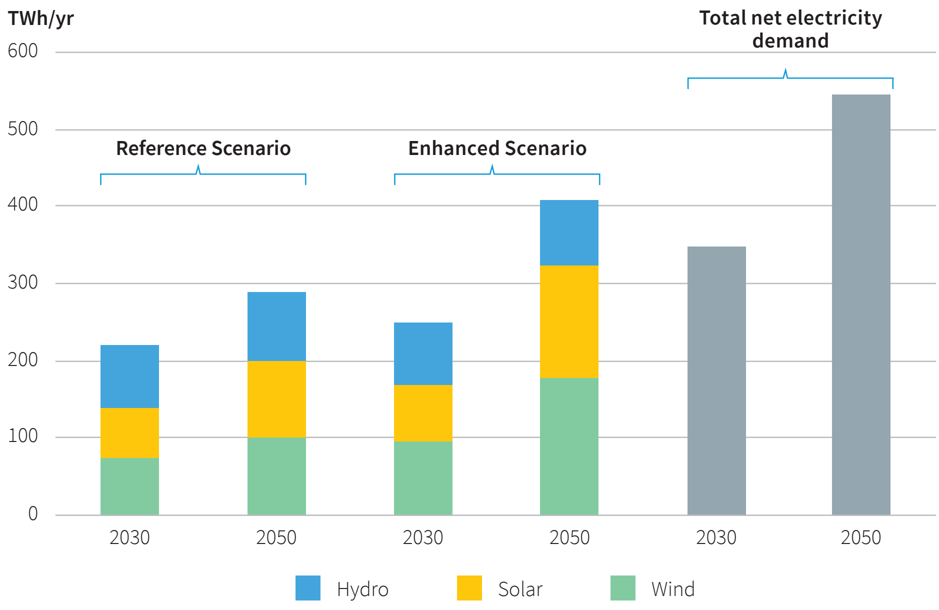
It is assumed that the development of renewable energy deployment will be supported by resource availability and potential. Renewable projects realized in these regions reflect investor cost sensitivity as well as grid capacity availability. The current pattern reflects cost and infrastructure constraints. Hence, it is safe to assume the continuity of this distribution for green hydrogen projects.

4.4 Renewable Energy Scenarios

Low-cost renewable generation in Turkey is assumed to follow current geographic trends with some minor deviations. It is also assumed that there are two possible scenarios for renewable energy capacity expansion. The reference scenario adheres to the current trends, whereas the second (enhanced) scenario assesses whether the maximum available technical capacity can be reached by 2050. In the reference scenario, a total of 44 GW of solar, wind, and hydro capacity in 2020 is expected to reach 129 GW in 2050. The expected total generation from these resources will be around 300 TWh annually. Assuming an annual net demand of 545 TWh in 2050, renewable energy sources can supply 62% of the demand. In the enhanced scenario an additional 45 GW of wind and solar technical potential capacity can be installed by 2050. By utilizing this potential renewable energy generation can supply 84% of the net demand by 2050 (see Figure 31).

In this study, a part of renewable power generation is specifically allocated to produce green hydrogen. Nevertheless, these renewable capacities may also be used for power system decarbonization and taking more actions toward system flexibility. In this decarbonization pathway, hourly excess renewable electricity production needs to be stored and seasonally well managed. It should be noted that the study is not seeking a net-zero carbon strategy for Turkey by 2050. The decisions for utilizing renewable generation are dependent on economic and political strategies.

Figure 31: *Solar, Wind and Hydro Supply Projections for Turkey*



As of 2020, Turkey has 9 GW of wind, 7 GW of solar, and 29 GW of hydro installed capacity. This capacity corresponds to around 114 TWh of generation capacity, excluding seasonal and drought effects. This generation capacity is expected to reach more than 200 TWh in 2030 and approach 300 TWh by 2050 in the reference scenario. Within the enhanced scenario, the technical potential value is reached by 2050. Utilizing these technical potentials will further push electricity generation from solar, wind, and hydro resources beyond 400 TWh. However, this generation capacity does not fulfill Turkey's growing electricity demand. As aforementioned, electricity demand growth is estimated as 2.5% per year on average from 2020 to 2050.

A summary of each renewable projection scenario is presented in Table 6.

Table 6: *Renewable Energy Supply Projections*

Solar + Wind + Hydro Supply		2020	2030	2050
Reference Scenario				
Solar	TWh	11.26	63.23	101.28
Wind	TWh	24.7	75.9	99.95
Hydro	TWh	78.1	82.18	87.86
Enhanced Scenario				
Solar	TWh	11.26	73.64	147.29
Wind	TWh	24.7	96.59	178.31
Hydro	TWh	78.1	82.18	87.86

4.5 Hydrogen Production Scenarios

Domestic demand and production costs of green hydrogen in Turkey are analyzed in the above sections. While defining an optimal production strategy might be challenging, it is important to understand the characteristics that bring the best outcomes for the development of the green hydrogen market in Turkey. The green hydrogen production options studied in this analysis are presented in this section.

4.5.1 Distributed Scenario 1/A

Distributed scenario 1/A provides green hydrogen generation and utilization at the province level by using excess renewable supply. Although regional differences need to be considered, this could provide adjusting the resources at the province level. The major issue in this scenario is water stress and regional cost differences. Investors may prefer low-cost provinces and prioritize their investments accordingly from a business perspective. The state may manage investor preferences through declared available capacity. For instance, for wind energy, cost-effective potential was limited mainly to western provinces in 2020. However, as costs decline toward 2050, this potential expands to southern and central regions as shown in the previous section. Another issue that needs to be addressed is green hydrogen consumption at the local level. Some regions may need massive green hydrogen inflows, while others may need less, and these two regions may be at the opposite ends of the country. A province's proximity to consumption centers like Istanbul, Ankara, and İzmir will be important.

4.5.2 Distributed Scenario 1/B

In this scenario, hydrogen will be produced next to renewable power production facilities by utilizing the unused technical potential of solar and wind resources. There may be obvious benefits to such a scenario but obstacles remain. Blending and accessing the local natural gas grid could be critical factors. From a water availability perspective, the terrain may increase environmental concerns, notably in Central Anatolia, over distributed hydrogen production.

According to the reference capacity deployment, wind, solar, and hydro capacity may reach 129 GW by 2050. An additional 45 GW of wind and solar PV plants can be installed using their unutilized technical potential. This will add an additional 124 TWh of power generation annually to the Turkish power generation mix by 2050. This scenario projects that green hydrogen production will be sourced from the unutilized technical potential of solar and wind energy.

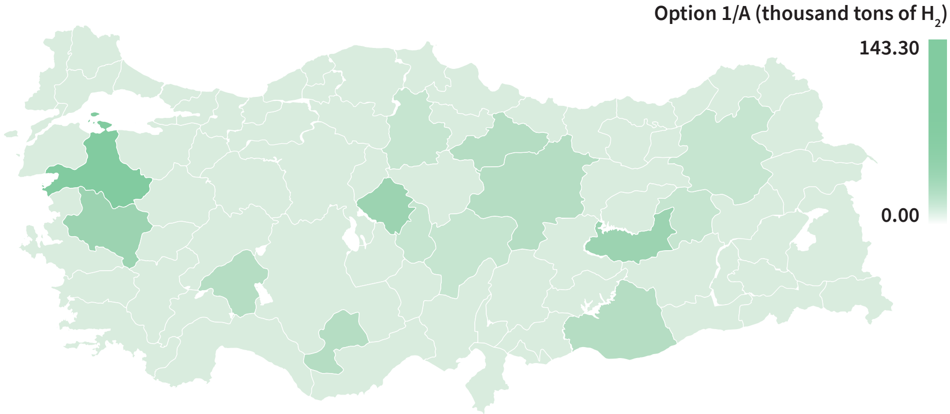
Whether Turkey's energy future moves toward electrification or a mix of low-carbon resources, the expected grid structure is much more federated in the distributed scenario. The distribution grid at the center of microgrids may provide better system security and reduce total system-wide events. From an equitable perspective, the regional economy, employment, and energy security at the local level will be improved. This will also reduce the flexibility and security needs at the country level, since it will be managed on the local level.

4.5.3 Hydrogen Production from Distributed Scenarios 1/A and 1/B

In distributed scenario 1/A, total excess electricity supply from renewable power across the various provinces is about 50–55 TWh with wind and solar contributing 28 TWh by the 2030–2050 period. Assuming electrolyzer efficiencies of 75%, total hydrogen supply from this excess power can reach 0.64 Mt/year (77 PJ) by 2050. Close to 85% (65

PJ) of this production can be achieved by 2030. The rest will gradually be realized by 2050. Three provinces in the Aegean part of Turkey, namely Balıkesir, Çanakkale, and Manisa, will account for 35% of total production. Seven other provinces in the central and eastern regions with high solar availability account for another 50% of production (Figure 32).

