



ANALYSIS OF THE HYDROGEN RESOURCES USAGE IN ESTONIA

SUMMARY

May 2021



The analysis of the hydrogen resources usage in Estonia was carried out at the request of the Strategy Unit of the Government Office. The work was financed from Measure 12.2 “Development of the quality of policy-making” of Priority Axis 12 “Administrative Capacity” of the Operational Program of the Cohesion Funds 2014-2020 financed from the European Union Social Fund. The initiators and cooperation partners of the project were the Ministry of the Environment and the Ministry of Economic Affairs and Communications.

The analysis was performed by Civitta Eesti AS (Civitta), the Tallinn Center of the Stockholm Environmental Institute (SEI) and the Institute of Chemical and Biological Physics (NICPB).

Authors of the analysis:

Piia Viks-Binsol (Civitta)	Lauri Tammiste (SEI)	Ivar Kruusenberg (NICPB)
Martti Rell (Civitta)	Kerli Kirsimaa (SEI)	Reio Praats (NICPB)
Renar Uiibooss (Civitta)	Adil Aslam (SEI)	
Alo Treial (Civitta)	Tyyab Ehsan Butt (SEI)	

During the analysis, the hydrogen experts advised and validated the results:

Enn Lust - Member of the Estonian Academy of Sciences, Head of the Institute of Chemistry at University of Tartu and CEO of the Estonian Hydrogen Technology Association.

Alexandru Floristean - Hydrogen Europe Project Manager, Member of the European Union Hydrogen Policy Development Working Group.

Jakub Kupecki - Head of the Centre for Hydrogen Technologies Institute of Power Engineering in Poland.

Luc Van Nuffel - Associate Senior Consultant at Trinomics and former Head of Regulatory Affairs at Electrabel-Engie (energy company in Belgium).

Amgad Elgowainy – Senior Scientist and Group Leader with the Energy Systems Division at the Argonne National Laboratory in USA.

The authors thank all entrepreneurs, hydrogen experts and all others who participated in the interviews and the workshop. The authors especially thank the owners of the hydrogen pilot projects analyzed in the study, who were ready to share information about business plans. In addition, we thank Enn Õunpuu from Elcogen AS and Marek Alliksoo from the Estonian Hydrogen Technology Association, who provided feedback on the draft version of the report.



INTRODUCTION

Hydrogen is one of the most promising renewable energy sources to replace fossil fuels in the energy and transport sectors. The introduction of hydrogen in everyday life is related to the existing technological possibilities for hydrogen production, storage and transportation. Several countries are already researching the possibility of widespread use of hydrogen to replace fossil fuels. The European Union and more advanced countries have taken a number of policy steps to encourage faster development of hydrogen technologies and their penetration into industry, transport, energy and other areas of activity.

At the time of this analysis, hydrogen is not produced on a large scale in Estonia, but there are some research and business projects at different development stages. In order to plan for the faster deployment of hydrogen technologies, it is important to identify the opportunities offered by large-scale hydrogen deployment and to analyze the potential and applications of hydrogen deployment.

AIM AND SCOPE | The aim of the analysis of hydrogen resource usage is to identify the potential and capacity of green and blue hydrogen production, distribution and consumption in Estonia and to map opportunities, bottlenecks, market barriers and threats for the future, including identifying and evaluating potential business projects. The analysis focuses on the period 2020-2030, as large-scale global hydrogen deployment will gain momentum over the next decade.

Analysis of the uptake of hydrogen resources is important for both the public and the private sector. The analysis provides a solid basis for public authorities to draft hydrogen legislation, infrastructure planning and construction. The results of the analysis will help to assess which areas will first be associated with hydrogen, what investments are needed, what the associated impacts are, and what risks may arise at different stages of development. For companies operating in related fields and interested in the production, distribution or use of green and / or blue hydrogen, the analysis provides information for the realization of business ideas and the assessment of profitability.

As the potential for hydrogen uptake depends on the stages of the whole hydrogen value chain, i.e., aspects related to the production, supply, storage and use of hydrogen, the analysis was based on the whole hydrogen value chain. The work focused in particular on the energy, industrial and transport sectors, as well as on buildings, which, according to the professional scientific literature and experts, are areas with greater potential for the use of hydrogen.

METHODOLOGY | The analysis was carried out in four work packages - 1) mapping of the existing situation (incl. mapping of technologies, best practices, strategic and legislative documents, risks and threats of hydrogen use and the situation in Estonia), 2) creation of a model of socio-economic impact assessment of hydrogen use, 3) hydrogen use pilot projects preparation of a cost-benefit analysis model and SWOT analysis; and 4) description of barriers to the wider use of hydrogen and appropriate measures to alleviate them.

The study was based on the analysis of secondary data, interviews with experts and market participants and the results of the workshop, and the analysis models developed during the project. In order to involve more thorough expert knowledge, including the collection of better information on the experience of foreign countries, an expert panel was involved to carry out the work. Cooperation with the expert panel took place through meetings and written consultations. The document analysis was based on professional scientific literature, previous research and analysis both in Estonia and the world in general. Materials available from public sources were used, in addition, the experts belonging to the expert panel shared their previous analyzes. The owners of the pilot projects were contacted to gather information about the pilot projects. Through interviews and written consultations, existing data was collected from pilot project owners to describe use cases and assess cost-effectiveness. In addition, experts in the fields of energy, transport, industry and gas were interviewed with the aim of understanding the readiness for the introduction of hydrogen in Estonia and in order to map the experts' assessments of the most suitable

areas of hydrogen use. In order to validate the results of the analysis and develop measures, a workshop was held with the participation of interested market participants, policy makers, representatives of research institutions and entrepreneurs.

The description of the final barriers and measures presented as a result of the analysis and their effects have taken into account the information gathered throughout the work, the recommendations of the expert panel, the results of the workshop and the results of the impact analysis and cost-benefit analysis of pilot projects.

OUTCOME AND RESULTS | The final report of the analysis of the usage of hydrogen resources in Estonian language summarizes the main conclusions and presents policy recommendations. The main part of the work is divided into six parts, where 1) the technological possibilities of hydrogen production, storage and transportation are described; 2) the current situation of Estonia in energy production and final consumption has been mapped and the capacity and readiness of the industrial sector, buildings and transport sector to use hydrogen has been analyzed; 3) the socio-economic impact of the use of hydrogen analyzed; 4) a cost-benefit analysis of ten pilot projects for the use of potential hydrogen based on economic aspects and risk factors presented; 5) possible technological, social and safety risks in the implementation of pilot projects are mapped; 6) an overview of the legal, administrative and economic barriers that hinder the introduction of hydrogen technologies in Estonia and the main measures that assist in the elimination or mitigation of these barriers is presented.

