Draft Roadmap
for production and use of hydrogen
in Ukraine

March 2021

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Cut-off date of this report is 9 March 2021.

List of Acronyms

AEL	Alkaline Electrolyzers
AEM	Alkaline Exchange Membrane
AMC	Anti-Monopoly Committee
atm	Standard Atmosphere (unit of pressure)
ATR	Autothermal Reforming
CAES	Compressed Air Energy Storage
CAPEX	Capital Expenditures
CCS	Carbon Capture and Storage
CO2	Carbon Dioxide
CoM	Cabinet of Ministers
ESU	Energy Strategy of Ukraine
EU	European Union
FCEV	Fuel Cell Electric Vehicle
FCH	Fuel Cell and Hydrogen
FCH JU	Fuel Cell and Hydrogen Joint Undertaking
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GTS	Gas Transportation System
GW	Gigawatt
IEA	International Energy Agency
IPCEI	Important Projects of Common European Interest
IPHE	International Partnership for Hydrogen and Fuel Cells in the Economy
IRENA	International Renewable Energy Agency
KPIs	Key Performance Indicators
LOHC	Liquid Organic Hydrogen Carrier
MCTD	Ministry for Communities and Territories Development
MENR	Ministry of Ecology and Natural Resources
MoE	Ministry of Energy
MoF	Ministry of Finance
NASU	National Academy of Science (of Ukraine)
NEEAP	National Energy Efficiency Action Plan
NEURC	National Commission for State regulation of Energy and Public Utilities
NGO	Non-Government Organizations
NO	Nitrogen Oxide
Nm3	Normal cubic meter
NPP	Nuclear Power Plant
NREAP	National Renewable Energy Action Plan
OPEX	Operational Expenditures

PEC	Photoelectrochemical Cell
PEM	Proton Exchange Membrane
POX	Partial Oxidation
PPE	Programmation pluriannuelle de l’énergie (Multi-Year Energy Plan)
PSPS	Pumped Storage Power Stations
R&D	Research and development
RES	Renewable Energy Sources
RPTC	Regular Programme for Technical Cooperation
SAEE	State Agency on Energy Efficiency and Energy Saving
SMR	Steam Methane Reforming
SMSS	Semiconductor Magnetic Storage Systems
SOEC	Solid Oxide Electrolyzer Cell
SOFC	Solid Oxide Fuel Cell
SPP	Solar Power Plant
toe	Tonnes oil equivalent
TPES	Total Primary Energy Supply
TPP	Thermal Power Plant
TRL	Technology Research Level
TWh	Terawatt hour
UPS	United Power System (of Ukraine)
UNECE	United Nations Economic Commission for Europe
USF	Underground Storage Facilities
WPP	Wind Power Plant

Executive Summary

Energy transition is an ambitious strategic choice of Ukraine, which will determine the main trends and directions of development of the national economy over the next 30 years. In order to realize this transition Ukrainian government will face many challenges:

- How to reduce the dependence on fossil fuels?
- How to decarbonize industry which is highly dependent on fossil fuels?
- How to decarbonize the transport sector?
- How to develop mobility on the basis of renewable energy?
- How to improve energy efficiency and energy storage?
- How to integrate flexibility options in order to match the generation of renewable electricity with demand?

All these questions and many more could be addressed with the help of many new technologies which will be needed to replace the current reliance on conventional energy. One of the most promising modern technologies to deliver the scaled up renewable energy to the economy are **hydrogen technologies** due to unique hydrogen chemical properties as the carrier of energy.

Combined with comprehensive energy efficiency measures and development of renewable energy sources, large scale production and use of hydrogen in Ukraine will allow to decarbonize its energy sector, as well as transport and many other industries. This will contribute to strengthening intersectoral ties and forming sustainable clusters in the economy, intensifying innovation and investment activities, creating new job opportunities, increasing the competitiveness of Ukrainian enterprises, promoting Ukraine in the world rankings to significantly improve the investment climate.

Implementation of recommendations outlined in this Report is meant to significantly improve energy efficiency of the economy with the aim to approximate the average level of the EU countries in terms of energy capacity of GDP, as well as to achieve the increase of the share of RES in the energy mix accompanied by the reduction of greenhouse gas emissions, aligning them to the average level of EU countries in terms of GDP carbon intensity.

Given the size and anticipated growth of the existing hydrogen market, the development of renewable hydrogen projects could present a significant investment opportunity in Ukraine. Not only does Ukraine enjoy some of the most abundant renewable resources in Europe, but it also is the country that is most in need of new and clean forms of energy to support economic development. Ensuring that the alternative fuels create zero emissions, are affordable, and are convenient to use is essential to avoid locking Ukraine (and ultimately global CO_2 emissions) into a trajectory that leads to significant climatic warming by the middle of the century.

But hydrogen applications do not come without challenges. Hydrogen is a gas difficult to contain, with properties that require careful consideration to ensure safe usage. Although technologies and procedures do exist to minimize leaks and to ensure that, where necessary, hydrogen is released in a controlled manner, they are not understood well outside the petrochemical industry. Indeed, where there have been safety incidents involving hydrogen, the cause has often been a fault in the assembly of the units, demonstrating the importance of having access to experienced installers and engineers. Access to such skills is also important for the ongoing maintenance of fuel cell systems, notably those operating at higher temperatures for which suppliers are advising some form of basic maintenance every three months. But storage and assembly concerns are not unique to hydrogen and are also considerations for the handling of other fuels such as ammonia - a toxic chemical - or new technologies such as electric battery storage, for which fires from poor assembly are also a concern. Indeed, the key takeaway is not that safety is an insurmountable barrier or that the issues are not sufficiently understood; rather, the knowledge around hydrogen needs to be more widely disseminated and practiced as these new applications gain traction.

One of the significant barriers to the use of hydrogen in Ukraine is the outdated and non-harmonized regulatory and technical safety regulations, as well as the lack of awareness of business entities in this area. Few businesses and utilities in Ukraine have a clear understanding of the potential applications for hydrogen inside their businesses, and thus they have not sought to engage with suppliers, financiers, or the government to promote its use. Concurrently, the country's policy makers have not sought to develop a policy framework or national strategy to support the uptake of renewable hydrogen and fuel cells because they may be unaware of the role hydrogen could play in their national energy strategy and industrial objectives. In addition, the technical expertise for hydrogen systems is frequently low and, in many cases, non-existent. Because training may take several years for professionals in Ukraine to gain the necessary skills to support these technologies, it will have to rely on a relatively small pool of qualified international experts who will be in high demand within their own markets. This requirement may increase short-term deployment costs and increase the timeframe for deployment of hydrogen technologies in Ukraine.

Given that different hydrogen technologies have different carbon impact – Ukraine needs to prioritize production of carbon-neutral (green) hydrogen while other forms of hydrogen technologies should mainly be considered in a transition period.

Introduction

The development of this Roadmap has been requested by the Ministry of Energy of Ukraine and was supported by the United Nations Economic Commission for Europe (UNECE) within the framework of the project “Improving capacity of the Government of Ukraine to develop infrastructure for production and use of hydrogen to support green post-covid-19 recovery” funded by the Regular Programme for Technical Cooperation (RPTC). The Roadmap attempts to draw attention to areas of current success with hydrogen technologies worldwide and areas in which renewable hydrogen could provide a compelling solution for Ukrainian economy to address the current and anticipated energy challenges faced by the country. In this way, the Roadmap focuses on how hydrogen and fuel cell technologies could be initially rolled out in the country by presenting a series of applications that could be initially deployed in some locations and could be scaled up in the future.

This Roadmap also focuses on some of the technology risks, implementation challenges, and knowledge gaps that are emerging as new hydrogen projects and technologies are being deployed and tested in greater numbers. Crucially, the Roadmap seeks to draw attention to where these challenges are universal and where they are more specific to Ukraine.