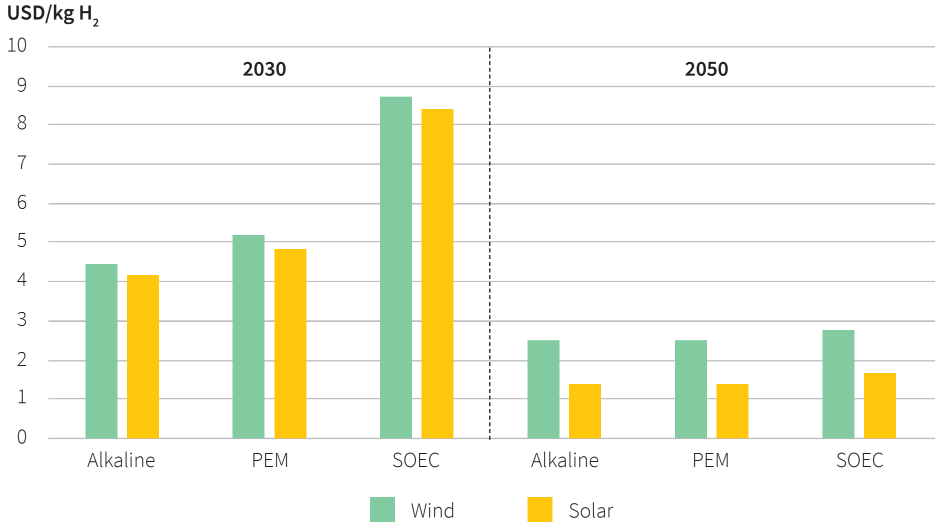
Figure 32: *Breakdown of H_2 production potential at the province level for distributed scenario 1/A in 2050*



If unutilized wind and solar potential is exploited further, an additional 2.8 Mt/year (335 PJ) of green hydrogen could be produced. The western provinces of İzmir, Balıkesir, Çanakkale, and Manisa represent half of the wind-based hydrogen production potential of 1.75 Mt/year. Ten cities in the center and southeastern provinces of Turkey account for half of the total solar-based hydrogen production potential of 1.05 Mt/year (see Annex Figure 46). Combining this portion of 2.8 Mt/year (335 PJ) with excess power supply, hydrogen production by 2050 will be 3.4 Mt/year (415 PJ). The cost curve of the different electrolyzer technologies will also be important for reaching this level. Utilizing the technical potential of wind and solar resources, green hydrogen could be produced with for average price of 1.5 USD/kg.

As the learning potential for each component is different, alkaline and PEM technologies could be on par by 2050, which means these technologies will provide the cheapest hydrogen production. Hydrogen generated from solar electricity will be cheaper than wind. Green hydrogen production costs could fall to 1.38–2.45 USD/kg for Alkaline and PEM technologies if the electricity is produced from wind and solar (see Figure 33). Yet, operational issues for electrolyzers such as cycling flexibilities are also important factors. In both alkaline and PEM technology, a smaller number of provinces have the upper hand in costs. Wind resources favor western regions, and solar resources favor southern and central regions.

Figure 33: *Estimated levelized costs of hydrogen production from different electrolyzer technologies in Turkey*



These cost estimates rely highly on capital expenditure (CAPEX) assumptions of electrolyzer investment, LCOE of solar and wind resources, and chosen discount rates. Efficiency and capacity factors are also important technical parameters to reach this level of cost effectiveness. For instance, capacity factors are expected to be much lower at the distributed level than in the centralized scenario.

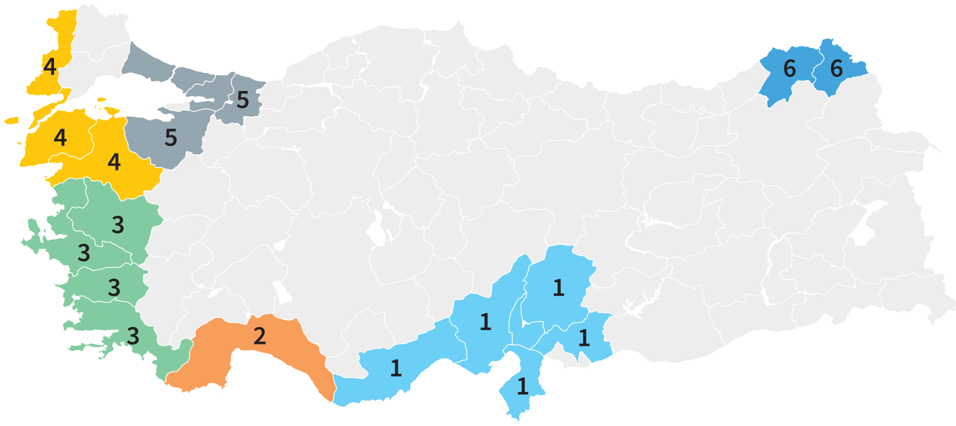
In the distributed scenarios a total of 3.4 Mt/year of hydrogen production is estimated for 2050. Approximately 2.8 Mt of this production will come from unutilized technical wind and solar capacity. The rest will be provided from excess power supply. Hence, an additional 35.3 GW of decentralized electrolyzer capacity is needed, assuming at least 75% electrolyzed efficiency and 50% hybrid renewable capacity factors. Approximately 6.6 GW of this capacity is needed for excess power supply, and 28.7 GW is harnessed from the technical potential of wind and solar. The total investment in such capacity will fluctuate between 17 billion USD in the alkaline case to 33 billion USD for the SOEC option. This excludes the investment of 50 billion USD needed for renewable power.

4.5.4 Centralized Scenario 2

In the centralized scenario, economies of scale, water availability, and export opportunities are the major determinants for the development of the green hydrogen economy. For green hydrogen to have a major share in Turkey's energy mix, it must be cost effective. These costs are mainly dictated by resources. Solar and wind costs are highly sensitive to geographic location. Therefore, it could be better to have centralized production in certain provinces and then transmit and store in the most cost-effective way within close proximity to consumption centers. Considering the resource availabilities described in the previous sections, six regions were determined for analysis (see Figure 34):

- Region 1 (Southeast Turkey): Adana, Gaziantep, Hatay, Kahramanmaraş, Kilis, Mersin, Osmaniye
- Region 2 (Southern Turkey): Antalya
- Region 3 (Western Turkey-1): Aydın, İzmir, Manisa, Muğla
- Region 4 (Western Turkey-1): Balıkesir, Çanakkale, Edirne
- Region 5 (Northwestern Turkey): Bursa, Istanbul, Kocaeli, Sakarya, Yalova
- Region 6 (Northeastern Turkey): Ardahan, Artvin

Figure 34: Provincial Breakdown of Centralized Scenario 2



Centralized production may enable the development of cost-effective hydrogen hubs around the country. The concentration of resources in a small number of geographically distributed regions may be preferred by grid operators, since it may help them in handling a smaller number of connections and plants. Table 7 shows a comparison of the characteristics of these six regions, which could be useful when prioritizing investments.

***Table 7:** Comparison of the characteristics of the selected six regions*[12,13]

Regions	1	2	3	4	5	6
Port Availability	+++	++	+++	+	+++	-
Industry (Refineries)	+++	-	+++	--	++	---
Renewable proximity	++	+++	+++	+++	-	+++
Water resources	+	++	+	++	-	+++
Demand centers	++	+	+++	+	+++	---
Infrastructure	++	-	+++	++	+++	+
Marine Safety	Med	Med	Med	Med	B.Sea	B.Sea

The first region is comprised of Adana, Osmaniye, Mersin, Kilis, Kahramanmaraş, Hatay, and Gaziantep. From a historical perspective, this region has been the traditional hub of the Turkish energy strategy. Currently, the city of Yumurtalık is a major outlet for Azerbaijani and Iraqi oil. A nuclear power plant is also currently under construction. There may be an option to produce low-carbon hydrogen from excess production in this plant. Although not included in this study, this option should not be omitted, at least for domestic purposes. The industrial base, electricity generation capacity, LNG infrastructure including FSRU shipping, proximity to major hydro projects, and benefits from the Seyhan-Ceyhan estuary are important opportunities for this region.

[12] Marine Safety : Med : Safe for Mediterranean only , B.Sea: Safe for Blacksea only
[13] (+++ very favourable, --- not very favourable, has major issues)

The second region, Antalya, is home to one of Turkey's major water export projects. The Manavgat River and its water potential have been discussed for decades in water diplomacy. Antalya is also relatively close to major solar projects. These projects include Konya Karapinar YEKA project, which has a 1,000 MW capacity. Neighboring provinces like Burdur have attracted recent tenders and investors' attention. Hence, this region is favorable because of both its solar and water availability, very seasonal demand, and low industrial bases as well as port availability.

The third region, which consists of Aydın, Muğla, Manisa and İzmir, is one of the most feasible regions within the analysis. A well-established and highly developed petrochemical/refinery industry is key to this region's success. High wind availability and capacity is another enabler. Since the hydrogen strategy may stem from hydrogen-consuming sectors, one of the most cost-effective ways to do this is through refineries and petrochemical industries. The main cons for this region are water availability and distance from possible solar projects. There is also a risk of consuming all the hydrogen in that region and not allocating any spare capacity for exports, depending on strategic decisions.

The fourth region, consisting of Çanakkale, Balıkesir, and Edirne, is important in terms of wind potential and proximity to Europe. The grid infrastructure has been recently strengthened, and both TANAP and the domestic gas transmission grid are accessible in that region. Its proximity to İzmir creates a trade-off, favoring one region over another. However, this region is close to the midpoint between Bursa and İzmir, two major industrial regions, and has a low population density. Desalination may be considered as an option in this region.

The fifth region consists of Yalova, Sakarya, Kocaeli, Istanbul, and Bursa. This region was chosen on the grounds of its proximity to Turkish natural gas developments in Filyos and the refinery in İzmit. It is very close to the industrial heartland of the İzmit-Gebze districts. For the safety of the Bosporus and Istanbul, a hydrogen or ammonia port in this region may serve the Black Sea region only. Renewable resources are scarce here; however, the grid structure is very strong and would benefit from various regional developments.

The sixth region, namely Artvin-Ardahan, has excessive water availability, low electricity demand, and a large hydro capacity. Moreover, possible hydrogen demand in this region is not expected to be much because of less industrial activity compared to the other provinces. The region also has port availability. Therefore, region six can be a major export point for the Black Sea rim.