This summary of the analysis of the usage of Estonian hydrogen resources in English presents the main results by these six topics. At the end of the summary, an overview of possible legal and economic measures that would increase and support the potential for the use of hydrogen in Estonia is presented.

MAIN RESULTS

The results of the analysis of the usage of hydrogen resources are based on the known and available information for the period of November 2020 - May 2021. When using and interpreting the results, it must be taken into account that hydrogen technology and the possibilities for the production, storage and consumption of hydrogen are evolving very rapidly. Therefore, estimates of investment needs, profitability, government support and socio-economic impacts may change significantly in just a few years.

WHAT ARE THE MOST IMPORTANT HYDROGEN TECHNOLOGIES? | What Are the Most Important Hydrogen Technologies? The introduction of hydrogen in everyday life depends directly on the existing technological possibilities for the production, storage and transportation of hydrogen. **The method of water electrolysis suitable for the production of green hydrogen** is becoming more and more widespread in the world. Electrolysis of water requires a lot of renewable electricity, which in the Estonian context can be produced from wind or solar energy. In addition to low-cost carbon-neutral electricity, successful use of water electrolysis requires gas compressors and suitable storage technologies. **However, the most important factors in the production of green hydrogen are the availability of carbon-neutral electricity and the price of electrolysis.** Of the available technologies, PEM electrolysis is best suited for the production of green hydrogen, which can be used for fluctuating wind and solar energy due to the fast switching on and off of the electrolysis (approximately 15 minutes). Although the technologies of electrolysis are very advanced, increasing the production volume will definitely require a large initial investment.

In addition to the above mentioned, solid oxide electrolysis is close to commercial use, as they can operate in both electrolyzer and fuel cell modes, making it possible to better optimize their energy use. The disadvantage of solid oxide electrolysis is the high operating temperature (700 – 800 °C), which requires stable electricity that is not only provided by the use of wind and solar energy. **Hydrogen production from biomass could be considered if CO₂ capture and storage systems are also used.** In this case, the hydrogen produced would be blue, which would contribute to security of supply in the transition to fully green hydrogen.

Today, the most reliable hydrogen storage methods are based on hydrogen gas. If hydrogen is used where it is produced, there is no reason to store hydrogen in any other way. However, the production and storage of hydrogen for export brings into question various chemical compound-based storage methods, as they are less expensive and do not require a specific infrastructure. **In the context of Estonia, due to the short distances, it is most suitable to store gaseous or liquid hydrogen in special gas cylinders.** For long-term storage, it is also conceivable to use old oil shale mines (requiring a separate study) or to store them as a chemical compound, such as ammonia or methanol, as these compounds have value in the chemical industry in addition to hydrogen storage and could be exported to thousands of kilometers). Ultimately, however, the choice of hydrogen storage technology should take into account its overall value chain in order to understand where, how much and for what purpose to use hydrogen.

There are several ways to transport hydrogen. Depending on the distance traveled, the cost and expediency of hydrogen transportation will be determined. **For shorter distances (a few hundred kilometers) and for the transportation of smaller quantities, the most suitable way is to transport pure hydrogen by heavy goods vehicles, either by gas or in liquid form. As volumes and distances increase, other modes of transport become attractive, for example, large quantities can be transported in pipelines (up to 1,500 km) very quickly.** If the distance is longer than 1,500 km, it becomes more reasonable to transport hydrogen using hydrogen carriers (ammonia, LOHC) using the existing natural gas, oil or similar infrastructure. Heavy trucks would be best suited for the transport of clean hydrogen within Estonia, if the volumes increase, the use of pipelines may also be considered. The choice of the most suitable mode of transport depends on the distance, the volume of hydrogen transported and the final consumption.

HOW CAN HYDROGEN BE USED? | Hydrogen can currently be used in two ways, firstly in various industrial processes (such as ammonia production and the metal industry) and secondly as a fuel in fuel cells to produce electricity and heat. The fuel cell converts chemical energy into electricity and heat. When hydrogen is used as a fuel, water vapor is the only residual product. Compared to internal combustion engines, fuel cells are more efficient, quieter, have little environmental impact and can be escalated from a few watts to several hundred megawatts by combining individual elements.

The application of fuel cells in the field of transport has great potential, as hydrogen vehicles have a longer range and a longer service life than electric vehicles. Many hydrogen vehicles are already commercially available (e.g., models produced by Toyota, Hyundai or Honda). A major obstacle to the wider use of hydrogen vehicles is the lack of a refueling network. Given the development of hydrogen technology, passenger cars, trains, buses for urban transport and forklifts could be introduced as quickly and sensibly as possible.

Cogeneration of electricity and heat with fuel cells is already gaining ground in the world, and several companies around the world are developing these technologies, including the Estonian fuel cell developer AS Elcogen. The greatest efficiency of such systems lies in cogeneration. At the same time, the main obstacle to their introduction is the high cost, which should fall with wider introduction.

The chemical industry is the largest user of hydrogen and its decarbonization is also one of the biggest challenges. The largest amounts of hydrogen are used to produce ammonia and methanol and replacing hydrogen from fossil fuels with green hydrogen in their production process could also make these areas more environmentally friendly.

WHAT ARE THE MAJOR TRENDS IN USAGE OF HYDROGEN IN THE WORLD? | The climate neutrality goals of the European Union and Estonia in general are factors that accelerate and support the use of hydrogen. In addition to the ambitious 2050 climate neutrality target, the European Union adopted on 8th June 2020 a European Hydrogen Strategy, which will account for 13-14% of the Union's total energy portfolio by 2050 and employ around one million highly skilled workers by 2030, reaching 5.4 million by 2050. In recent years, Estonia has taken several strategic steps to support the use of hydrogen (for example, the Association of Hydrogen Technologies in 2016, various working groups have been formed at the level of government and ministries, etc.). However, the use of hydrogen has not yet been reflected in several relevant Estonian sectoral strategies and legislation. Recent government decisions (11th February 2021 Kaja Kallas's government approved a 100-day action plan) to develop a hydrogen strategy and pilot project and to direct EUR 50 million from the European Union's Recovery and Resilience Fund to promote the deployment of integrated hydrogen technologies will play an important role in accelerating the uptake of hydrogen.

There are many progressive countries around the world that have **good practices in the use of hydrogen.** In the field of transport, Japan is one of the leading countries in the development of hydrogen and fuel cell technologies, forecasting the introduction of 200,000 fuel cell vehicles by 2025. The European Union's and many countries' hydrogen strategies highlight the transport sector as the most important area of hydrogen use. **The second important area is considered to be the industrial sector (European Union, Germany, the Netherlands) and the third is energy production (France, UK).** Individual countries are focusing on the use of hydrogen in the building sector (e.g., the UK, Japan, Korea) and the production of hydrogen for export (e.g., Chile, Spain, Australia, Russia). This sequence is influenced by the need to reduce greenhouse gas emissions by sector and the timing of the preparation of national strategies in this respect.