This Roadmap is structured to provide readers first with an overview of why hydrogen has gained traction in recent years, why that is relevant for Ukraine, and what implementation challenges remain. In Chapter 1 the report offers a historical context to the development of the current global hydrogen and fuel cell markets and then explains what has changed and provides examples of how these technologies could be used in Ukraine in Chapter 2. To help frame the discussion of hydrogen within the global context, Chapter 3 provides a recap of how hydrogen technologies work and details costs and the size of global markets today. Chapters 4 and 5 then explore a list of implementation challenges for hydrogen and fuel cell projects, including problems of technical regulations of safety at all stages from hydrogen production to its transportation, storage and use, as well as the country’s experience of manufacturing equipment to produce hydrogen domestically - with the aim of helping stakeholders understand some of the technical factors involved in developing projects and of assisting policy makers, developers, and investors who are considering these types of projects in Ukraine. Finally, Chapter 6 suggests a detailed Roadmap for introduction of hydrogen technologies and areas for further research to help Ukraine reach its decarbonization goals and the potential for hydrogen projects.

Although there are varying methods for classifying the different applications for hydrogen and fuel cell technologies, this Roadmap will group potential uses into three core areas of interest:

- hydrogen for electricity and heat generation;
- hydrogen for mobility; and
- hydrogen for industry.

Within these areas, the types of potential hydrogen projects can be extremely diverse, both geographically and with respect to their application.

For fuel cells the uses are just as diverse, with fuel cells being considered, for example, by the Ministry of Energy of Ukraine to be deployed at coal mining facilities, which could potentially become centers of development and application of fuel cells and hydrogen technologies in the course of carbon-intensive industries transformation and decarbonization[1].

Nonetheless, these classifications do help provide an analytical reference point, given that mobility applications typically represent the most expensive form of energy, followed by electricity and heat generation and then by hydrogen for industrial uses. Accordingly, the categories help influence assessments about when certain applications are likely to become commercially viable and competitive against alternatives, and what conditions are needed to achieve this.

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[1] http://mpe.kmu.gov.ua/minugol/control/uk/publish/article;jsessionid=CB2E08F1694A7CAB1991BDF44D6DEE89.app1?art_id=245480813&cat_id=244895180

1. Analysis of best international practices and plans for the use of hydrogen

The European practice of use of hydrogen has both ecological and technological aspects. Europe has been in a transition to the decarbonized energy system. All European Union (EU) member states have signed and ratified the Paris Agreement, which aims to strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2 ºC above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 ºC. Transition to a new energy model will drastically transform the ways of the energy generation, supply, storage and consumption. This requires a practically carbon-free energy generation, improvement of the level of energy efficiency and a deep decarbonization of vehicles, construction and industry. As is clear from the studies, in order to reach the energy transition in the EU, a wide use of hydrogen technologies will be required. The EU will not be able to reach decarbonization without them (Hydrogen Roadmap Europe 2019). Certainly, hydrogen is not the only leverage, but it is an important factor along with other technologies.

Firstly, hydrogen is one of the best options at the massive decarbonization of a range of sectors: transport, industry and construction. Electrification along with heat pumps can substitute natural gas for heating new houses, but requires an expensive or even impossible modernization of the old ones. A full direct electrification will also lead to great seasonal disproportions of demand for electric energy, which, in turn, will require a mechanism of storing energy on a large scale. Hydrogen does not have such disadvantages and can serve as an addition to heat pumps. Some portion of hydrogen (up to 20% according to various data) can be mixed with natural gas without a need for a significant modernization of gas networks, and networks can be adapted to work on hydrogen. Another option is to substitute natural gas with a synthetic gas, generated from hydrogen and CO_2. In the transport sector the most promising is the use of hydrogen for freight vehicles, buses, ships, trains. As the transport sector accounts for approximately one-third of CO_2 emissions in the EU countries, its decarbonization is a key element of energy transition. The development of hydrogen fuelling stations, which makes hydrogen attractive for business, is required[2].

The only available solution for a direct decarbonization in aviation is to use hydrogen and synthetic fuel on the basis of it. Industry may use hydrogen directly for heat generation and use as the fuel in various processes, directly or along with synthetic fuel or fuel cells. When using it as the starting material for chemical production and hydrofining at refineries the use of carbon is reduced; hydrogen can also substitute hydrocarbons, for example, natural gas, in other chemical processes.

Secondly, hydrogen will play a systemic role in the process of transitioning to renewable energy sources by improving the flexibility of the energy system. The EU energy transition stipulates the necessity of integration of renewable energy sources into the energy system. Hydrogen technologies are capable of ensuring a great transformation of the generated energy into the forms suitable for use, storing it and directing to the end user to meet the current demand. At the increase of the amount of energy, coming from renewable sources, both a short-term and a long-term disbalance between the demand and supply grows. This creates the necessity to increase daily grid balancing and optimization within a year and seasonal energy storage. Although batteries can ensure a short-term flexibility, hydrogen is the only massive technology available for a long-term energy storage. It can use the existing gas networks for storage for a long period of time with minimum losses. Hydrogen also ensures a connection between regions with cheap renewable energy sources and consumption centers (for Europe it is, for example, a connection of regions with a great amount of geothermal and wind energy in the north, continental regions and renewable energy sources from North Africa). Hydrogen can be transported through pipelines, by ships or trucks in a liquefied state or can be stored in other forms.

Thirdly, transitioning to hydrogen creates additional advantages and conveniences for consumers. Energy companies can mix hydrogen or synthetic methane in the gas network, using the existing

[2] Fuel cell electric vehicles (FCEVs) can be refuelled in 3-5 minutes at a hydrogen refuelling station (HRS), offering refuelling times similar to those of conventional petrol or diesel cars.

pipelines without affecting consumers. Although in order to reach a 100% transition to hydrogen, equipment and pipelines will have to be modernized, this will not affect the existing heating infrastructure inside the buildings.

The potential of use of hydrogen in all the above-mentioned sectors for generation of electric energy by the EU countries is about 2,250 TWh, which is about a quarter of the general demand (Hydrogen Roadmap Europe 2019). Reaching such a level would help the EU countries cut the CO_2 emissions by 560 Mt, i.e. to ensure the third part of the necessary volume of emissions to be cut according to the climate commitment of the European countries. Moreover, this would ensure a deep decarbonization of the energy sector and indirectly reduce the carbon emissions. Except for the reduction in carbon emissions, development of use of the hydrogen technology and fuel cells will eliminate a range of negative impacts: NO_X emissions (approximately up to 0.5 Mt per year in 2050) can be reduced in the transport sector; water bodies will be less polluted, steel plants and other industrial plants would reduce their emissions of dust and tar, and the noise from railway and road transport would be reduced as well. In general, the hydrogen industry of the EU can generate employment of about a million of highly skilled specialists by 2030, and potentially reaching 5.4 million by 2050 (Wietschel and Seydel 2007).

In order to understand the growing attention, which is being paid to hydrogen technologies, this Chapter will provide a short analysis of plans/strategies/roadmaps on their global development in selected developed countries.

Australia's National Hydrogen Strategy, adopted in 2019, is the main goal of the country till 2030. The strategy was developed as a “live document” – it will be updated and revised with the development of the industry. In total, the Strategy defines 57 joint actions. The actions are related to coordination at the national level; development of production potential, which is maintained by the local demand; sensitive regulation; international interactions; Research & Development (R&D) and the trust of the community. These actions consider the use of hydrogen in the export, transport sectors, industrial production, gas networks, electrical energy systems and other related areas, such as security and environmental impact.