In this scenario, 16.9 GW of 35.2 GW electrolyzer capacity will be reallocated throughout these six regions. This means that hydrogen production from all 81 provinces of Turkey will shift to these six regions. The electricity demand arising from green hydrogen generation will be exported to these regions from the nearest renewable resource bases. Hydrogen production will shift to major industrial regions and the Northeastern Black Sea region. Table 8 details the reallocation process of the centralized scenario.

Table 8: Breakdown of electrolyzer capacity for distributed and centralized generation of H_2 production in the six regions

	Before reallocation (distributed)	After reallocation (centralized)	Total electricity demand for electrolysis	Share imported from other provinces
Unit	[GW]	[GW]	[TWh/yr]	[%]
Region 1	3.1	7	30.3	55%
Region 2	0.2	1.2	5.3	79%
Region 3	8.4	11.5	50.3	27%
Region 4	5.8	6.7	29.3	13%
Region 5	0.6	8.5	37.1	92%
Region 6	0.006	0.07	0.3	92%
Total	18.3	35.2	153	48%

However, this scenario adds significant grid investments. Transmission grid investments may increase solar and wind costs by 0.02 USD per kWh. This will inflate hydrogen production costs (1.5 USD/kg) by 0.1 USD/kg of hydrogen. Expected grid investments will require close to 2,000 km of new lines and over 40,000 MVA of transformer capacity (see Table 9). Grid costs differ by region, with a minimum of practically zero to up to 0.026 cents USD/kWh. After the reallocation of electrolyzers, transferring electricity produced from excess supply, and utilizing the technical potential, 3.4 Mt of hydrogen could be produced within these regions by 2050. In the centralized scenario green hydrogen could be produced for 1.6 USD/kg by 2050.

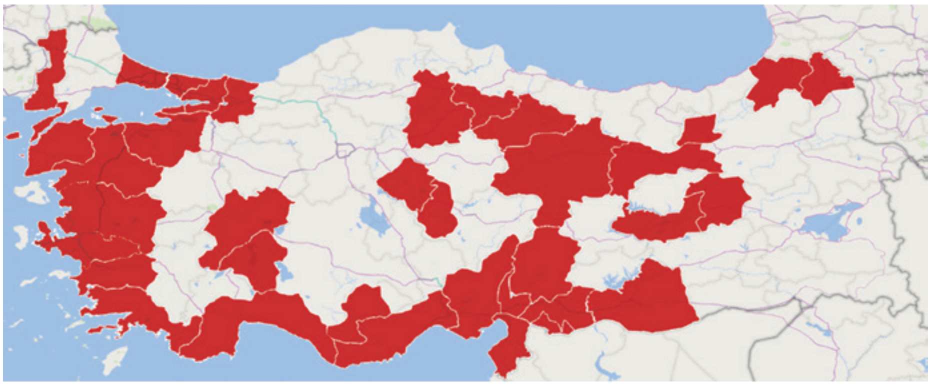
Table 9: Breakdown of transmission grid investment needs and the impact on levelized costs of electricity generation by 2050

Region	Electrolyzer Capacity (MW)	Transmission Lines (km)	Transformer Capacity (MVA)	Transmission Line Costs (bln USD)	Transformer Costs (bln USD)	Total Grid Cost (bln USD)	Unit Grid Cost (USD cent/kWh)
1	7,002	449	9,102	0.94	0.07	1.02	0.018
2	1,240	192	1,612	0.07	0.01	0.08	0.001
3	11,594	622	15,072	2.16	0.12	2.28	0.067
4	6,765	273	8,793	0.55	0.07	0.62	0.009
5	8,567	342	11,136	0.88	0.09	0.97	0.026
6	73	5	94	0.00	0.00	0.00	0

4.6 Water Availability

One of the biggest unforeseen obstacles for hydrogen generation is water availability. A distributed scenario will require transferring water between provinces. This may further escalate environmental and societal pressures. Hydrogen consumption and balance should be watched carefully, and the existing demand from agriculture, industry, and other sectors that use water feedstock should be considered. Desalination must be an alternative to solve these issues. While planning future hydrogen strategies, policy makers should keep a close eye on future climate change-related water shortages. The other issue is cross-border rivers. These may provide low-cost hydroelectricity, but using this water for hydrogen production may result in geopolitical issues. Potentially water stressed regions are depicted in Figure 35 (desalination is not considered).

Figure 35: *Provinces that could potentially face water shortages*[14]



Possible provinces to face water shortage

On the macro level a review of the literature shows that water availability will not be a significant reason to avoid green hydrogen production in scale. Although green hydrogen production will require 15 liters of fresh water for every kilogram of hydrogen, the water requirements are much less than water requirements for the extraction and processing of fossil fuels (see Annex Figure 47) (Energy Transitions Commission, 2021).

[14] Stressed regions are determined according to water demand in each province (2018) – H_2 electrolyzer water demand (2050)

5. Hydrogen Exports

5.1 Opportunities for Hydrogen

As green hydrogen takes its place among the leading global decarbonization strategies, Turkey has the opportunity to utilize its abundant renewable resources and play a role in the potential hydrogen trade game through 2050. This would imply transitioning to a low-carbon economy fueled by renewable energy sources such as wind, solar, and hydro. As shown above, this would be possible with considerable investments, subsequently followed by appropriate demand planning around the country.

One of Turkey's motivations for implementing a hydrogen strategy with cross-border trade components is its relations with and proximity to the EU. The EU foresees a promising outlook for large-scale imports of green hydrogen by 2050. The European Commission has indicated an important role in international trade with the EU's neighbors. It has also highlighted that its hydrogen supply will mainly consist of hydrogen produced from renewable resources, while blue hydrogen will play a role in the short to medium term (COM, 2020).

Industrial players in Turkey trade a substantial portion of their production with the EU. From automotives to appliances and energy-intensive sectors, European companies have shares in Turkish companies, too. Turkey's manufacturing industries generally do not have two separate production lines for Europe and another for the domestic market. Moreover, they market the same products manufactured for export markets within the domestic market. Hence, EU rules and strategies shape the Turkish manufacturing industry. Politically, EU-Turkey relations may stagnate; however, trade relations will be important for both parties.

Our estimates indicate that hydrogen might have a 10% share in Turkey's total energy supply by 2050. This implies that there will be some kind of trade for arbitration and supply-demand timing issues. Export options may cause further increases in renewable energy capacity deployment. Electrolyzer capacity can serve as a demand response unit for balancing the grid during periods of excess electricity generation from renewable resources without curtailing resources. Hence, electrolyzer capacity can be regarded as a demand response unit providing flexibility and storage in certain setups. A seasonal perspective should also be considered for export assessment. Electricity generation from renewable resources in Turkey, like other countries' profiles, has large seasonal discrepancies. Apart from solar, these discrepancies may not concur with demand patterns.

Turkey's opportunities for exporting hydrogen will depend on the hydrogen supply and demand balance through 2050. When the country-wide supply potential of 3.4 Mt of hydrogen is matched with a local max demand of around 1.9 Mt/year, this implies a 1.5 Mt/year hydrogen export potential for Turkey. However, there are large differences between supply and demand at the regional level. In the centralized scenario, with the exception of region six, there is more electricity available for hydrogen production after the hydrogen demand is met, since the hydrogen demand will be concentrated in six regions, not all 81 provinces. This would imply an export potential of 1.9 Mt (225 PJ/year) for hydrogen by 2050. It should be considered that Turkey may not reach this export potential, if there would be limitations on the hydrogen supply or if there would be more local demand.

5.2 Blending into International Pipelines and Conversion to Ammonia

Quantitative and qualitative assessment of Turkey's hydrogen export potential has been carried out in order to assess blending into international pipelines and shipping means after converting hydrogen to ammonia.

The use of existing pipelines, namely Bulgaria and Greece interconnectors, are well-integrated into Turkey's gas grid. However, exports through these lines are currently limited. Blending up to 10–15% may change the agreement structure and should comply with recipients' grid codes. This option may be cost efficient and further pave the way for more renewable energy penetration in Turkey, which could be investigated in the future.

To blend hydrogen, the most viable option is utilizing TANAP. TANAP officials have declared a possibility of up to 20% hydrogen blending. This 20% blending would mean that 0.2 Mt (20 PJ) of hydrogen (10% of export potential, 1.9 Mt/year or 225 PJ/year) could be transported through international pipelines. TANAP can be transformed from a methane to a blended methane and into a low-carbon hydrogen pipeline in the long term.

TANAP has two exit points in Turkey, one is in Eskişehir and the other in Thrace. The options for blending are as follows:

1. A dedicated hydrogen pipeline can be extended to Eskişehir or Thrace to pressurize hydrogen and inject it into the TANAP pipeline.
2. Domestically blended gas may be pressurized and mixed with TANAP.
3. Electrolyzers may be installed at the exit points of TANAP to produce, pressurize, and inject hydrogen into TANAP.

Hydrogen blending may require changes to several agreements, including financial ones. The insurance terms and compressor operations should be adjusted accordingly. The conversion of TANAP may benefit neighboring countries with rich renewable energy sources.

In the distributed scenario, a dedicated hydrogen grid should connect regions with rich renewable resource potential to industrial demand centers. This grid can also reach port outlets. The current Turkish natural gas grid consists of close to 15,000 km of steel and 95,000 km of polyethylene pipelines. Figure 36 shows a potential hydrogen grid for Turkey that is 7,756 km long and has a price tag of 19–26 billion EUR. Compressors and other equipment costs will total an additional 0.6–0.8 billion EUR. This infrastructure would increase hydrogen costs around 0.12-0.21 USD/kg and enable both exports from marine ports and pipeline connections, creating the flexibility for export options. This pipeline can be extended to Bulgaria and Greece to be integrated with European hydrogen pipeline projects.