WHAT IS ESTONIA'S READINESS FOR THE INTRODUCTION OF HYDROGEN, ACCORDING TO THE SECTORAL PARTNERS? | As of the preparation of this analysis, hydrogen is not yet being produced or used in significant quantities in Estonia. In order to assess the potential for the usage of hydrogen, the situation and readiness of potential sectors and the existing infrastructure in Estonia for the use of hydrogen were analyzed through literature sources and expert interviews.

A qualitative analysis of the current situation shows that **Estonia has the potential to reduce emissions the most in the transport sector, which is still heavily dependent on fossil fuels.** From the point of view

of the energy system, it is more sensible to electrify different processes in the first place than to convert renewable electricity into a third energy carrier, which means that **heavy goods vehicles** or other long-distance vehicles, where electrification is more difficult to perform, have the greatest potential. In addition, for the introduction of hydrogen in the transport sector, it is important to focus on the further development of the filling station network, as temporary filling station projects have been completed, but there is no consistently functioning and compact hydrogen filling station chain.

In addition to the transport sector, hydrogen could replace the current use of natural gas in the building sector, where energy consumption is mostly covered by biomass or central heating and less than 10% of buildings' energy consumption is based on fossil fuels (where natural gas accounts for the majority). However, hydrogen is one of the tools in the sector to replace the current use of natural gas. In particular, micro-cogeneration plants could potentially be installed in the building sector, as the addition of hydrogen to the existing natural gas network is, according to several experts in the study, rather questionable.

In the industrial sector, the potential of hydrogen lies in reducing the dependence on imports of chemical products based on fossil sources. The quantities of chemical products could be reduced by setting up a domestic ammonia and methanol industry based on hydrogen. In addition to the transport sector, the industrial sector has a high readiness to use hydrogen, which is due to the fact that Estonia previously has the infrastructure for the production of chemical products.

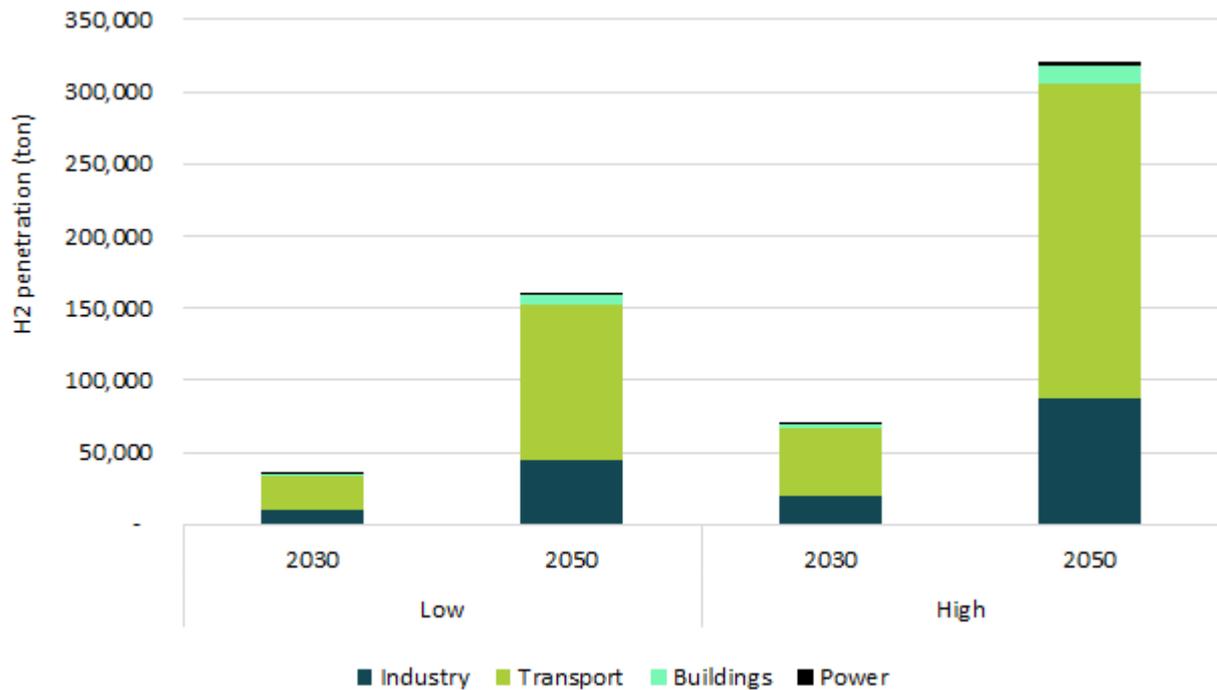
From the point of view of electricity generation, it would be reasonable to produce hydrogen primarily to generate backup energy both to cover off-grid areas (islands or other off-grid territories) and to provide vital services (e.g., telecommunications, medical services).

The experts interviewed in the framework of the analysis generally agree that there is great potential for hydrogen production and consumption in Estonia. It was emphasized that the main focus should be on the production of green hydrogen, for which it is first necessary to increase the production of solar and wind energy.

TO WHAT EXTENT CAN HYDROGEN BE USED IN ESTONIA, HOW MUCH INVESTMENT DOES IT REQUIRE AND WHAT ARE THE MAIN SOCIO-ECONOMIC IMPACTS? | In the course of the analysis, a sectoral model was developed to help quantify the potential for hydrogen uptake in Estonia, the related investments and the impact on reducing CO₂ emissions and creating jobs. The model takes into account the other environmentally friendly alternatives while making the decarbonization scenarios and explains where hydrogen is the only way forward to decarbonize the specific sector. **Two scenarios are modeled, the high scenario**, where maximum potential of hydrogen consumption is modeled through the main sectors in the Estonian economy, **which would make Estonia one of the frontrunners globally** and the **low scenario, where Estonia is expected follow the penetration rates probably more in line with European Union average levels** and which is almost half of the high scenario. Different targets based on expert interviews, desk research and expert analysis have been set across different sectors. Figure 0.1 shows the high and low scenarios for hydrogen consumption potential in Estonia.