The Strategy stipulates the revision and reform of relevant laws in order to ensure the development of a strong hydrogen sector in Australia. Second priority is the creation of international markets to support investments. Australia is eager to take charge of the development of the international hydrogen certification scheme, taking part in multilateral forums and cooperating closely with the like-minded countries, local and international companies. Another priority is acceleration of commercialization of technologies. The Government of Australia supports the development of clean energy technologies, including hydrogen, from research and development to commercialization through the Australian Research Council, the Commonwealth Scientific and Industrial Research Organization (CSIRO), the Australian Renewable Energy Agency (ARENA), the Clean Energy Finance Corporation and the Northern Australia Infrastructure Facility. Thanks to these investments the technologies, necessary for reaching the goal of the country under the Paris Agreement and reducing emissions after 2030, will be developed. It is noteworthy that financing different areas of development of hydrogen technologies in Australia began as early as in 2015, and by 2019 the amount of support had reached 146 mn Australian dollars.

The Strategic Roadmap for Hydrogen and Fuel Cells was adopted in **Japan**. Japan relied on the use of hydrogen as a new energy carrier to ensure the energy supply, cutting CO_2 emissions and the industrial development. Within the framework of the so-called “3E+S” energy policy (Energy Security, Economic Efficiency, Environment + Safety) Japan is eager to position itself as an international leader in the future “hydrogen community”. After the programs started in 1970s Japan adopted the first National Roadmap for Hydrogen as early as in 2014. It developed the Roadmap with an indication of particular actions in 2019. This Roadmap is focused on the organization of the supply chain, diversification of use (mobility, electric energy production, industry, housing sector) and creation of a global “hydrogen community”. Japan participates in the development of technologies for the CO_2 capture and storage, which it considers important for hydrogen implementation in the long term and in anticipation of the cost-effective renewable production, which is expected approximately in 2032 with the reduction of the cost of electrolysis up to 50,000 Yen/kW (approx.

USD 480/kW) instead of 200,000 Yen/kW in 2019 (approx. USD 1,920/kW). Japan is eager to promote hydrogen for transport and housing sector, as well as in the large-scale production of electric energy, substituting natural gas. The Roadmap is aimed at mass-producing vehicles, accelerating allocation of hydrogen refuelling stations and a simple regulation. At the technical level Japan actively collaborates on development of international standards and is the world leader in the number of patents in the hydrogen sector.

Being fully committed to the strategy, pursued by the national government, several Japanese communities and manufacturers mobilize for creation of the "hydrogen community". So, the gas pipeline for the hydrogen supply is installed in the Olympic Village, which will later be used as a house and a trade center. Tokyo is also planning to supply 100 hydrogen buses, manufactured by Toyota. In its budget Japan allocates significant resources for development of hydrogen sector and formation of the "hydrogen community".

Hydrogen Economy Plan in **South Korea** includes the Hydrogen Economy Roadmap. The main purpose of this roadmap is to create an eco-system of the hydrogen industry, including production, storage, energy transportation, safety and use. Therefore, it is expected that the hydrogen economy will become the next engine for economic growth, which will ensure 43 trillion Won (approximately 24 bn Euro) and 420,000 jobs by 2040. Korea hopes that, having become a leader of the hydrogen energy, it will be able to improve its catastrophic situation with the air quality, reach its ambitious goals on cutting emissions, strengthen its energy base and create an export branch of the future. South Korea has started its activity, aimed at realizing a "hydrogen community" with the help of measures of the state-private partnership. The government's goal is to reach the hydrogen community earlier than other countries in accordance with the Roadmap, which stipulates the use of hydrogen as the energy source in all the sectors. However, an emphasis is placed on the massive increase in the number of fuel cell vehicles, manufactured in the country. Although only about 2,000 such vehicles were produced before 2018, their number is expected to rise up to 100,000 by 2025 with a further sharp increase of their number up to 6.2 million in 2040, of them – 3.3 million are planned to be exported. It is expected that the public transport and the sector of commercial vehicles will play their role: a long-term goal of the government – 40,000 buses, which run on hydrogen, 80,000 taxi cabs and 30,000 trucks, as well as assistance in domestic production of relevant automobile parts. The government is eager to reach it, having expanded the infrastructure: a number of hydrogen refuelling stations will increase from 14 in 2018 to 310 by 2022 and 1,200 by 2040.

Roadmap to the **United States** Hydrogen Economy stipulates the use of hydrogen as the fuel for vehicles, houses and commercial buildings, as a raw material for industry, for energy generation and storage, balancing of the electric network, etc. The United States intends to extend its leadership in this sector. A special progress is seen in the West Coast, particularly in California, which is a leader in hydrogen transport as a way of cutting emissions. While Asia and Europe in partnership with the industry invest over 2 billion US dollars a year in the hydrogen production, the USA is a market for more than a half of the total fuel cell vehicles in the world. Over 7,600 of them travel on the American roads. In addition, there are about 25,000 of hydrogen-powered vehicles, such as forklifts, which are used in various logistic centers and warehouses all over the country. State support on the purchase is stipulated until 2025 with the purpose of eliminating the difference of prices between an automobile and fuel cell elements compared to its petrol or diesel analogues. Later, depending on achievement of parity, these subsidies can be changed or terminated.

Between 2026 and 2030 the USA is planning to transition to the hydrogen production by electrolysis with the use of renewable sources. This gas will be used for railway transport (4% of the market in 2030 and 17% in 2050) and aviation sector. If the annual volume of sales of light hydrogen vans in 2019 was 2,500 pieces, it will be increased up to 30,000 pieces in 2022, 150,000 in 2025 and 300,000 in 2030. In order to provide them with hydrogen, a number of hydrogen refuelling stations will increase from 63 to 4,300 respectively. Annual investments have to be 1 billion dollars in 2022, then 2 billion and 8 billion dollars respectively in future periods.

In **Germany** the National Hydrogen Strategy (Die Nationale Wasserstoffstrategie) was adopted on 10th of June 2020. At the same time the Federation of German Industries (BDI) opposes the use of the so-called "blue" hydrogen, generated from natural gas, using the technology of carbon capture and storage (CCS). The association insisted on the goal concerning the import of green hydrogen for creation of a higher safety of investment planning. As Germany will not have huge renewable facilities necessary to obtain huge volumes of green hydrogen, it will have to import a great amount of hydrogen fuel from other countries. The National Strategy, adopted by the Government, will involve 7 of 130 billion EUR, stipulated by the German COVID-19 post-pandemic recovery plan. It is planned to finance research and infrastructure development to ensure the conditions necessary for the green hydrogen production. As it is important for the sector decarbonization, the green hydrogen production is a top priority of the German government. The goal is to build industrial hydrogen generation facilities with a production capacity of 5 GW in 2030. It is to be increased further by another 5GW by 2035 or 2040 at the latest.

Facilitating the production by electrolysis, the government hopes that in order to reach the goal of 5 GW, planned for 2030, it will need 20 TWh of the renewable energy. The task requires an intensive development of renewable energy. In order to reach such levels Germany will have to import the green hydrogen. It already cooperates with the countries, which have a relevant potential for production of hydrogen (especially in the North Africa). Here is a real opportunity for Ukraine to get involved in such projects. In total, about 2 billion Euro will be additionally allocated to open opportunities for such initiatives. The system is represented as “win-win” for both parties – Germany will supply its technologies to the partner countries and it will be able to import green hydrogen in return.

Of the 38 measures of the Hydrogen Strategy, developed by the government of Germany, 9 are related to the transport sector. In this context the budget in the amount of 3.4 billion Euro is planned. In addition to the infrastructure development, the government is intended to support investments in hydrogen vehicles to “activate the market”.