Figure 36: *Projections for Turkey's Hydrogen grid*

Possible hydrogen pipelines

The alternative option to pipeline use is the conversion of green hydrogen into its derivatives such as ammonia, which has recently attracted the attention of policy makers. Almost 30% of low-carbon hydrogen is estimated to be in the form of ammonia and synthetic liquids and gases by 2050 (IEA 2021). The role of ammonia should not be underestimated in achieving climate goals. From the remaining 200 PJ/year of hydrogen export potential (or about 1.7 Mt H_2 after injecting this into pipelines), it is possible to produce 9.5 Mt NH3/year (based on stoichiometry of 0.178 t H_2/t NH3).

Turkey's renewable energy potential may enable a supply price of 1.5–1.7 USD/kg for green hydrogen and 300 USD/t ammonia by 2050. Market players and policy makers may use that leverage to foster trade and benefits from expanding market size. Foreign investors may also see an opportunity from Turkish green hydrogen development and potential market size. Just like Turkey's power grid integration with the European Network of Transmission System Operators for Electricity (ENTSO-E), which brought benefits to both Southeastern European grid security and Turkish grid operations, hydrogen and ammonia may also serve these purposes.

6. Key Findings

The results of this report help us to understand the potentials of green hydrogen production considering renewable energy potential, its use in the domestic market, and its export opportunities within the distributed and centralized geographical parameters.

Total hydrogen demand may reach 1–2 Mt/year if green hydrogen is well-integrated into the processes of decarbonizing the gas grid and the transport and manufacturing industries. In a 10% substitution scenario, expected green hydrogen consumption for steel, cement, petrochemical, natural gas blending, and the transport sector would be 0.30 Mt/year, 0.18 Mt/year, 0.02 Mt/year, 0.45 Mt/year, and 0.90 Mt/year, respectively, by 2050.

Table 10: *Comparison of Hydrogen Demand in the H5 and H10 case*

Hydrogen Demand Total		2030	2050
H5 (5% substitution)	Mt/year	0.24	0.94
H10 (10% substitution)	Mt/year	0.5	1.87

Total hydrogen supply from excess renewable power is projected as 0.55 Mt/year (65 PJ) by 2030 and 0.64 Mt/year (77 PJ) by 2050 in distributed scenario 1/A. Distributed scenario 1/B depicts a scenario in which all the technical potential of wind and solar energy capacities is utilized (i.e., installing 45 GW more than in the reference case) by 2050. This would result in an additional 2.8 Mt/year of green hydrogen supply. Using a centralized approach for hydrogen production will require the transfer of renewable power that is produced from the technical capacity of wind and solar and the excess renewable supply from six key regions. Total hydrogen supply in this scenario is assessed as 3.4 Mt/year.

Table 11: *Comparison of Total Hydrogen Supply for Different Production Scenarios*

Total Hydrogen Supply		2030	2050
Distributed Scenario 1/A	Mt/year	0.55	0.64
Distributed Scenario 1/B[15]	Mt/year	0.63	2.8
Centralized Scenario 2	Mt/year	1.17	3.4

Additionally, water availability is essential to consider while developing the overall green hydrogen strategy. This report specifically underlines the importance of water availability for a sustainable hydrogen future in Turkey. Decentralized production of hydrogen would mean transferring water from one region to another, whereas in the centralized scenario the water availability in six key regions is considered. It is assumed that around 15 kg of fresh water is needed to produce 1 kg of hydrogen. The ecological impacts of water use need to be carefully evaluated in developing a hydrogen strategy. If the electricity costs produced from solar continue their downward trend, desalination will be another cost-effective option for coastal areas.

[15] Distributed scenario 1/B is complementary and additional to distributed scenario 1/A. Total hydrogen supply for the distributed scenarios (1/A + 1/B) reaches 3.4 Mt/year in 2050.

The potential cost effectiveness of green hydrogen production in Turkey is assessed on a geographical level. Total average production costs of hydrogen may decrease to below 1.5 USD/kg H_2 by 2050 in accordance with expected developments in electrolyzer technologies and renewable electricity costs. The centralized approach would require additional power grid investments, and these costs will add up to 0.02 cents USD over the LCOE of solar and wind energy, which will increase hydrogen production costs around 0.1 USD/kg H_2. This would mean a hydrogen production cost of 1.6 USD/kg H_2 by 2050 in the centralized scenario.

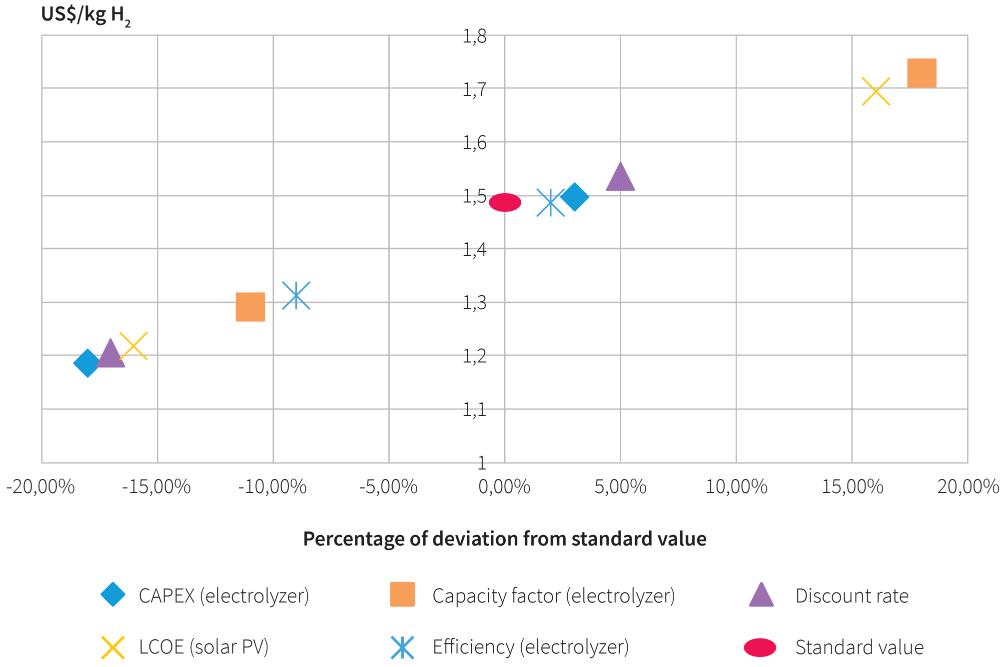
Table 12: *Comparison of Hydrogen Production Costs for Different Electrolyzer Technologies*

Hydrogen Production Costs[16] (Solar, Wind, Hydro)		2030	2050
Alkaline	[USD/kg H_2]	4.14–4.45	1.39–2.47
PEM	[USD/kg H_2]	4.85–5.17	1.38–2.46
SOEC	[USD/kg H_2]	8.40–8.71	1.66–2.77

The results of the local sensitivity analysis for Turkey are shown in Figure 37 in order to better visualize the effects of each parameter on hydrogen production costs. A standard value of ≈ 1.5 USD/kg for hydrogen production costs, which is depicted as a red dot in the figure, is assumed in order to perform a standardized sensitivity analysis. The table below the figure shows the values that is used to perform the sensitivity analysis. The values used to reach the standard value ≈ 1.5 USD/kg are marked in red. The increase/decrease of the parameters are reviewed according to their percentile deviations from ≈ 1.5 USD/kg, while other parameters stay constant. According to the sensitivity analysis, renewable electricity costs are one of the most important parameters in the cost reduction of green hydrogen. This confirms the positive relationship between green hydrogen and renewable electricity. Additional renewable cost decreases will make green hydrogen competitive, among other hydrogen resources. For instance, if the LCOE of solar would decrease to 1.5 cents USD/kWh (from 1.8), the reduction rate in production costs would be 16%, and the price would fall to 1.2 USD/kg. Higher deviations from normal values for the capacity factor demonstrates its importance for green hydrogen cost sensitivity. If system integration is not carefully orchestrated, then capacity factors may drop to 25%, and the increase in production costs would be 18%, which implies a hydrogen production cost of 1.7 USD/kg. Capacity factors are expected to be much lower at the distributed level than in the centralized scenario, since the quality of solar and wind power are well established in centralized locations. The effect of reaching 100 USD/kW for electrolyzer CAPEX would mean an 18% reduction in hydrogen costs. The discount rate is another important parameter for green hydrogen. As the discount rate increases, the cost of borrowing increases, and the return on investments also decreases in real terms. Another implication of the discount rate is whether tapering monetary policy may increase in the future, which may affect borrowing costs for such large and new technologies. If discount rates increase to 15%, the increase on hydrogen production costs would be 5%, which implies a hydrogen production cost of 1.53 USD/kg. The effect of electrolyzer efficiency is also important for further cost reductions, however its effect on hydrogen production price is rather limited compared to other parameters.

[16] The lower bound represents solar PV-based hydrogen, while the upper bound represents wind-based hydrogen.