Analysis showed that transport sector (road, rail and marine), ammonia & methanol industry, buildings and power sector should be the main targets for possible hydrogen penetration. In industry, ammonia and methanol are the main targets, where large quantities of hydrogen as feedstock are always required. **In transport sector, road, rail, and marine transport are considered.** Hydrogen's role in sustainable aviation fuel (SAF) is not considered in this study as Estonia does not have a local industry of synthetic fuels. In building sector, the opportunity of hydrogen-based micro-CHPs deployment and hydrogen blending is tapped. Since Estonia has natural gas fired emergency power plants (peaker plants), stationary fuel cell power generation is also considered.

FIGURE 0.1 OVERALL HYDROGEN PENETRATION POTENTIAL ACROSS DIFFERENT SECTORS OF ESTONIAN ECONOMY. A COMPARISON OF TWO SCENARIOS (LOW & HIGH)



The above figure shows hydrogen penetration potential across the main sectors. **For 2050, ammonia, urea and methanol industry have an overall potential of 43,922 – 87,845 tons of hydrogen, while the transport sector has the potential to consume up to 108,587 – 214,174 tons of hydrogen.** Buildings and power sector has the potential to consume 6,588 – 13,175 tons of hydrogen and 1,250 – 2,500 tons of hydrogen respectively.

Penetration at this level of hydrogen consumption would mean significant changes in respective sectors. For example, in transport sector it could mean that in low scenario 25% private vehicles i.e. ca 200,000 or even 50% i.e. ca 400,000 FCEVs, between 15,000 – 31,000 trucks respectively, depending on a scenario between 630-1,260 hydrogen buses on public transport lines (the number is based on the current PSOs), between 10-20 hydrogen trains, 43-85 hydrogen locomotives for freight transport, and up to 4-7 ferries (number is based on the current PSOs and is assumed while taking the current routes in to account). In industry sector, realizing this potential would mean, that Estonia switches from importer to major exporter of ammonia, methanol and urea. In buildings sector, biggest deployment would come through micro-CHPs, meaning up to 21,700 – 43,400 households/houses could be supplied with clean heat and power by 2050 producing up to 239 GWh of hydrogen-based heat. In power sector, high scenario would mean switching 250 MW of gas-powered emergency plants to hydrogen.

Such transformative changes also require significant investments. **The study concludes that all those changes would need total investment of EUR 22,412 – 44,7 billion** in different parts of the hydrogen value chain, majority of the investments coming from private sector i.e., companies and private consumers (in transport and heat sector). However, the analysis of economic attractiveness of possible pilot projects showed that majority of hydrogen use-cases are currently still not competitive, also the legal framework and infrastructure need development, hence **in early phase of development, there is significant need for public investments to kick-start the deployment of hydrogen and create attractive conditions for private sector to follow.**

These significant investments can also bring about significant impacts. In terms of positive environmental impact, implementation of low and high renewable hydrogen deployment scenarios will bring about **reduction of 2,2-4,4 million tons of CO₂ equivalent emissions**. Transport and industry sector combined contribute the most to emission reductions – accounting together for more than 90% of those reductions. **In addition, 21,169 – 42,432 number of jobs can be created** with an extremely high penetration of hydrogen in different sectors. **Majority of those jobs will come from hydrogen production and distribution related economic activities**, as they account for more than 64% of the possible 42,432 jobs in high penetration scenario. It is assumed that local manufacturing of fuel cells, electrolysis and fuel cell based micro-CHPs will be undertaken locally after 2030, thus the number of jobs boost as manufacturing-based jobs are added in addition to operations and maintenance jobs. The purpose of this study is to show the maximum possible decarbonization potential that can be achieved by Estonia till 2050 with the help of renewable hydrogen penetration.

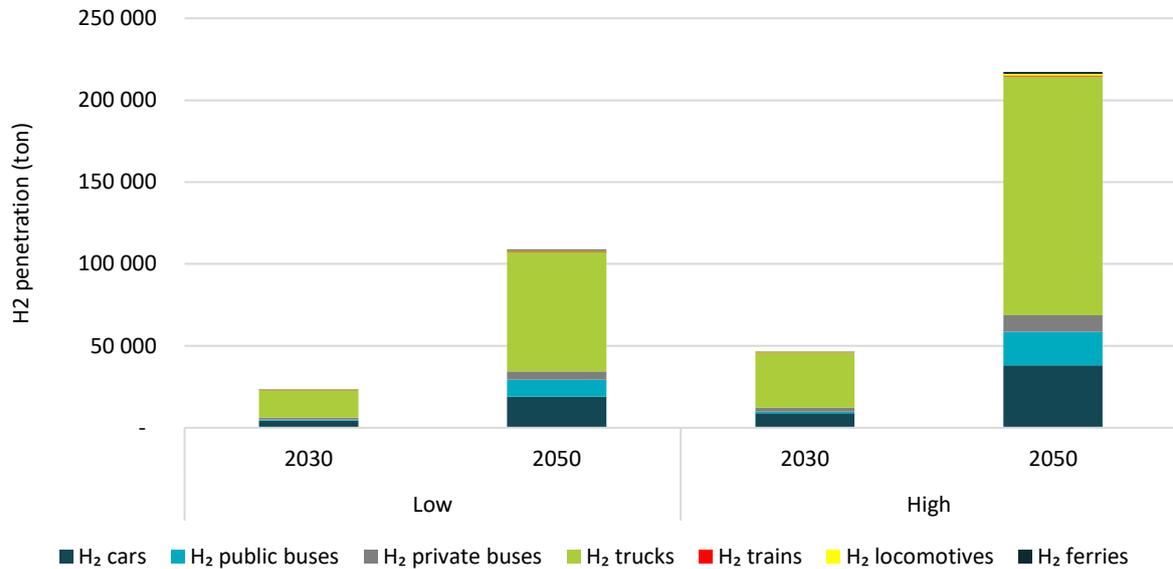
But unlocking the green hydrogen potential will require significant amount of climate neutral electricity – with low scenario needing ca 8 TWh and high scenario 16 TWh of clean electricity. In our scenario we assumed an electricity mix which consisted of 500 MW of onshore wind capacity, 700 MW of solar PV and around 3,500 MW of offshore wind (for the high scenario by 2050). For the low scenario, it is approximately half. Major renewable electricity coverage is set to be covered by offshore wind deployment. **This is way beyond that has been assumed in most scenarios about electricity production and consumption in Estonia. Thus, hydrogen economy will require additional investments of the size of EUR 5,317-10,634 billion by 2050 into clean electricity production and probably additional public policies to support that.**

It is realized from the model assessment that industry and transport sectors can be the main sectors of hydrogen penetration. The large requirement in the chemical industry (ammonia and methanol) shows the need for rapid deployment of green hydrogen infrastructure as soon as the revival of the ammonia industry and new plants of the methanol industry are constructed. **The methanol plants can be installed adjacent to the oil shale power plants or biogas plants where the large sources of CO₂ can be captured and utilized further as value-added methanol.** In near future with the advancement of the emission trading system (ETS) and carbon taxation, the necessary CO₂ that is required for the potential hydrogen penetration in the industry will be available at cheap rates.