France adopted the New Energy Roadmap of France (la nouvelle feuille de route énergétique de la France ou Programmation pluriannuelle de l’énergie - PPE) or Multi-Year Energy Plan. The law on the energy transition stipulates reaching the renewable energy at the level of 32% in the end energy consumption and 40% in electric energy production before 2030. The law also stipulates the reduction in consumption of fossil fuels by 30%. Hydrogen is an important element in reaching these goals, but, first of all, is important for energy transition to reach the carbon neutrality by 2050. Moreover, in order to reach the energy autonomy by 2030 in the territories with no interconnectors and taking into account high needs for flexibility of networks, these territories are defined as a priority for implementation of pilot projects in the area of accumulation, particularly with the help of hydrogen. Hydrogen can play a key role in the network stabilization in the long term, when a share of intermittent energy sources in the network is high.

The Hydrogen Plan, as part of the PPE, is the Roadmap for hydrogen sector development and includes three areas: industry, transport and energy. The plan offers to start the informational campaign in the sector of electrolytic hydrogen production for industrial use, having created the mechanism of public support for distribution, which will complement the existing support in the sector of research and innovations. The task of the government is to obtain carbon-free hydrogen in industrial use at the level of: 10% in 2023 and from 20 to 40% in 2028. This goal will be supported by operation of the hydrogen origin monitoring system to ensure the ability of all participants to identify carbon-free hydrogen, obtained from renewable sources. The PPE emphasizes the task to reduce expenses for hydrogen production by electrolysis and stipulated the reduction of the cost from 4-5 EUR/kg of the “green” hydrogen to 2.5-3.5 EUR/kg by 2030.

State support of the sector development is provided through a number of various programs. As of January 2020, about 90 mn EUR were allocated, of them – 11.5 mn to support 5 projects on production of the green hydrogen in the industry and about 80 mn to finance the winners of the competition within the framework of the program “Hydrogen Mobility Ecosystems” aimed at creation of hydrogen refuelling.

In the **United Kingdom,** the Committee on Climate Change published a report in 2018 with the assessment of a role of hydrogen in the low-carbon economy of the United Kingdom. A necessary reduction in emissions by 2050 in accordance with the Climate Change Act means that energy has to be completely non-carbon. In the electric energy field, for which several cheap production technologies without carbon emissions are available, there's a role for hydrogen which can be produced in a low-carbon way with the help of electric energy or with the use of the carbon capture and storage method (CCS). Authors of the report have drawn up the following key recommendations: the government must undertake a commitment to develop a low-carbon heating strategy within the next three years; significant volumes of hydrogen with a low content of carbon must be produced in a "cluster" of the carbon capture and storage (CCS) by 2030 in order to support the early demonstration of the everyday use of hydrogen in order to show the practicability of transitioning from natural gas to hydrogen; awareness among the wide public, concerning the reasons of transitioning from heating with natural gas to alternatives with a low content of carbon, should be raised; a strategy concerning low-carbon trucks, which encourages the transitioning from fossil fuels and biofuel to zero-emission solutions by 2050, should be developed.

At the moment the United Kingdom does not produce a significant volume of green hydrogen and does not have technologies, which would create the market of this hydrogen. One of the key challenges for hydrogen and related technologies is to entrench itself in the energy system. This goal can be reached by determining the amount of hydrogen with a low content of carbon that can be placed in the existing energy infrastructure (for example, by mixing hydrogen in the gas network and/or energy generation from the obtained hydrogen), implementing technologies that can be transitioned to hydrogen (for example, boilers or gas turbines).

The hydrogen strategy of **Norway** was presented by the government in 2020. The government defines priority efforts in the areas, where the Norwegian companies and technological clusters can influence the development of technologies connected with hydrogen and where there are opportunities for the "green" growth. According to the Strategy the government of Norway has to allocate 120 mn Norwegian krones (about 12.4 million USD) for the ENERGIX program within the framework of the Norwegian Research Council. Hydrogen technologies and solutions will play the central role in this program. In Norway some sectors are particularly suitable for the use of hydrogen. These are the maritime sector and the sector of cargo vehicles and industrial processes. Thanks to the NO_x Fund the state company Enova facilitates fast implementation of the hydrogen market for modes of transport and vessels, as well as the development of technologies in the industry. The government proposes to increase financing by 20 mn Norwegian krones for high-speed vessels within the framework of the green reconstruction package, which helps promote passenger ferries with zero and low emissions, including the hydrogen vessels.

The strategy of the **Netherlands** concerning hydrogen (Government's Vision on hydrogen) was officially announced in March 2020. This document is the first step in a row of initiatives concerning the implementation of an ambitious goal of the country on hydrogen, which had been earlier defined by the National Climate Agreement and the Hydrogen Roadmap. The Netherlands has a "unique starting position", as the country has the experience of hydrogen implementation. It has an extensive network and is geographically in the center of an industrial region of the North Europe. The country wants to use its "unique starting position" in the gas infrastructure in order to become a world leader in production and use of green hydrogen. The Netherlands is eager to decarbonize their energy system, using renewable electric energy. Gas is expected to account for 30-50% of the end energy consumption in 2050, though in a decarbonized way. Hydrogen without CO_2, which is produced from renewable energy sources or the natural gas with the use of CCS technologies, is viewed as a promising area of energy for end consumption sectors that are technically or economically cannot be electrified – for example, manufacture of steel, cement, chemicals and cargo vehicles.

Hydrogen is also viewed as a strategic component of a wider industrial strategy. In order to increase the demand for green hydrogen, the Netherlands offers to install an obligatory mixture of hydrogen in gas networks at the level of 2%, which can be gradually increased up to 10-20%. The green hydrogen production is expected to be supported, in particular, by a new financial aid in the amount of 35 mn EUR. Gas can be imported from the regions that are able to produce green hydrogen in large volumes as a result of electrolysis with the use of solar energy, such as the Near East, the North Africa, Portugal, Spain or, possibly, Ukraine.

Portugal aims for hydrogen to account for 5% of energy consumed by automobiles by 2030. In addition to the construction of electrolyzers with an aggregate capacity of 1 GW, which can be connected to solar farms of the equivalent capacity worth almost 500 mn EUR, the government plans to additionally allocate 6.5 bn EUR for many other hydrogen projects.

In **Poland,** the state-controlled Polish oil and gas company (PGNiG) released its hydrogen programme for 31 mn zloty (7.4 mn USD), which includes construction of the hydrogen station and plant for production of the green hydrogen. The company studies opportunities of storage and transfer of hydrogen through the gas network and signed the agreement on the design and construction of an experimental hydrogen station.

In the **Russian Federation**, Gazprom (state oil and gas giant) announced in February 2020 that it intends to produce hydrogen from natural gas. The Rosatom company announced in September 2019 that it was launching the programme of hydrogen production from the excess nuclear energy by electrolysis both for the domestic market and for export. This company signed the agreement with the Japan's Agency for Natural Resources and Energy on carrying out a feasibility study in 2020-2021 for hydrogen export from Russia to Japan. The Minister of Energy of Russia has announced the creation of a working group to develop a roadmap for hydrogen energy system in the Russian Federation. The Russian Federation is willing to involve itself in the relevant sector and become a world leading supplier of hydrogen, though not "green".

2. Analysis of the importance of hydrogen technologies and the potential for their use in Ukraine

2.1. Use of hydrogen in the energy sector

Today power and transport sectors of Ukraine satisfy their energy needs primarily with traditional types of fuel − coal, gas, oil and oil products, a significant share of which is imported. It is also important to note the current role of nuclear power, which accounts for about 50% of the country's current electric power output. One of the most promising ways of diversification of sources of energy is the increase of a share of energy from renewable sources in the structure of the fuel-energy balance of the country.

Ukraine in its development relies on the practices of the European countries, taking into account the Association Agreement with the EU, international agreements, in particular in the energy sector. The Energy Strategy of Ukraine until 2035 stipulates the increase of a share of "green" energy up to 25% in the energy mix of the country, reduction of the dependency of the energy sector of Ukraine on import from 51% in 2015 to 33% in 2035, as well as full integration with the EU energy system. Target value for RES in the National Renewable Energy Action Plan is at the level of 11% from the final energy consumption. Targets of Ukraine as a signatory of the Paris Climate Agreement include reduction of CO_2 emissions by 25% till 2020, by 40% till 2030[3].