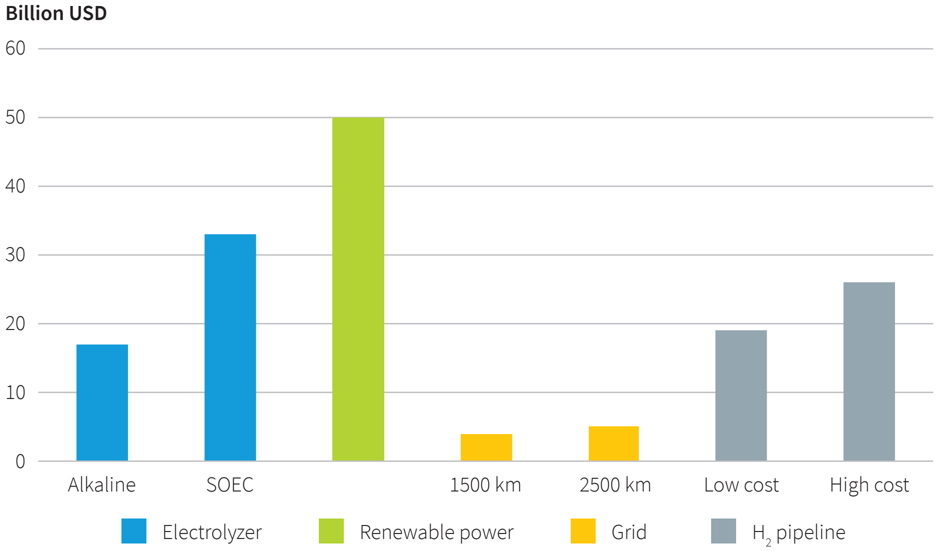
Figure 37: *Sensitivity analysis results for solar PV-based H_2 production costs in 2050 (alkaline electrolysis)*



Parameters		1.5 USD/Kg H_2	
CAPEX (USD/kW)	100	200	250
Capacity factor (%)	25	50	75
Discount rate (%)	2	10	15
Solar PV LCOE (USDcent/kWh)	1.5	1.8	2.5
Efficiency (%)	70	75	80

Considering the importance of each parameter, the assessed hydro economy in this report requires 35.3 GW of electrolyzer capacity to be constructed assuming 75% electrolyzer efficiency and 50% hybrid solar and wind capacity factors. Depending on technological developments, total investment needs for electroyzers could range from 17 billion USD for alkaline to 33 billion USD for SOEC. This excludes investments in renewable energy capacity, which can amount to an additional 50 billion USD. Adding grid and hydrogen infrastructure needs, a total of 85–119 billion USD will need to be invested into the formation of the hydrogen economy. It is estimated that the total investment costs will be lower in the centralized generation strategy because of the required hydrogen pipeline infrastructure needed in the distributed generation strategy. On average, 3–4.8 billion USD of investment per year between 2021 and 2050 is needed to form the proposed hydrogen economy (see Figure 38).

Figure 38: *Investment needs for the H_2 economy*



To put this into perspective, power sector investments in Turkey are currently around 7 billion USD annually. The total gross benefit of this hydrogen eco-system would be around US$ 6 - 8 billion per year in 2050 for the Turkish economy (after accounting possible export potential and avoided import fuel costs). This would lower Turkey's imported natural gas, oil and coal consumption assuming that substituting 10% of the related sectors total demand with blending green hydrogen in to natural gas grid, replacing diesel use of freight transport and feedstock need of industry, which brings a benefit around 2-3 billion USD/year. A new export market, with an export potential ranging from 1.5–1.9 Mt/year by 2050 and estimated supply costs of 1.52–1.73 USD/kg of hydrogen would mean 300 million USD/year for blending (0.15–0.2 Mt/year) and 4.5 billion USD for ammonia (1.35–1.7 Mt/year) with a cost of 500 USD/t NH3 by 2050 (see Table 13). The potential for new job creation and economic activity as well as potentially reducing the impacts of Carbon Border Adjustment also need to be considered.

Table 13: *Comparison of Hydrogen Export Potentials*

Export Potential		2050
Green H_2 Export Potential[17]	Mt/year	**1.5-1.9**
Injection into Pipelines	Mt/year	0.15-0.2
Ammonia Exports[18]	Mt/year	1.35-1.7

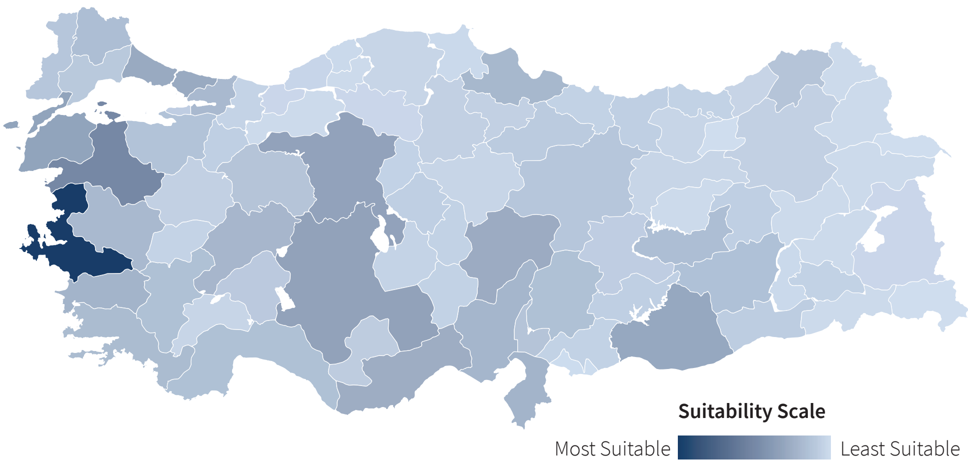
6.1 Suitability Indexes

This analysis yielded two types of suitability indexes. For the maps, a colorful suitability scale is used for the illustration purposes where darker blue represents better suitability for the pioneer projects in Turkey. (check table 14 for detailed results). The domestic suitability index reveals the provinces in which green hydrogen projects may be initiated. From an investor's perspective the domestic suitability index shows that İzmir offers the best business conditions under which to construct the

[17] It is important to consider that these values can depend on the strategic decisions utilizing renewable potentials.
[18] Based on the stoichiometry of 0.178 t H_2/t NH3, 1.7 Mt of green hydrogen would mean 9.5 Mt NH_3/year.

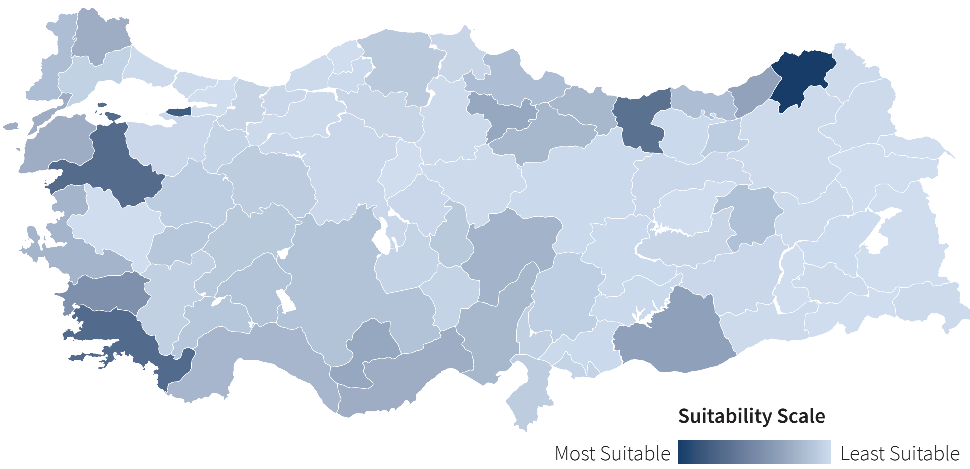
first hydrogen production plants when considering its renewable energy potentials (especially wind), water availability (given that desalination might be an alternative in the future since İzmir is a coastal area), and its existing hydrogen demand. Other provinces such as Konya, Balıkesir, and Çanakkale might also be pioneers in hydrogen production (see Figure 39).

Figure 39: *Map of Domestic Suitability*



The most promising regions from which to export hydrogen from Turkey are Artvin, Yalova, Muğla, Balıkesir, and Giresun (see Figure 40). The first hydrogen projects in Turkey may be located in these regions if targeting exports. In the centralized scenario, the six regions determined in this study have better suitability index scores. The indicators for this suitability index can be further examined (with their rankings) in the annex (see Table 14).

Figure 40: *Map of Export Suitability*



7. Conclusion

After ratifying the Paris Agreement, Turkey may need to formulate a long-term energy transition and climate strategy toward 2030 and 2053. Within this strategy, it is necessary to specify what roles green hydrogen and its derivatives can play after all priority areas for the use of renewable electricity are determined. A better understanding of how hydrogen will be produced in Turkey can also contribute to the country's economic development and create new industrial areas in international markets considering related global developments such as the EU Green Deal, Paris Agreement, and Carbon Border Adjustment Mechanism. The development of a sustainable green hydrogen strategy demands a variety of elements, including the close cooperation and collaboration of stakeholders and institutions, financial incentives, and a solid regulatory framework. The challenges of creating a hydrogen strategy are huge, but developing solutions is possible. The starting point should be more cost-effective renewable integration into the power system and creating a local hydrogen market as well as considering water availability and cost barriers. However, the end goal is a decarbonized Turkish energy system with better security of supply using domestic resource utilization and export possibilities, which can help the EU and the wider region to cultivate a more effective and secure energy transition.

Turkey's national energy policy has strengthened the course for the use of domestic resources and technologies. Although Turkey does not have an official hydrogen strategy yet, studies are ongoing, and a strategy plan may be published during 2022. Developing a hydrogen strategy will be an opportunity to reduce fossil fuel imports and decrease CO_2 emissions in sectors that are hard to decarbonize. In this report, an assessment is carried out to better understand potential green hydrogen supply, costs, and demand in Turkey, with particular attention on export opportunities that will create additional value for Turkey's economy through the production of green hydrogen by 2050.