The public procurement of hydrogen buses, passenger trains & freight locomotives, and ferries can give a rapid boost to the hydrogen economy. Hydrogen cars (FCEVs) and hydrogen trucks can get rapid public and commercial acceptance once governmental incentive policies are developed. **It is pointed out in from the model that in the Estonian scenario, converting the conventional heavy duty road transport (trucks and buses) can really play a role in overall decarbonization of transport sector due to their longer routes and frequent road usage** (Figure 0.2).

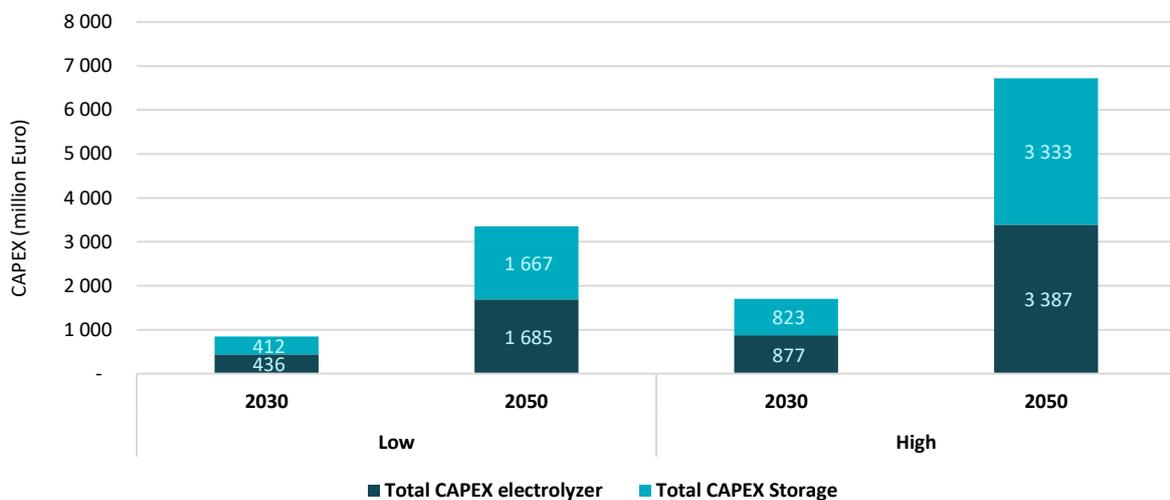
The building sector remains highly dependent on the gas provider's decision to deploy new dedicated hydrogen pipelines. Until dedicated hydrogen pipelines are deployed NG blending can partially decarbonize the decentralize heating in building sector. Once the new pipelines are deployed, a national campaign for installing FC micro-CHPs instead of NG boilers can be launched with the initial investment incentives. The power sector is the least favorable hydrogen penetration sector as a limited consumption is pointed out through the model only in emergency power plants, which are a point of discussion for their limited activity throughout the year. It is still worth mentioning that if carbon neutrality is desired by 2050, **the NG-fired power plants should be replaced with other suitable alternatives. At this point, FC power plants despite their high investment costs can be an option to provide electricity at peak demand hours.** It is assumed in the model that from 2030 onwards Estonia will have fuel cell and electrolyze manufacturing industry. This will boost the number of jobs created from 27 – 54 jobs till 2030 to 1,799 – 3,599 jobs combined in buildings and power sector.

FIGURE 0.2 HYDROGEN PENETRATION IN TRANSPORT SECTOR



To keep the hydrogen supply cost as low as possible, hydrogen production at more than one location is necessary. For example, an electrolyze facility near the industrial region will provide hydrogen at low levelized costs rather than having hydrogen production at only one central location far away from the industrial consumption points. In the model it is assumed to have a hydrogen storage facility adjacent to the hydrogen production plant, to give a maximum 5-day supply flexibility. A potential problem for hydrogen storage is pointed out during modeling as Estonia does not have positive feasibility for underground hydrogen storage. That gives rise to the barrier of long-term hydrogen storage. The short-term mature storage options for supply flexibility are liquification or compressed hydrogen storage in large vessels. The compressed hydrogen storage option presents large capital investment costs (almost as large as the electrolyze CAPEX – see Figure 0.3) as large storage volumes are required, and currently available hydrogen vessels provide limited hydrogen storage and have high material costs.

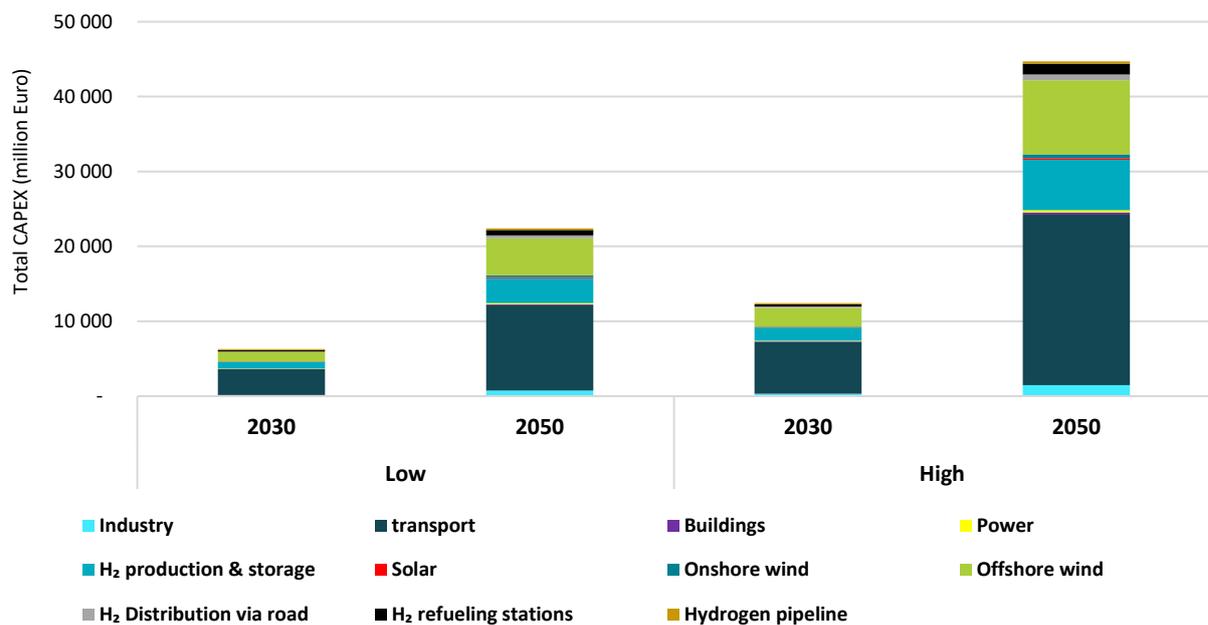
FIGURE 0.3 CAPEX BREAKDOWN OF FOR HYDROGEN PRODUCTION AND STORAGE



To maintain a smooth hydrogen supply to industry, buildings, and power sector, dedicated hydrogen pipelines are considered. For the transport sector, gas bearing (GH₂) truck-trailer are considered with an assumption that with increasing hydrogen demand more truck-trailer can be added. While modeling, it is also realized that the cost-efficient way of hydrogen supply depends on the daily demand and the distance between hydrogen production location and consumption locations.