At the same time, electric power sector of Ukraine particularly requires transition to new technologies, taking into consideration a number of circumstances: dependency on fuel imports, obsolete generating facilities, lack of uniformity of distribution of energy generation and consumption amongst the regions, insufficient flexibility of the power system, poor environmental conditions, which limit the energy development opportunities, etc.

The status of generating facilities is characterized by aging of the technical resource: most of the power-generating units of nuclear power plants have an extended design lifetime. In particular, of the 15 power-generating units of nuclear power plants as of late 2020, lifetime of only three plants is still within original design lifetime – the 4th power-generating unit of the Rivne nuclear power plant (NPP), the 6th Unit of the Zaporizhzhia NPP and the 2nd Unit of the Khmelnytskyi NPP. All the rest are at different stages of extension of original operating life[4]. The same situation is with thermal power plants (TPP): lifetime of boilers and turbines of the Ukrainian TPPs is typically 40 years, but in reality, many of them have been operating up to 80 years (the average age is 55 years), they are obsolete and need to be renovated or replaced. Equipment deterioration results in wasted fuel, decreased productivity and poor environmental performance.

As for the energy infrastructure, the service life (25 years) of over 90% of power lines under the voltage of 220 kV and higher and 55% of the basic equipment of substations has expired, and 56% of overhead lines and 17% of substations have been in operation for over 40 years (data by the Ukrainian TSO Ukrenergo as of 2017).

The capacities of the United Power System (UPS) of Ukraine are characterized by the deficiency of maneuvering and regulation facilities; the share of NPPs, power-generating units with very limited flexibility, exceeds 50%. Power-generating units of TPPs, designed for operation in the basic mode, are used to support the variable part of the load curve of the energy system. Increase in the share of RES squeezes out the TPPs, which decreases maneuvering capabilities of the system. Due to the intensive development of RES facilities, when planning the power reserve in the United Power System of Ukraine, it is necessary to take into account additional reserves for compensation of variability of RES generation. Currently the volume of maneuvering facilities is already less than 10% at the estimated need for over 15%. At the same time electric energy losses within the network are

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3 https://www4.unfccc.int/sites/submissions/INDC/Published%20Documents/Ukraine/1/150930_Ukraine_INDC.pdf

4 2035 Energy Strategy of Ukraine provides for possibility to extend the service life of existing NPPs based on periodic safety assesments; additional (more flexible) NPPs may be built in accordance with energy development programs of Ukraine

almost 12% (data by the Scientific and Technical Association of Power Engineers and Electrical Engineers of Ukraine).

Significant problems in the UPS of Ukraine arise due to the lack of power line capacity for NPP power distribution and energy transmission to load centers; with an insufficient level of security of supply in a number of regions of the country (south of Odessa region, Chernivtsi region, city of Kyiv and Kyiv region); with non-compensation of the grid in terms of reactive power and the complexity of ensuring the regulatory quality of voltage. The mismatch between generation capacity and energy consumption is typical for all regions, especially noticeable in the Northern (2,440 MW vs. 610 MW), Central (4,260 vs. 2,360), Western (2,760 vs. 4,650) power systems (rounded data at the winter maximum). Accordingly, the consumed and generated energy of regional power systems differ. Thus, for the Northern power system it constitutes the ratio of 20 to 7 billion kWh, Central (33 to 12), Southwest (12 to 29). Such inequality causes the need for significant interchanges, which leads to excessive energy losses.

Hourly modelling of the UPS of Ukraine has shown that achieving a stable energy supply throughout the year in all weather conditions in Ukraine is possible through a combination of existing RES technologies, gas turbine stations (intermediate stage) and energy storage and transformation technologies, whose role will become significant after 2030. According to one of the scenarios developed by the NASU (National Academy of Sciences of Ukraine) Institute for Economics and Forecasting already in 2035, 90% of power generation can be provided by renewable energy sources. According to Energy Strategy of Ukraine until 2035 the target for the RES share is only 25% of the final energy consumption. At the same time, according to the above-mentioned scenario, in 2035 it is possible to achieve an increase in the share of renewable sources up to 40% while reducing total consumption by 28% due to energy saving measures and increase in energy efficiency.

According to the NASU Institute of Renewable Energy, Ukraine has a significant potential of energy production from **renewable sources, which is about 68 million toe**[5] (tons of oil equivalent) per year.

Table 1. RES capacity potential, MW[6]

Region	Solar energy	Wind energy	Small-scale HPP	Geothermal energy	Biomass energy	Total
Autonomous Republic of Crimea	3 603	22 128	1	840	1 273	**27 844**
Vinnytsia	3 646	13 393	24	40	6 192	**23 295**
Volyn	2 770	7 184	1	40	2 239	**12 234**
Dnipropetrovsk	4 388	38 978	2	120	5 128	**48 616**
Donetsk	3 646	32 387	5	200	2 835	**39 072**
Zhytomyr	4 102	10 640	8	50	4 575	**19 374**
Zakarpattia	1 757	1 163	132	1 400	1 209	**5 661**
Zaporizhzhia	3 737	33 196	0	40	3 646	**40 620**
Ivano-Frankivsk	1 911	2 416	59	600	1 671	**6 658**
Kyiv	3 868	11 983	3	40	4 961	**20 855**
Kirovohrad	3 381	21 226	15	40	4 482	**29 144**
Luhansk	3 669	32 591	2	80	2 042	**38 384**
Lviv	3 002	8 015	46	1 400	2 672	**15 135**

[5] https://www.ive.org.ua/wp-content/uploads/tpp-may-2017.pdf
[6] Atlas of energy potential of renewable energy sources of Ukraine, Instutute of Renewable Energy Sources, 2019

Mykolaiv	3 382	30 043	3	80	3 435	**36 943**
Odessa	4 580	34 719	1	240	4 912	**44 453**
Poltava	3 953	14 522	6	1 400	5 662	**25 544**
Rivne	2 756	7 745	3	40	2 594	**13 139**
Sumy	3 277	11 096	2	560	5 009	**19 945**
Ternopil	1 901	6 983	12	80	3 019	**11 995**
Kharkiv	4 320	27 119	10	1 300	5 160	**37 908**
Kherson	3 913	34 761	1	1 300	3 360	**43 335**
Khmelnytskyi	2 839	10 429	8	40	4 668	**17 984**
Cherkasy	2 874	10 558	8	40	4 150	**17 630**
Chernivtsi	1 113	2 414	24	40	1 252	**4 843**
Chernihiv	4 381	12 311	1	800	5 932	**23 425**
Total	***82 768***	***438 000***	***376***	***10 810***	***92 078***	***624 033***
Territorial waters and inland waters		250 000				
Total	**82 768**	**688 000**	**376**	**10 810**	**92 078**	**874 033**

Table 2. Potential of average annual electricity generation by RES, million kWh/year[7]

Region	Solar energy	Wind energy	Small-scale HPP	Geothermal energy	Biomass energy	Total
Autonomous Republic of Crimea	4 323	60 090	3	6 255	5 236	**75 907**
Vinnytsia	4 375	36 371	83	298	25 327	**66 453**
Volyn	3 324	19 510	4	298	8 310	**31 446**
Dnipropetrovsk	5 266	105 849	7	894	20 646	**132 662**
Donetsk	4 375	87 949	16	1 489	11 673	**105 502**
Zhytomyr	4 922	28 893	27	372	16 619	**50 834**
Zakarpattia	2 108	3 157	439	10 424	4 180	**20 308**
Zaporizhzhia	4 485	90 148	1	298	14 089	**109 020**
Ivano-Frankivsk	2 294	6 562	196	4 468	6 415	**19 935**
Kyiv	4 642	32 540	11	298	20 116	**57 606**
Kirovohrad	4 057	57 641	53	298	17 724	**79 773**
Luhansk	4 403	88 503	7	596	8 032	**101 540**
Lviv	3 602	21 766	153	10 424	10 428	**46 373**
Mykolaiv	4 059	81 584	11	596	13 448	**99 697**
Odessa	5 496	94 283	5	1 787	19 693	**121 264**
Poltava	4 743	39 437	22	10 424	22 425	**77 051**