A regional view of renewable energy costs, availabilities, and capacity factors is used to understand the relationship between renewable energy sources and hydrogen. This study assumes that lower costs for renewable electricity production will lower the cost of hydrogen production. As more renewable generation capacity is deployed, Turkey may increase its hydrogen production potential as a green energy alternative for decarbonizing its gas grid, energy-intensive industries, and transport. Additionally, seasonal supply and demand patterns in Turkey's hydrogen strategy can make international trade a viable option. In parallel, there may be multiple decarbonization paths due to differing renewable energy development strategies. Potential excess supply of renewable energy could also be used in Turkey's energy system without its conversion to green hydrogen. Possible strategies could vary depending on different factors that need to be more widely evaluated.

Beyond costs, exporting green hydrogen would provide Turkey leverage in international trade and its integration into the EU. The recently commissioned TANAP pipeline can be utilized to export domestic green hydrogen and will benefit the wider region in the energy transition. Instead of transporting hydrogen to a single destination via pipelines, hydrogen can also be exported to various destinations via shipping by converting it to different compounds such as methanol, ammonia, or liquid hydrogen. There are multiple benefits to harmonizing a national strategy with a wider foreign trade outlook.

The EU and Turkey should begin to consult common hydrogen roadmaps and studies when undertaking related industrial and trade interactions. The year 2050 may look far off, but the EU might benefit from Turkey's green hydrogen supply in the meantime. Turkey might also benefit from EU markets, standards, policy documents, and common pathways. Hydrogen trading has the potential to constitute a win-win situation both for the EU and Turkey. However, Turkey needs to achieve economies of scale for the production of hydrogen, since the prices of the final product will determine Turkey's role in the global/European hydrogen market.

Creating a hydrogen strategy is a long journey considering all the implications for different sectors that impact Turkey's account deficit and climate goals. The key findings of this analysis are as follows:

- **Planning for renewable energy integration remains the main pillar for creating a green hydrogen strategy:** Turkey should prioritize planning for the energy transition and climate change mitigation toward 2030 and 2050. The first step in developing a hydrogen strategy in Turkey would be to continue to accelerate Turkey's successful renewable energy capacity development. This will decrease costs, lower CO_2 emissions from electricity generation, reduce import dependency, and provide other opportunities like low-cost hydrogen for hard to decarbonize sectors. Between 2030 and 2050, it is expected that producing and consuming green hydrogen will be the most economic option for the refinery and petrochemical industries. Renewable energy capacity targets, especially for solar and wind energy, need to be updated with more ambitious ones to accelerate renewable energy capacity development. Decreasing generation costs of renewable energy by 2050 will be driving the production of green hydrogen in terms of economies of scale. Turkey needs to plan how it can use its large renewable energy resource availability to decarbonize its energy sector and create opportunities for hydrogen exports.

- **The cost and supply potential of green hydrogen stands as the main bottleneck in the development of markets:** Green hydrogen prudction costs could fall to 1.39–2.45 USD/kg H_2 for wind- and solar-based electricity using Alkaline and PEM electrolyzers. There is a country-wide supply potential of 3.4 Mt/year by 2050 if favorable conditions are met. Learning by doing, establishing economies of scale, and standardizing supply chains are the key pillars to reach this threshold.

- **Domestic use of hydrogen drives opportunities for green hydrogen to reduce energy import dependency:** Further development of renewable power will ensure the production of low-cost green hydrogen for hard to decarbonize sectors in Turkey. This analysis is carried out for a green hydrogen substitution potential of maximum 5% (minimum 1%) in 2030 and maximum 10% by 2050. The consumption of green hydrogen can be the most cost-effective feedstock within manufacturing industries, especially for the refinery and petrochemical sectors. Additionally, hydrogen blending in the gas grid needs to be investigated in detail. Current studies favor a 10% blending potential. These numbers should be viewed as an opportunity for multiple stakeholders.

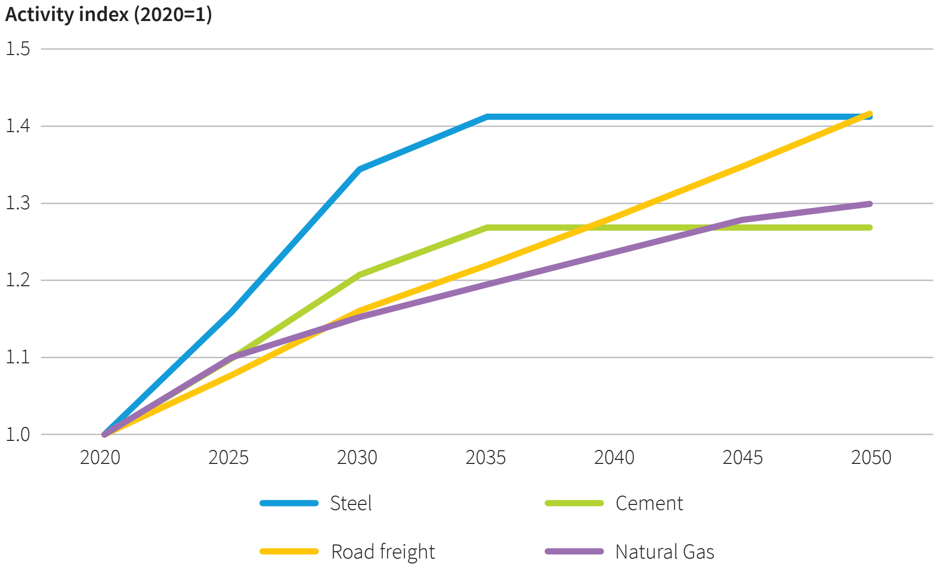
- **A strategy for exporting green hydrogen needs to be created:** The results show that green hydrogen can be exported after considering Turkey's hydrogen supply and demand balance by 2050. Turkey will have a hydrogen export potential ranging from 1.5 to 1.9 Mt by 2050 if favorable conditions are met. This potential could be exported through the conversion of hydrogen into ammonia and transporting it via shipping as well as injecting it into transnational pipelines. As the global hydrogen economy is formed and green hydrogen is traded like any other energy commodity, Turkey could play a significant role in this trade game by optimizing the right business models and strategy. There are many factors that will impact strategies for green hydrogen exports such as production costs, export price levels, infrastructure, and political relations. Creating a hydrogen export strategy requires a holistic approach addressing all related factors.

8. Annex

Activity Index

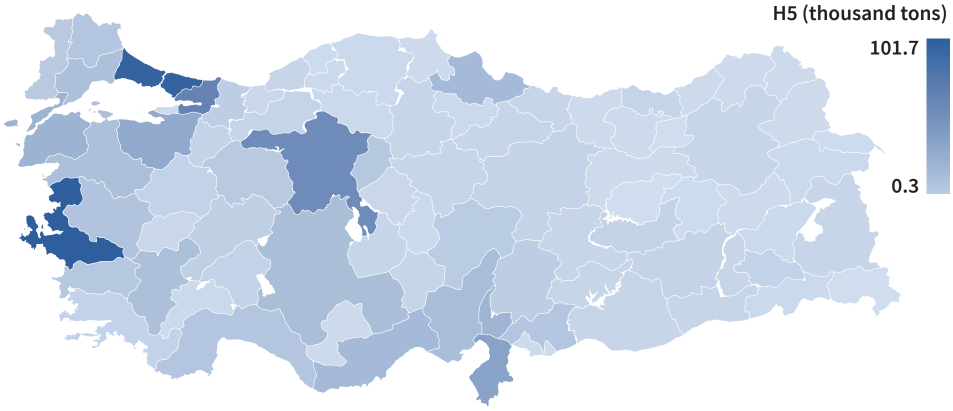
The activity index is a set of assumptions for each sector in which hydrogen demand is assessed in this report. These assumptions are based on government targets and interpretations from prior SHURA studies, since there is no officially published long-term forecast available for these sectors. Based on near-term policy papers, the assumed growth rates will reach their saturation point for the steel and cement sectors by 2030. The gas sector may replace some coal in terms of consumption levels; therefore, its trajectory only decreases toward 2050. Road freight will continue to increase, as Turkey's regional development goals will spread the production of goods and services from Istanbul to Central Anatolia.