During the overall CAPEX investment calculations, the future cost reductions in certain technologies like FCEVs, micro-CHPs, fuel cells, and electroliers are considered to make more realistic scenarios. Figure 0.4 shows overall CAPEX investments needed by 2030 and 2050 to deploy the hydrogen economy.

FIGURE 0.4 TOTAL CAPEX BREAKDOWN



HOW ATTRACTIVE ARE INVESTMENTS IN THE PILOT PROJECTS TODAY? | In the course of the work, ten pilot projects were analyzed based on the potential of these use cases, economic profitability (ROI and IRR¹), required investment, environmental impact and expected need for support. **In the comparison of pilot projects, those with the higher potential were those where the hydrogen use technology is sufficiently mature and efficient compared to the alternatives currently in use, and at the same time the initial hydrogen use is sufficient to apply at least 5 MW of electrolyser.** In addition to hydrogen production, electrolyser uptime (at least over 50% to ensure a sufficiently low cost of hydrogen), the cost of renewable electricity used, the proximity of the renewable electricity fleet to hydrogen production, so that there is no significant additional cost for transporting hydrogen, as well as advanced and efficient technology of hydrogen usage are important for the cost-effectiveness of pilot projects.

Due to these factors, according to the cost-benefit analysis the **project with the most potential is the project about the use of hydrogen ferries (Table 0.1; PP 5)** (both mainland and inter-island passenger and international cargo between Estonia and Finland), **since a couple of ships to hydrogen transfer ensures sufficient hydrogen for use by volume, hydrogen production takes place in a port near renewable electricity parks and the use of hydrogen technology in these vehicles is now relatively efficient.** The ROI of the project without subsidies is -1% over a 20-year period, and the conversion of two passenger ferries to hydrogen would save more than 10 kilotons of CO₂ emissions per year. **In order to carry out the pilot**

¹ ROI - Return on investment; IRR - Internal rate of return

project, additional support would be needed for the purchase of hydrogen vessels with 2.7 million euros, which would increase the ROI of the pilot project to 10%. In addition to the use of hydrogen in various means of transport, **the production of ammonia from hydrogen and its export also stands out in terms of positive potential (Table 0.1; PP 8)**, which has a high escalation potential due to the widespread use of ammonia and the multiplicity of target markets - an electrolyser with a capacity of 24 MW could save around 30 kilotons of CO₂ emissions per year from ammonia production compared to ammonia production from methane.

TABLE 0.1. KEY INDICATORS FOR PILOT PROJECTS

#	ROI	IRR	REDUCTION OF CO ₂ (%)	REDUCTION OF CO ₂ (KT PER YEAR)	INVESTMENTS (MLN EUR)	NEED FOR SUPPORT (MLN EUR)
PP 1	-31%	-1%	83%	1.03	9.2	3.0
PP 2	-6%	-1%	88%	2.25	37.0	6.0
PP 3	-32%	-1%	40%	0.84	18.5	6.2
PP 4	-17%	0%	81%	3.98	26.0	4.0
PP 5	-1%	1%	83%	10.58	35.0	2.7
PP 6	-565%	n/a	91%	2.43	9.0	11.0
PP 7	-81%	-11%	90%	0.72	4.5	9.0
PP 8	-18%	-3%	80%	28.10	24.0	8.0
PP 9	-10%	-5%	74%	1.12	4.2	0.5
PP 10	-9%	-12%	85%	0.14	3.7	0.3

PP 1 - Use of hydrogen as fuel for city buses; **PP 2** - Use of hydrogen as a fuel for passenger cars; **PP 3** - Use of hydrogen as a truck fuel; **PP 4** - Use of hydrogen as fuel for trains; **PP 5** - Use of hydrogen as fuel for ships and ferries; **PP 6** - Addition of hydrogen to increase the calorific value of the natural gas pipeline; **PP 7** - Use of hydrogen as a fuel for forklift trucks; **PP 8** - Export of ammonia produced from hydrogen; **PP 9** - Use of hydrogen as a fuel for autonomous vehicles; **PP 10** - Use of hydrogen as a back-up fuel for communication networks

The area with the greatest potential for the use of hydrogen is the transport sector, where on the one hand it is possible to create high demand and on the other hand the technology is also effective for different vehicles. The use of hydrogen in the transport sector has a major environmental advantage over a diesel engine, as well as a functional advantage due to fast refueling and a longer range over an electric motor, especially over longer distances. Thus, **the most promising projects in the transport sector are shipping and rail transport** (20-year ROI of -17% and -1% respectively), where hydrogen technology is mature, hydrogen consumption is high and energy demand per hour is high. **The hydrogen-powered passenger car project is also highly scalable and has relatively good economic potential**, but here electrical technology may prove even more promising in the near future. Heavy goods vehicles could also be a successful area in the development of technology, but currently diesel vehicles have a clear competitive advantage in terms of cost-effectiveness (20-year ROI -32%). Hydrogen buses will also be technologically mature enough for widespread use in the near future, and hydrogen will have an advantage over the electric motor there due to faster refueling time and longer driving range. At present, hydrogen buses are more than twice as expensive as diesel buses, as well as gas buses, which makes it more favorable

to achieve the expected environmental impact with the latter. As the price of hydrogen buses falls over the next five years, the profitability of this project could increase significantly.

The use of hydrogen in the industry is mainly divided into two categories - meeting the energy needs of production and fuel for various machines and vehicles. Using hydrogen to meet the energy needs of an industrial plant means adding hydrogen to the natural gas pipeline through which the hydrogen is transported to the site. However, **the addition of hydrogen to the natural gas pipeline has limited scalability due to the capacity of the existing natural gas infrastructure to absorb hydrogen** (through investments, it is estimated that the share of hydrogen in the natural gas pipeline can be increased by 10-20% by volume). As the price of natural gas per unit of energy is currently much cheaper than the price of hydrogen, neither gas traders nor industry would have to pay such a much higher price for hydrogen, which would require a large amount of public support for the project. **The use of hydrogen in production machines would be suitable for companies that have renewable energy production in the immediate vicinity of the site, for example in the form of a solar park,** but the low use of hydrogen means that the use of hydrogen would be very costly compared to alternative solutions.