[7] Atlas of energy potential of renewable energy sources of Ukraine, Instutute of Renewable Energy Sources, 2019

Rivne	3 308	21 033	10	298	9 396	**34 045**
Sumy	3 933	30 133	8	4 170	19 445	**57 689**
Ternopil	2 281	18 963	42	596	12 301	**34 182**
Kharkiv	5 183	73 645	33	9 680	20 171	**108 713**
Kherson	4 696	94 397	2	9 680	13 212	**121 987**
Khmelnytskyi	3 406	28 321	29	298	18 719	**50 774**
Cherkasy	3 449	28 671	28	298	16 964	**49 410**
Chernivtsi	1 336	6 554	80	298	4 714	**12 982**
Chernihiv	5 258	33 433	2	5 957	22 879	**67 528**
Total	***99 323***	***1 189 433***	***1 272***	***80 494***	***362 161***	***1 732 682***
Territorial waters and inland waters		984 337				
Total	**99 323**	**2 173 770**	**1 272**	**80 494**	**362 161**	**2 717 019**

According to Ukrenergo, the optimal capacity of wind farms and solar power plants, which the power system can integrate without serious deviations in operation in its current state**, is 4.7 GW** (3.5 GW for holidays). However, as of 01.02.2021, the installed capacity of RES facilities is 8.5 GW, of which SPP and wind farms are almost 8.2 GW.[8]

Most RES projects are concentrated in the southern regions of Ukraine. Typically, there are no large consumers in the locations of RES power plants, so the excess energy is transferred to other regions via power lines. These lines are built to provide energy to consumers in these areas and cannot meet the growing needs of RES in the near future. This may block further implementation of RES projects. In addition, a further increase in the power output from RES will squeeze out NPPs and increase the share of more flexible TPPs, which would be contrary to the policy of decarbonization (the so-called green and coal paradox). Therefore, increasing the installed capacity of WPP and SPP requires the introduction of new high-maneuvering capacities. The construction of quick-start power plants and electrochemical storage facilities is included in the development plan of the United Power System of Ukraine. The solution to these problems without increasing CO_2 emissions is possible through the use of excess electricity for hydrogen production with its subsequent use to generate electricity in fuel cells and transport it through existing pipelines. This technology has a number of advantages over the construction of electrical networks and quick-start TPPs, which are explained below.

Energy storage. Electrolyzers and fuel cells can be used quite efficiently to balance the power system. This will optimize the operation of other power plants with a corresponding reduction in fuel consumption. The choice of rational technology of energy storage in each case depends on the following parameters: required power, amount of energy, number of charge-discharge cycles, service life, incremental cost of generated energy and others. Fixed costs include, for example, control systems, construction management, construction and operating permits.

A comparative analysis of technical and economic technologies (Energy Storage Technology Roadmap, 2014) showed that the most common storage technologies are chemical batteries, semiconductor magnetic storage systems (SMSS), pumped storage power stations (PSPS), compressed air storage power plants and hydrogen-based batteries. Chemical and semiconductor magnetic storage systems are characterized by low unit cost (from $ 100/kW of installed capacity) and high efficiency, but a small number of charge-discharge cycles (100-2,000) and high cost of

[8] See section "Integration of RES into the UESO" at https://ua.energy/renewables/do-kintsya-2020-roku-vyrobnytstvo-elektroenergiyi-z-vde-dorivnyuvatyme-13-generatsiyi-aes-ta-24-tes/

disposal of components after the end of the life cycle. The results of research (Lifecycle Cost Analysis of Hydrogen Versus Other Technologies for Electrical Energy Storage, 2009) showed that at this stage of technology development there are only three storage technologies that provide the ability to store significant capacity. These include the storage of potential energy in the form of compressed air or gas (CAES) and in the form of water (PSPS) or hydrogen reserve (more than 20,000 charge-discharge cycles).

These technologies are characterized by the lowest incremental cost of power generation, the average value of which for compressed air storage power plants is $ 0.1/kWh, for PSPS - $ 0.13/kWh and for hydrogen - $ 7.5/kg. Accumulation of air (gas) requires the presence of large natural reservoirs for storage. Given the potential of hydropower resources and the natural elevation difference, the most efficient of all is the system of storage of fresh or sea water with the help of PSPS. Hydrogen technologies are a competitive alternative to CAES and PSPS battery systems in places where these technologies cannot be implemented.

2.2. Use of hydrogen in the transport sector

In Ukraine, the need for the transition to the use of hydrogen in the transport sector is due to environmental and economic factors. Ukraine is 49th in the rating of 73 countries with the most polluted air. The Ministry of Ecology and Natural Resources of Ukraine insists on the need to develop plans to improve air quality based on the analysis of its environmental indicators. Effects of air pollution are often quite visible in the capital of Ukraine, the city of Kyiv. Existing transport uses mostly imported fuel, which increases the costs to the economy. According to the state statistics, in 2018 about 1.8 million tonnes of gasoline and 5.1 million tonnes of diesel fuel was consumed in Ukraine as motor fuel, while production of crude oil only slightly exceeded 2 million tonnes. Therefore, the need for alternative eco-friendly domestic energy sources for transport is extremely urgent.

In the transport sector worldwide, special attention is paid to the use of hydrogen and fuel cells in automobile transport. Developed countries, in particular many European countries, are faced with the urgent task of creating an appropriate hydrogen infrastructure, i.e. a sufficient number of hydrogen fuelling stations. France, for example, predicts that by 2030 it would be possible to get hydrogen for a car in every part of the country. Autonomous fuelling stations are already being set up in some countries, which use wind and/or solar energy to produce hydrogen, store it, for example, in a compressed state and supply it for fuel cell electric vehicles (FCEVs) fuelling. Hydrogen transport can overcome the disadvantages of other electric vehicles with a low range and the need for frequent charging. This requires the full use of economy power to electrolyze water into hydrogen. At the same time, materials with a high density of hydrogen storage are required to overcome the low energy density of traditional hydrogen storage in gas cylinders. According to Minxiart (Hydrogen Energy Industry Outlook, China, 2018), the mileage of hydrogen vehicles can be increased to 700-1,000 kilometres or even more.

As for FCEVs, it is expected that these vehicles will enter the stage of mass production in 2020-2025. It is supposed that the production of commercial fuel cell vehicles in China will reach 20 thousand in 2025, and after 2025 will be at the stage of large-scale development. The current tasks for this are: optimization of equipment for hydrogen production; development of materials for storage of high-density hydrogen; optimization of hydrogen fuel cells. On the territory of Ukraine there is a number of long-haul routes, where hydrogen buses could compete with traditional ones. The cell fuel bus is a very efficient public transport with zero emissions for long-distance travel in the city, and also effectively solves the shortcomings of electric vehicles with low range and long charging time. Hydrogen buses are expected to replace diesel and electric buses.

The creation of infrastructure for long-distance FCEVs in medium and difficult operating conditions, is a trend in the logistics industry development. Fuel cell vehicles can reach a single mileage of 350 to 1,200 kilometres, and the total resource reaches 500,000 kilometres. Cars can be fuelled in 3-5 minutes, have a range of up to 500 km and a total mileage of more than 200 thousand km (Minxiart data).