Figure 41: *Estimated activity index of end-use sectors*



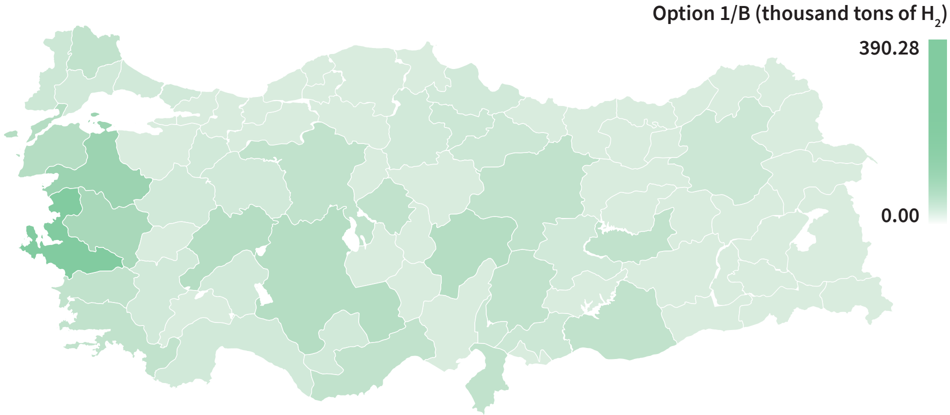
Hydrogen demand for H5 case

Figure 42: *Regional Hydrogen Demand, H5 Case*



Hydrogen Production Potential for Distributed Scenario 1/B

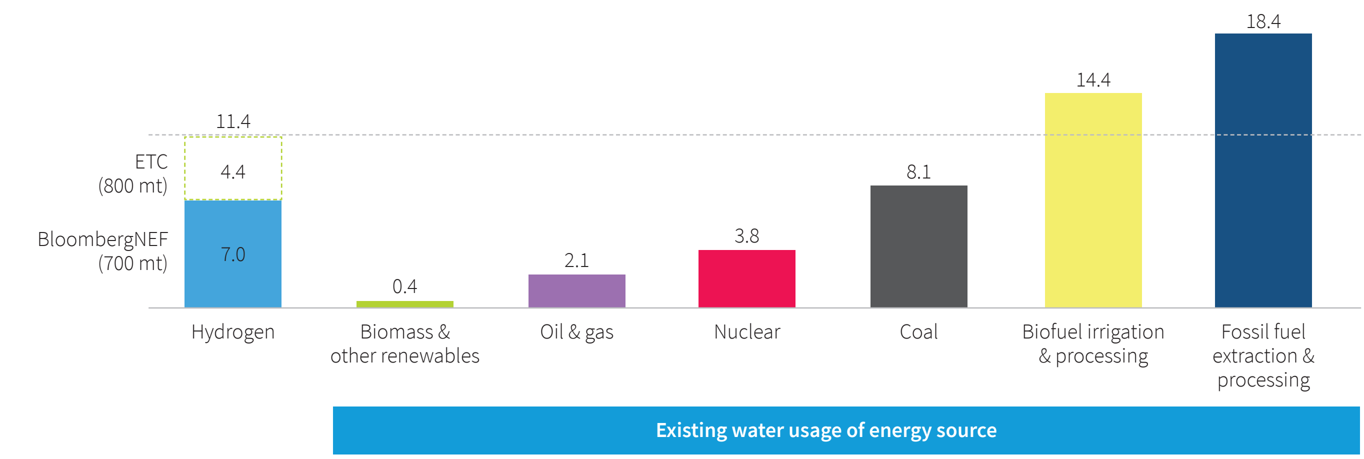
Figure 43: *Breakdown of H_2 production potential at the province level for distributed scenario 1/B by 2050*



Global comparison of water consumption for different energy sources

Figure 44: *Water consumption by energy source, globally*

Billion tonnes per year



Note: The estimated waker consuption for hydrogen is calculated for 100% production from water electrolysis. In the BloombergNEF scenario it is calculated based on demand of 696 Mt in the policy scenario. Water consuption for other sectors is based upon 2016 data from the IEA. Other renewables include wind, PV, geothermal and solar thermal, and excludes hydropower. Fossil fuel and biofuel numbers represent water consuption during primary energy production. All other numbers (except hydrogen) represent water consuption during power generation.

Source: BloombergNEF (2019), Hydrogen Economy Outlook; IEA (2017), Water-Energy Nexus

Suitability Index

The suitability index for each province is outlined in Table 14. A cut-off value of 500 has been determined to simplify the results. The final rankings of each province according to the domestic and export indexes can be observed in the “Domestic Rank” and “Export Rank” columns.

Table 14: *Suitability Index (indicators)*

Province	Water Availability	Renewable Supply	Prox. Infrastructure	H_2 Demand	Domestic Suitability	Domestic Rank	Export Suitability	Export Rank
Adana	3.88	1.22	5.00	1.17	2.01	12	100.66	19
Adiyaman	3.59	0.59	1.00	0.20	1.41	39	10.52	56
Afyonkarahisar	2.71	2.18	2.00	0.46	2.00	13	51.64	28
Ağrı	3.61	0.04	1.00	0.12	1.13	76	1.29	75
Aksaray	3.60	0.35	2.00	0.22	1.30	54	22.86	42
Amasya	3.36	0.68	3.00	0.14	1.38	42	149.39	10
Ankara	3.88	1.41	3.00	3.25	2.52	4	15.13	49
Antalya	3.88	0.88	5.00	0.83	1.77	21	102.68	16
Ardahan	3.57	0.10	1.00	0.09	1.14	74	3.71	67
Artvin	3.88	0.92	5.00	0.04	1.63	27	500	1
Aydin	3.88	1.55	5.00	0.67	2.07	11	223.05	6
Balikesir	3.88	3.83	5.00	1.05	3.29	2	354.20	4
Bartın	3.88	0.00	5.00	0.03	1.17	68	0.00	79
Batman	3.62	0.08	1.00	0.24	1.18	67	1.20	76
Bayburt	3.59	0.05	1.00	0.00	1.10	79	39.56	34
Bilecik	3.60	0.55	2.00	0.32	1.42	37	24.51	40
Bingöl	3.54	0.63	1.00	0.03	1.38	40	75.65	23
Bitlis	3.61	0.09	1.00	0.14	1.15	71	2.29	71
Bolu	3.60	0.05	3.00	0.28	1.16	69	6.32	63
Burdur	3.60	0.28	3.00	0.16	1.25	57	57.25	27
Bursa	3.88	0.26	5.00	1.96	1.68	24	12.76	52
Çanakkale	3.88	2.05	5.00	1.53	2.49	5	130.36	11
Çankırı	3.60	0.20	2.00	0.15	1.21	64	18.69	44
Çorum	3.50	0.55	1.00	0.23	1.37	45	8.49	60
Denizli	3.64	0.94	3.00	0.99	1.76	22	31.25	37
Diyarbakır	3.62	1.18	1.00	0.33	1.74	23	13.04	51
Düzce	3.88	0.03	5.00	0.18	1.21	63	15.52	48
Edirne	3.88	0.60	5.00	0.66	1.60	28	87.79	20
Elazığ	3.24	1.58	1.00	0.28	1.82	19	18.09	45
Erzincan	3.58	0.28	1.00	0.07	1.23	61	13.86	50
Erzurum	3.59	0.50	1.00	0.26	1.38	43	6.90	62
Eskişehir	3.62	0.84	3.00	0.64	1.63	26	42.71	31
Gaziantep	2.49	0.86	2.00	0.83	1.34	47	10.32	57
Giresun	3.88	0.39	5.00	0.11	1.38	41	336.02	5
Gümüşhane	3.59	0.28	1.00	0.09	1.23	59	11.30	53
Hakkari	3.59	0.01	1.00	0.01	1.09	80	4.28	65
Hatay	3.88	0.98	5.00	2.23	2.10	10	42.67	32
Iğdır	3.59	0.00	1.00	0.03	1.08	81	0.30	78
Isparta	3.41	0.81	3.00	0.34	1.50	31	73.89	24
İstanbul	3.88	0.24	5.00	5.23	2.33	7	4.36	64
İzmir	3.88	6.33	5.00	5.47	5.42	1	112.15	15

Province	Water Availability	Renewable Supply	Prox. Infrastructure	H_2 Demand	Domestic Suitability	Domestic Rank	Export Suitability	Export Rank
Kahramanmaraş	2.70	1.71	2.00	0.51	1.77	20	35.92	35
Karabük	3.60	0.06	3.00	0.17	1.14	73	10.96	55
Karaman	3.33	0.86	2.00	0.08	1.45	33	151.12	9
Kars	3.60	0.12	1.00	0.10	1.16	70	4.11	66
Kastamonu	3.88	0.08	5.00	0.15	1.23	60	49.10	30
Kayseri	3.55	2.19	3.00	0.59	2.27	8	118.29	14
Kırıkkale	3.59	0.22	1.00	0.68	1.32	52	1.16	77
Kırklareli	3.88	1.05	5.00	0.78	1.84	18	130.08	12
Kırşehir	3.12	0.90	1.00	0.18	1.42	38	15.63	47
Kilis	3.53	0.08	2.00	0.04	1.11	78	26.40	39
Kocaeli	3.88	0.06	5.00	3.62	1.92	16	1.66	73
Konya	3.69	2.45	3.00	1.12	2.56	3	72.44	25
Kütahya	3.61	0.44	3.00	0.36	1.37	44	39.67	33
Malatya	3.65	0.58	1.00	0.21	1.42	35	10.12	58
Manisa	0.00	3.52	4.00	0.88	1.94	15	0.00	79
Mardin	3.63	0.58	1.00	0.26	1.43	34	8.08	61
Mersin	3.88	1.62	5.00	1.23	2.22	9	128.17	13
Muğla	3.88	1.27	5.00	0.34	1.87	17	362.60	3
Muş	3.60	0.08	1.00	0.10	1.14	75	2.88	70
Nevşehir	3.49	0.50	2.00	0.14	1.33	51	51.14	29
Niğde	3.60	0.40	2.00	0.25	1.33	49	23.44	41
Ordu	3.88	0.24	5.00	0.23	1.33	50	101.12	18
Osmaniye	2.80	1.07	4.00	1.46	1.67	25	32.97	36
Rize	3.88	0.16	5.00	0.09	1.26	56	169.58	8
Sakarya	3.88	0.11	5.00	0.50	1.32	53	20.66	43
Samsun	3.88	1.08	5.00	1.27	1.96	14	82.31	22
Siirt	3.65	0.34	1.00	0.36	1.34	48	3.44	69
Sinop	3.88	0.01	5.00	0.07	1.18	66	17.08	46
Sivas	3.40	0.99	1.00	0.31	1.58	29	10.99	54
Şanlıurfa	3.36	2.63	2.00	0.21	2.37	6	170.70	7
Şırnak	3.62	0.06	1.00	0.14	1.15	72	1.59	74
Tekirdağ	3.88	0.31	5.00	1.05	1.53	30	28.55	38
Tokat	3.40	0.81	3.00	0.24	1.47	32	101.17	17
Trabzon	3.88	0.25	5.00	0.28	1.34	46	86.86	21
Tunceli	3.59	0.10	1.00	0.00	1.13	77	0.00	79
Uşak	3.60	0.33	3.00	0.18	1.28	55	59.61	26
Van	3.64	0.13	1.00	0.23	1.20	65	2.00	72
Yalova	3.88	0.47	5.00	0.11	1.42	36	407.36	2
Yozgat	3.61	0.24	1.00	0.24	1.25	58	3.66	68
Zonguldak	3.88	0.03	5.00	0.25	1.23	62	9.63	59

9. References

Acil Allen Consulting, ARENA, (2018). OPPORTUNITIES FOR AUSTRALIA FROM HYDROGEN EXPORTS

Agora Energiewende, Guidehouse . (2021): "Making renewable hydrogen cost-competitive: Policy instruments for supporting green H_2".