Like in industry, hydrogen can be used to meet the energy needs of residential buildings by adding hydrogen to the natural gas pipeline, thereby increasing the calorific value and purity of natural gas, but this would require large support measures to compensate for the price difference. As an alternative, the possibility of supplying buildings with local fuel cells that would produce energy from a hydrogen cylinder has also been discussed, but at the moment there are no more specific developments in this direction in Estonia and the use of the corresponding technology is in its infancy.

Alternatively, hydrogen produced from green energy can produce **ammonia**, which, unlike methane ammonia production, does not emit large amounts of carbon during the process. **The production of ammonia from hydrogen and its transport by ships to other countries would be an economically promising undertaking in the coastal areas of Estonia,** which would be highly scalable due to the abundance of possible target markets and the widespread use of ammonia in various sectors.

The use of hydrogen as a fuel for generators in base stations and the conversion of autonomous vehicles to hydrogen fuel are currently topical issues in Estonia. The use of hydrogen as a fuel for communication base station generators is economically expensive due to the large network of base stations, which results in high transportation costs, but the small amount of hydrogen used. **However, this project could be extended to other vital service providers in the future, such as the use of hydrogen as a fuel for hospital back-up generators, which would ensure a higher volume of hydrogen use and thus a lower cost.** In the case of autonomous vehicles, the use of hydrogen on a larger scale could be attractive, but this will probably not be the case on the Estonian market in the near future. The production of autonomous vehicles powered by hydrogen would be an attractive source of exports for the country in the broadest sense, but it would also require the movement of hydrogen production and consumption to the country of destination.

WHAT SOCIAL, TECHNOLOGICAL AND SAFETY RISKS EXIST FOR THE USE OF HYDROGEN? | With the wider use of hydrogen, it is also important to assess the potential risks associated with the use of hydrogen and the measures to mitigate them. The introduction of hydrogen is mainly associated with the **risks related to social acceptance, technology and safety.** The risk analysis focused on the use cases of the analyzed pilot projects in order to provide mitigation measures that can actually be used in the implementation of business ideas.

The main problems with social acceptability are people's low awareness of hydrogen use and the fear and ignorance of previous accidents. The higher cost and low availability of hydrogen technologies also play a role, giving preference to existing conventional technologies.

At present, either AE or PEM electrolysis are mainly used for the production of hydrogen based on renewable energy. **The main problem with the production of hydrogen by electrolysis is the high energy consumption of the production process,** which increases the price of the hydrogen obtained. When using an AE electrolyser with mature technology, the biggest risk factors are use under load, the provision of

different input capacities and frequent start-up are technologically limited and in addition this reduces productivity, which precludes the use of AE electrolyser in renewable energy systems.

Hydrogen is mainly stored as compressed gas or liquefied hydrogen and is transported by pipeline or by compressed gas and cryogenic trucks. Compressed gas transportation is more suitable for shorter transports because of the low hydrogen density and the maximum pressure limits on the tanks, which limit the amount of hydrogen that can be transported at one time. **There is also a risk of damage to the container due to frequent decompression or complete breakage in the event of an accident resulting in hydrogen leakage and possible explosion or fire.** When transporting cryogenic hydrogen, it must be taken into account that as the temperature rises, the hydrogen evaporates, and losses occur. When storing liquefied hydrogen, air and moisture can leak into the tank, where low temperatures create ice that damages the equipment. There is also a risk of hydrogen ignition and explosion in the event of a leak. Although the risk of the aforementioned leaks or accidents is medium to high, the realization of these risks is highly unlikely due to the conditions imposed for the storage and transport of hydrogen.

The main technological risks of hydrogen vehicles are related to the fuel tank and fuel element, but also to infrastructure and equipment maintenance. The fuel tanks of hydrogen vehicles are several times larger in volume than petrol or diesel tanks, which require extra space. Lightweight but mechanically strong composite tanks decompose under thermal stress and pose a risk to humans, but with thermal protection this effect can be mitigated to a low level. **The lack of qualified personnel and facilities in our region must currently be assessed as a higher level of risk.** However, this can be addressed through the creation of new curricula or modules at universities, the organization of in-service training and retraining abroad, where hydrogen technologies have been used for a long time. We consider the greatest risk of the introduction of hydrogen vehicles to be the lack of infrastructure and the cost of its construction compared to the construction of traditional filling stations and battery charging stations.

With nitrogen production, there is a risk of oxygen entering the ammonia synthesis circuit, causing catalyst poisoning. The likelihood of this occurring is low when safe materials and sensors are used. In addition, there is a risk of ammonia leakage, as ammonia is a toxic compound that can pose a risk to human life and health if inhaled. The presence of buffer tanks plays an important role in the production of ammonia from renewable energy sources, as systems with complex high-pressure ammonia synthesis compressors and sensitive catalysts require a stationary process and the non-stationary mode causes disturbances in ammonia synthesis. **Additional energy sources should be used to mitigate this risk, but they are not sustainable in the context of the climate goals set. With regard to ammonia synthesis, this level of risk is considered to be the highest.**

WHAT ARE THE MOST IMPORTANT BARRIERS AND MEASURES TO THE WIDER USE OF HYDROGEN? | The analysis mapped 28 barriers and 46 measures across the entire hydrogen value chain, including 32 legal, administrative and 14 economic measures.

Before implementing specific measures, an important precondition is the existence of a national hydrogen strategy, which would choose between the options analyzed in this study, set out specific policy objectives and guidelines, in which sector and to what extent hydrogen technologies are to be introduced and how much CO₂ is to be reduced. Without a national hydrogen plan, investors are uncertain and reluctant to invest in hydrogen solutions.

A coordinated division of competences and activities between authorities should be ensured in order to implement the measures. In particular, the ministries responsible for a specific field (Ministry of Economic Affairs and Communications, Ministry of the Environment, etc.) and government agencies should be responsible for directing and coordinating activities between sector-specific state electricity and gas network management organizations (Eesti Energia AS, Elering AS) or non-state market participants. The first step towards greater cooperation between market participants has recently been taken, when the Estonian Hydrogen Cluster was established, the aim of which is to carry out general information work and exchange information between different parties. In addition, the Estonian Hydrogen

Technology Association has been active in Estonia for the last three years, which has also been involved in connecting market participants and government agencies, but according to experts, financial and communicative support would be needed for more effective work.