In Ukraine, half of ***passenger traffic*** is performed by buses. The railway carries 441 million passengers a year (as of 2016), while road transport carries 7.5 times more (more than 3 billion passengers a year), and, taking into account private transportation, passenger traffic exceeds 5 billion.[9] According to the statistics, every inhabitant of Ukraine uses buses on average 70 times a year. At the same time, the fleet of large public buses has mostly exhausted its resource and should be replaced with more comfortable, spacious and high-quality vehicles. Today, most transportation in cities is carried out by minibuses, which belong to business entities and do not meet modern environmental requirements.

There are several main segments in the market of regular bus transit: international, intercity interregional, intercity intraregional, suburban and urban. These are mainly small size buses (with the carrying capacity of 5 to 7 tons) built on the chassis of trucks. To use newer and more modern buses on urban and suburban routes, appropriate incentives for auto carriers are needed. Currently, the rules for issuing permits for carriers on urban and suburban routes set only minimum requirements for buses, both in terms of comfort and environmental friendliness. When defining the rules of competition on urban and suburban routes, it is necessary to give preference to carriers that use more eco-friendly buses and provide a higher level of service. Particular attention should be paid to buses running on alternative fuels: hybrid buses, buses with liquefied natural gas (methane) engines, and electric buses.

With regard to ***railway transport***, hydrogen fuel cell (FCH) trains are an environmentally friendly and cost-effective alternative to existing technologies in branched networks with low levels of electrified lines («Study on use of fuel cell hydrogen in railway environment», Fuel Cells and Hydrogen Joint Undertaking, 2018). Long-haul locomotives based on FCH continue to face barriers to market entry but can already be competitive when it comes to long distances and heavy idle loads.

Their market potential will also depend on the project volume of purchases of diesel locomotives. Commercial use of FCH trains has begun in Germany to replace diesel trains on non-electrified lines, allowing system providers to avoid high capital costs for the construction of electrical networks. Several other countries are planning similar steps in the next few years (including the United Kingdom, the Netherlands and Austria).

In Ukraine, the operational length of the main tracks is 19.8 thousand km, including 9.9 thousand km (47.4%) of electrified tracks[10]. The fleet of diesel locomotives is 1.9 thousand units and the fleet of electric locomotives is 1.6 thousand units (as of 2018). In 2018, transport consumed 7.0 billion kWh of electricity. This determines the potential market for FCH transport. First of all, FCH trains will replace diesel traction locomotives.

In the ***maritime sector***, ships with fuel cells are at the stage of demonstration projects. Hydrogen fuel cells can also be used to replace onboard and onshore energy to reduce pollutant emissions and avoid significant costs for electrical connections in the harbour. In Ukraine, the use of hydrogen in water transport has its own prospects. In particular, over the last 5 years there has been an increase in the volume of freight traffic by river transport, the potential of which is not used at full capacity. The share of agricultural products traffic by river transport is currently 7%. The potential of river transport has been used only by a third. In general, it is able to reach 20% with a volume of traffic of 10-12 million tonnes per year[11]. There are all prerequisites for increasing the volume of traffic by river, as the cost is lower compared to the transportation by road and rail. In 2018, 9.9 million tonnes of cargo were transported by the Dnieper River, which is more than twice as much as in 2013; the volume of cargo flow by the Southern Bug River amounted to 850 thousand tonnes.

Hydrogen production and distribution ***infrastructure*** requires significant investments, and such investments are risky without the long-term visible prospect of hydrogen demand and without the guarantees (including political commitments) needed to secure the market. This is especially problematic for passenger vehicles. On the one hand, manufacturers are reluctant to invest in fuel cell vehicles without hydrogen fuelling infrastructure, as no consumer would buy a car without fuelling possibility. On the other hand, energy and industrial gas companies are not ready to deploy the

[9] https://mtu.gov.ua/en/content/statistichni-dani-pro-ukrainski-zaliznici.html
[10] https://mtu.gov.ua/en/content/statistichni-dani-pro-ukrainski-zaliznici.html
[11] https://mtu.gov.ua/en/content/informaciya-pro-vodniy-transport-ukraini.html

necessary hydrogen infrastructure until FCEVs (fuel cell electric vehicle) with mileage and fuelling time, comparable to conventional transport, become commercially acceptable, with a clear timeframe of return on their investment. Therefore, in some countries, governments are trying to provide not only investment support, but also to ensure the comprehensive legislation and taxation support.

State support in the field of cargo transportation (freight transport) as well as public transport should be a priority for sustainable development. Ensuring a critical level of hydrogen demand is a key factor for infrastructure investment. Therefore, to create viable hydrogen technologies, large enough units must be installed that provide cost-effectiveness due to economies of scale and thus reduce the cost of hydrogen for the end user. However, in the short and medium term, hydrogen can initially be produced locally to provide smaller fuelling stations, in particular for fleets that will have their own fuelling base. These stations can be open to the public.

In general, the structure of the supply system will be affected by the following circumstances:

- the availability of sources of hydrogen or raw materials for its production in the immediate vicinity or at the place of consumption, because hydrogen production is the most capital-intensive part of the supply chain;
- until a certain consumption threshold is reached, on-site production or delivery by existing gas pipelines may be the only viable supply mode; they are likely to remain so in the near future;
- from the point of view of risk management, investments in new large-scale production are traditionally possible if a large share of production is sold to one customer (or a limited number of customers) with signed long-term contracts, or if it can be justified by sufficient reserve capital to cover initial losses or financial instruments to reduce risk.

2.3. Use of hydrogen in the industry sector

“Grey” hydrogen (the one produced using fossil fuels such as natural gas) is widely used in industry today. The scaling up of renewable hydrogen provides companies and policy makers with a powerful tool to decarbonize existing and new sources of industrial energy demand and industrial processes. Ammonia production, refining processes and methanol production constitute over 90% of the total hydrogen demand today. Renewable hydrogen could be a clean alternative to coal in the reduction of iron ore and could replace natural gas as a source of high-temperature heat in the iron and steel industry. Hydrogen carriers such as methanol, ammonia and synthetic methane are easier to store and transport than hydrogen but come with higher efficiency losses. Still, their physical properties make them more appropriate than hydrogen for specific industrial applications. Producing green ammonia[12] in Ukraine, using low-cost renewable energy and electrolysis, creates a more distributed production model, reducing transport costs and creating opportunities for local industrial development.

Iron and steel

The industries increasingly look to decarbonize their industrial heat requirements; a number of companies worldwide are studying the role of green hydrogen in processes such as steelmaking, chemical production, oil refineries, etc.

Steel production is a particularly interesting area for hydrogen because of the process’s high carbon emissions and the relative lack of viable alternatives. Currently hydrogen is already partly used in metal processing to yield iron reduction, and the estimations are that the typical hydrogen consumption in this type of plant is between 360 tonnes per year and 720 tonnes per year (Fraile and others 2015). Thus, steel represents an addressable market by electrolysis and renewable hydrogen. There are companies using hydrogen as the protection gas in the production of steel plate, with a unit supplied by THE China providing this service to a site in Bulgaria (THE n.d.a.). Hydrogen is also used in the iron industry to prevent partial oxidation of iron ore while the ore is in the furnace.

[12] Green ammonia refers to ammonia, which has been produced through a process that is 100% renewable and carbon-free.

Some sites will flood the furnaces with hydrogen, so that it will react with any fugitive oxygen molecules and prevent oxidation.