Alfa Laval, Hafnia, Haldor Topsoe, Vestas, Sıemens Gamesa. (2020) "Ammonfuel- an industrial view of ammonia as marine fuel".

Arena Ocean Hyway Cluster, (2020). 'Hydrogen and Ammonia Infrastructure'.

Armijo J, Philibert C. (2020), "Flexible production of green hydrogen and ammonia from variable solar and wind energy: Case study of Chile and Argentina", International Journal of Hydrogen Energy, Volume 45, Issue 3, Pages 1541-1558.

Benner, J., van Lieshout, M., Croezen, H. (2012). "Identifying Breakthrough Technologies for the Production of Basic Chemicals. A Long Term View on the Production of Ammonia, Olefins and Aromatics in the European Union." s.l. : University of Delft.

BMWi (2020). The National Hydrogen Strategy. https://www.bmwi.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-strategy.html

Caldera, U. et al. (2018), "Role of seawater desalination in the management of an integrated water and 100% renewable energy based power sector in Saudi Arabia", Water, Vol. 10, DOI: 10.3390/w10010003

Christensen, A. (2020). "Assessment of Hydrogen Production Costs from Electrolysis: United States and Europe", International Council on Clean Transportation.

Eichman, J., K. Harrison and M. Peters, (2014). "Novel Electrolyzer Applications: Providing More Than Just Hydrogen", National Renewable Energy Laboratory, www.nrel.gov/docs/fy14osti/61758.pdf.

Energy Transitions Comission (2021). "Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy"

Enerji ve Tabii Kaynaklar Bakanlığı (2018). "Denge Tabloları" https://enerji.gov.tr/enerji-isleri-genel-mudurlugu-denge-tablolari

European Comission (2020). "A hydrogen strategy for a climate-neutral Europe" https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1599052948314&uri=CELEX:52020DC0301

Enerji ve Tabii Kaynaklar Bakanlığı (2020). "Enerjide Arama Buluşmaları", January 2020, Ankara. https://boren.gov.tr/uploads/dosyaYoneticisi/479628-enerjide-aramabulusmalari-hidrojen-program.pdf

Enerji ve Tabii Kaynaklar Bakanlığı (2021). "Türkiye'nin hidrojen stratejisini oluşturacağız" https://enerji.gov.tr/haber-detay?id=803

Fuel Cell and Hydrogen Energy Association (2019). "Roadmap to a US Hydrogen Economy." www.ushydrogenstudy.org.

Freshfields Bruckhaus Deringer LLP (2021), The amendment of the German renewable Energy ACT (EEG 2021). http://knowledge.freshfields.com/en/Global/r/4390/the_amendment_of_the_german_renewable_energy_act__eeg_2021_

GAZBİR(2021). "Doğal Gaz Sektörü Hidrojene Geçişte Yol Haritası Önerileri"

Global Energy Ventures (2021). “GEV SCOPING STUDY DELIVERS ZERO EMISSION SUPPLY CHAIN FOR GREEN HYDROGEN” https://gev.com/wp-content/uploads/2021/03/c-h2-scoping-study-delivers-green-hydrogen-supply-chain.pdf

Gouvernement Français (2020). Stratégie nationale pour le développement de l’hydrogène décarboné en France,

Government of the Netherlands (2020), Government Strategy on Hydrogen https://www.government.nl/documents/publications/2020/04/06/government-strategy-on-hydrogen

Guidehouse (2020), European Hydrogen Backbone. https://guidehouse.com/-/media/www/site/downloads/energy/2020/gh_european-hydrogen-backbone_report.pdf

IEA (n.d), Global electrolysis capacity becoming operational annually, 2014-2023, historical and announced, IEA, Paris https://www.iea.org/data-and-statistics/charts/global-electrolysis-capacity-becoming-operational-annually-2014-2023-historical-and-announced

IEA (2019), The Future of Hydrogen, IEA, Paris https://www.iea.org/reports/the-future-of-hydrogen

IEA (2021), Net Zero by 2050, IEA, Paris https://www.iea.org/reports/net-zero-by-2050

Ikäheimo J, Kiviluoma j, Weiss R, Holttinen H, (2018), “Power-to-ammonia in future North European 100 % renewable power and heat system”, International Journal of Hydrogen Energy, Volume 43, Issue 36.

Institute for Sustainable Process Technology, (2017). “Power to Ammonia”

IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5^{0}C Climate Goal, International Renewable Energy Agency, Abu Dhabi

IRENA (2021), World Energy Transitions Outlook: 1.5°C Pathway, International Renewable Energy Agency, Abu Dhabi.

Isaac T, Lewis A. (2021) Hydrogen Blending- Lessons from HyDeploy, The Oxford Institute for Energy Studies.

Jake Stones (2020), French strategy boasts largest 2030 electrolyzer capacity, I.C.I.S https://www.icis.com/explore/resources/news/2020/09/11/10551839/french-strategy-boasts-largest-2030-electrolyser-hydrogen-capacity

Lampert David J, Cai H, Wang Z, Keisman J, Wu M, Han Je, Dunn J, Sullivan John L., Elgowainy A, Wang M, Keisman J. (2015) Development of a Life Cycle Inventory of Water Consumption Associated with the Production of Transportation Fuels. United States.

Lampert David J, Cai H, Elgowainy A. (2016) “Wheels to wheels: Water consumption for transportation fuels in the United States, Energy and Environmental Science.

Noussan, M.; Raimondi, P.P.; Scita, R.; Hafner, M. (2021), The Role of Green and Blue Hydrogen in the Energy Transition: A Technological and Geopolitical Perspective. Sustainability 2021, 13, 298. https://doi.org/10.3390/su13010298

Ram M., Galimova T., Bogdanov D., Fasihi M., Gulagi A., Breyer C., Micheli M., Crone K. (2020). Powerfuels in a Renewable Energy World - Global volumes, costs, and trading 2030 to 2050. LUT University and Deutsche Energie-Agentur GmbH (dena). Lappeenranta, Berlin.

Renewable Energy Institute Tokyo (2021). 2050 Climate Neutrality and the Role of green H2 https://static.agora-energiewende.de/fileadmin/Projekte/2021/VAs_sonstige/2021-03-18_Presentation_RenewableEnergyInstitute_on_H2_in_Japan_BETD.pdf

Rivarolo, M.; Riveros-Godoy, G.; Magistri, L.; Massardo, A.F. (2019). Clean Hydrogen and Ammonia Synthesis in Paraguay from the Itaipu 14 GW Hydroelectric Plant. ChemEngineering , 3, 87

Sabancı University Istanbul International Center for Energy and Climate (2020). "Turkish Energy Outlook", November 2020, İstanbul

Schöffel, M. (2021) Hydrogen and the decarbonization of steel making, The Oxford Institute for Energy Studies.

SHURA Energy Transition Center (2020a). "Optimum electricity generation capacity mix for Turkey towards 2030", August 2020, İstanbul.

SHURA Energy Transition Center (2020b). "The most economical solution for Turkey's power system: Energy Efficiency and Business Models", October 2020, İstanbul

SHURA Energy Transition Center (2021), Priority Areas for a National Hydrogen Strategy for Turkey, February 2021, İstanbul. https://www.shura.org.tr/priority-areas-for-a-national-hydrogen-strategy-for-turkey/

Tractebel (2018), "Oportunidades para el desarrollo de una industria de hidrógeno solar en las regiones de Antofagasta y Atacama: Innovación para un sistema energético 100% removable" "[Opportunities for the development of a solar hydrogen industry in the Atacama and Antofagasta regions: Innovations for 100% renewable energy system]", report prepared for Comité Solar – CORFO, www.comitesolar.cl/wp-content/uploads/2018/08/Comite-Solar-2018-Oportunidades-Industriadel-Hidr%C3%B3geno_Informe-Final.pdf

Türkiye Cumhuriyeti Sanayi ve Teknoloji Bakanlığı. (2018)."Kimyasal Gübre ve Azot Bileşiklerinin İmalatı Sektörü, Kaynak Verimliliği Rehberi".

TÇMB (2020). Member Factories https://www.turkcimento.org.tr/en/member_factories

TÇÜD (2019). Steel Map of Turkey http://celik.org.tr/en/harita/

TEİAŞ (2020). "Türkiye Elektrik Üretim-İletim 2019 Yılı İstatistikleri "https://www.teias.gov.tr/tr-TR/turkiye-elektrik-uretim-iletim-istatistikleri

U.S. Department of Energy (2020)." Hydrogen Program Plan"

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Agora Energiewende develops evidence-based and politically viable strategies for ensuring the success of the clean energy transition in Germany, Europe and the rest of the world. As a think tank and policy laboratory, Agora aims to share knowledge with stakeholders in the worlds of politics, business and academia while enabling a productive exchange of ideas. As a non-profit foundation primarily financed through philanthropic donations, Agora is not beholden to narrow corporate or political interests, but rather to its commitment to confronting climate change.

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