Also, any legal, administrative changes and actions should be based on the final objectives agreed in the Hydrogen Plan and not on airborne approaches. Based on the objectives set out in the National Hydrogen Plan, Estonia should identify the most logical needs for local regulation changes and implement the changes as soon as possible, that by the time the European Commission proposes the introduction of several new regulations or significant changes to the existing ones, Estonia would be a country with an already existing energy storage regulation. It would also reduce the risk that Estonia will wait for decisions to be made at the European level and only then will it begin to eliminate the shortcomings already identified.

Another important basic premise for the production and placing on the market of green hydrogen in Estonia is not only the setting, but also the implementation of ambitious renewable energy targets, as the volume of renewable electricity demand in Estonia may increase approximately two times compared to the forecast so far if hydrogen technology is fully introduced. This additional demand can be met by planning additional supply of renewable energy, streamlining planning and permitting procedures, easing national defense restrictions in the form of acquiring additional equipment contributing to national defense, and preparing an action plan for the implementation of offshore wind farms in Estonia.

The main regulatory and administrative amendments and activities relate to:

- easing of land use restrictions (heritage protection, environmental, nature, health and national protection restrictions) necessary to increase renewable energy capacity;
- development of guidance materials for the construction of hydrogen production and storage facilities and the existence of clear rules for applying for planning and building permits, as there is still no practice in this area in the field of planning.
- reviewing relevant technical and gas quality issues for the deployment of hydrogen in gas networks and supporting the regulatory framework;
- the establishment of guidelines and a legal framework for restrictions and drivers required for the transportation of hydrogen by road or sea;
- the development and implementation of a definition, common standards and certificates for green hydrogen and hydrogen-based synthetic fuels as soon as they are developed at European Union level;
- development of guidance materials to facilitate the permitting, construction and operation of hydrogen filling stations and related amendments to alternative fuel infrastructure legislation;
- the implementation of national carbon levies to reduce fossil fuels in both the transport and building sectors in order to favor alternative fuels, including hydrogen;
- implementing exemptions from taxes and registration fees in favor of hydrogen-based solutions;
- development of instructional materials in Estonian for various on-site maintenance works (for hydrogen vehicles, in micro-cogeneration plant buildings) and creation of a corresponding on-site skilled workforce (who would perform the necessary maintenance and repair work on behalf of the user);
- carrying out the technical and economic feasibility of CO₂ capture and storage facilities for the production of green methanol;
- developing the legal basis for electricity generation (facilitating the connection of fuel cells to the electricity grid; clarifying the operational framework for electrolysis plants and related energy storage; reorganizing the price of network service for electricity entering the energy storage);
- the necessary research and development; establishing an action plan for public involvement; review of state aid measures; strengthening the necessary risk assessments and rescue capabilities.

The total cost of support measures to meet the hydrogen potential under the low-level scenario would be EUR 2.2 billion in the public sector by 2030 and EUR **5.8 billion by 2050 (excluding the energy sector)**. The

need for private sector support would be EUR 4 billion by 2030 and **EUR 16.5 billion by 2050**. To meet the **ambitious scenario**, the private sector would need **EUR 8.1 billion in support by 2030** and **EUR 32.9 billion by 2050**. In the public sector, the need for support under the same scenario would be **EUR 4.3 billion by 2030** and **EUR 11.5 billion by 2050**. The greatest need for investment is in the transport sector and in production and storage sector.

The estimated increase in jobs by 2050 is 20,254 in the low-level scenario and 40,604 in the ambitious scenario (excluding the energy sector). Under the low-level scenario, CO₂ emissions would fall by a total of 2.2 million tons by 2050 (excluding production and storage measures). Under the ambitious scenario, CO₂ emissions would fall by 4.4 million tons by 2050. With the introduction of hydrogen technologies, CO₂ emissions would fall the most in terms of the volume of hydrogen production and its subsequent use in production and storage.

The results of the study provide a summary list of all support measures, their effects on barrier mitigation and assessments of technological readiness, as well as the estimated cost of each measure and the CO₂ reduction potential and potential impact on jobs under the two different scenarios. **This list of support measures can be used as a supporting tool, but the final need for implementation depends on the potential to be realized.** The most important primary steps regardless of whether to decide on the path of realizing a low or ambitious scenario:

Subsidies for the promotion of wind and solar energy production projects through renewable energy auctions targeting capacity to support hydrogen production.

- Investment support for the promotion of hydrogen production technologies: CAPEX (investment in fixed assets) incentives for electrolysis.
- Public investment support for the construction of hydrogen filling stations.
- Investment support for the introduction of buses on fuel cells.
- Investment support for the introduction of cars on fuel cells.
- Public procurement obligations for cities, municipalities, public transport companies, for the introduction of fuel cell vehicles by public transport sector organizations.

The highlighted measures focus in particular on increasing the amount of renewable energy needed for hydrogen production, promoting hydrogen production technologies and investing in the development of a hydrogen distribution network (gas network, investment subsidies for hydrogen distribution by road) **without which the deployment of hydrogen in any sector will be difficult**. In addition, the **first five years are seen as the introduction of hydrogen in the transport sector**, where an existing and operational hydrogen filling station chain is an important precondition and where public procurement obligations for local authorities to introduce hydrogen vehicles by public transport organizations would be one of the fastest ways for the public sector. At the same time, taking into account the technological readiness, the biggest potential in the years 2025 - 2030 is in cars and buses.

The **second largest sector in realizing the hydrogen potential is the industrial sector**, where previously imported fossil ammonia and methanol could be replaced by locally produced green hydrogen-based ammonia and methanol to help reduce the carbon dioxide from production and transportation. In addition, **the construction of methanol plants at oil shale power plants or biogas plants help to capture the carbon dioxide generated there and further convert it into methanol**. The support measures in this sector aim to realize this potential to help launch the local green ammonia and methanol industry and thus ensure competitiveness with fossil-based methanol and ammonia readily available from neighboring countries.

In the building sector, the uptake of hydrogen depends on the installation of hydrogen pipelines, and only after the gas supplier has installed new pipelines can investments be made to replace natural gas boilers with fuel cell micro-cogeneration plants. In addition to the building sector, the installation of hydrogen pipelines is important for the industrial and energy sectors. The potential of hydrogen is lowest

in the energy sector, where the model focuses mainly on emergency power plants. However, in order to achieve climate neutrality by 2050, natural gas-fired power plants should be replaced by fuel cell power plants, despite their high investment costs. The capacity to implement measures in both the building and electricity sectors should therefore be realized from 2030 onwards.