The bigger question that researchers are attempting to assess is whether hydrogen can play a greater role by replacing coal and other heating fuels. Three flagship projects operate in this space: International conglomerates (Tata Steel [headquarters in India] and Nouryon [headquarters in the Netherlands]) and the Port of Amsterdam develop the largest green hydrogen cluster in Europe; HYBRIT in Sweden; and H2FUTURE in Austria. By far the largest of these is the Port of Amsterdam, which is at the feasibility study phase and is looking at a 100 MW electrolyzer that would produce 15,000 tonnes of renewable hydrogen a year and create oxygen for the steel site as well. The first pilot that is actually installed and operating is H2FUTURE in Austria, where a 6 MW PEM (proton exchange membrane) electrolyzer provided by Siemens is working on a Voestalpine steel site, using power from Verbund's almost entirely renewable-based portfolio (Voestalpine 2018).

For the HYBRIT project, SSAB, LKAB, and Vattenfall are using a 4.5 MW alkaline electrolyzer to operate in Luleå, Sweden, from 2021 until 2024, before the project enters a demonstration phase with the goal to have an industrial process in place by 2035. The HYBRIT process is based on direct reduction of iron ore using renewable energy and hydrogen; the hydrogen reacts with the oxygen in the iron ore, thus creating metallic iron and water (Cision 2019). At this time, in the absence of supporting policies, evidence from HYBRIT studies suggests that the costs from electrolysis remain too high. The capital expenditure required for setting up a direct iron processor, an electrolyzer, and a hydrogen storage facility is estimated at EUR 1,000 per tonne of crude steel, comprising almost 80% of the total production costs and yielding a steel price of EUR 1,200 per tonne (*WEC Netherlands 2019*). For a comparison, the conventional cost of crude steel supplied by top 10 countries-exporters varied from EUR 360 to 560 per tonne in 2013[13].

Ammonia

Ammonia is the largest demand source for hydrogen today and a prime option for decarbonization efforts with renewable hydrogen. Two large-scale projects that are being considered for investment are a 20 MW electrolyzer unit at Air Liquide's ammonia site in Quebec (Air Liquide 2019) and a 100 MW solar PV combined with a 50 MW electrolyzer for YARA's ammonia site in Western Australia (ENGIE 2019). These projects are following pilot hydrogen-from-wind to ammonia projects that already have been deployed and which provide evidence of the technical feasibility and cost considerations for such an application. Ammonia as a market for renewable hydrogen is particularly appealing because of the scale of demand. A study for the Fuel Cell and Hydrogen Joint Undertaking (FCH JU) in 2015 estimated that a typical ammonia plant has the capacity to produce between 1,000 and 2,000 tonnes of ammonia per day, thus requiring 57,500 to 115,000 tonnes of hydrogen per year (Fraile and others 2015), while Thyssenkrupp suggests a traditional plant would produce closer to 3,000 tonnes per day (Thyssenkrupp n.d.). Such a level would require electrolyzer units significantly larger than those currently commercially deployed, and a single site would likely absorb many manufacturer's annual capacity for several years, given the current installed capacity of electrolyzer suppliers.

The other appeal is that if the cost of hydrogen from electrolysis were to fall below the cost from SMR, it would be conceivable that the centralized ammonia production process itself would change and move toward a more distributed production model. Such a situation would reduce transport costs and would also create the opportunity for many countries to produce greater volumes of ammonia domestically, creating jobs. It is for this reason that companies such as Thyssenkrupp have begun to market smaller-scale ammonia solutions based on systems that can run on a 20 MW power input, with modular scaling up to 120 MW.

While the primary interest in ammonia is its use as a fertilizer, it can also be used as a mechanism for storing energy hydrogen cheaply and for long periods of time, before the hydrogen is extracted out of the ammonia again. Although this process entails high efficiency losses, with round-trip efficiency figures around 20–30%, depending on the initial efficiency of the electrolyzer/ SMR used, it may still be viable in areas where the production of hydrogen is low. In addition, more recent

[13] https://publications.jrc.ec.europa.eu/repository/bitstream/JRC100101/ldna27729enn.pdf

research has examined whether ammonia can be used directly as a fuel, whether with a reformer on a fuel cell or combusted in a turbine. Some companies in the power sector already use ammonia. The largest user of ammonia for fuel cell applications is GenCell, whose units provide off-grid power supply using ammonia with a reformer (GenCell n.d.). These units have lower system efficiency than typical hydrogen or SOFC (Solid Oxide Fuel Cell) cells, but they can store ammonia easily on-site for up to six months at a time. Companies such as Baker Hughes and MAN Group have also been working to develop and commercialize turbine technology that could generate power from 100% ammonia fuel. This is being closely monitored by business in countries with existing natural gas turbines installed, who see green ammonia as a potentially more convenient hydrogen-derived fuel for zero-carbon-emission power.

Refining

One of the most immediate sources of potential industrial demand for renewable hydrogen is refining. A typical refinery might require between 7,200 tonnes and 108,800 tonnes of hydrogen per year, with new and complex large-scale refineries requiring up to 288,000 tonnes per year (Fraile and others 2015). Although the economics at this time appear challenging, the segment may be driven by policy if it is accepted that the use of green hydrogen can be counted toward reduction in national transportation emissions. Thus, the first big test is likely to be ITM Power's 10 MW unit inside Shell's Rhineland factory, closely followed by BP's 250 MW feasibility study in the Port of Rotterdam that is looking at producing up to 45,000 tonnes of green hydrogen per year (Port of Rotterdam 2019).

Glass, food and other areas

Other segments of interest for hydrogen in industry include the food industry and glass industry. Hydrogenation of fats is the core area of application for the food industry, with the demand profile suitable for electrolyzer units between 0.5 MW and 2 MW. This amount is based on estimates from the FCH JU that on average hydrogenation of fats sites require hydrogen production of up to 28 kg per hour, corresponding to 672 kg a day if operating 24 hours.

Glass manufacturing is also a growing area of interest for hydrogen, with suppliers indicating growing awareness in Asia, Europe, and North America. Given the low demand for hydrogen from a typical glass plant, around 3.95 kg per hour, this market segment is well suited to on-site generation via electrolysis[14]. In Slovenia, one company is using rooftop solar PV to create hydrogen that is blended with natural gas into the glass site furnaces (Willuhn 2019). A company in Vietnam has been using hydrogen in its glass manufacturing processes (THE n.d.b.).

Other notable areas are the use of green hydrogen in the semiconductor industry as a heat transfer fluid (when kept in a vacuum) and as a rocket propellant for the aerospace industry.

Other hydrogen-based fuels

Although hydrogen itself is a valuable and effective fuel, several alternative fuels can also be created from renewable hydrogen. These fuels have differing properties from hydrogen that can sometimes be more attractive than pure hydrogen for specific use cases and applications. Examples commonly include methanol, ammonia, and, increasingly, synthetic methane, all of which are considerably easier to store and transport than hydrogen but come with higher efficiency losses in generation.

Methanol

By some estimates, methanol production accounts for around 10% of global hydrogen demand. Although it is used in a wide array of applications, methanol is particularly useful for fuel cell units that provide uninterruptible power supply services, especially in off-grid areas. One liter of methanol is approximately 4.8 kWh, or 1 kg is about 5.6 kWh. This is a significant reduction from the 33.33 kWh held in a kg of hydrogen. Nonetheless, the fuel is a very light liquid and can be easily stored and carried. Further, it is readily available across both emerging and developed markets, making it attractive for locations where hydrogen infrastructure and safety capabilities are low. Today, methanol is largely created via natural gas and is the result of a two-stage process that requires both

[14] Converting 44 normal cubic meters per hour at 0.08988 kg per 1 normal cubic meter per hour, using http://www.uigi.com/h2_conv.html with source data from Fraile and others 2015

the production of hydrogen and its subsequent bonding with carbon inside a new molecular structure. The average plant capacity is around 5,000 tonnes per day with a yearly hydrogen consumption of 266,104 tonnes. Key industrial players include Methanex and Sabic (Fraile and others 2015).

Synthetic methane

One of the largest areas of interest, particularly for European companies and policy makers who are exploring renewable hydrogen applications, is the ability to synthesize hydrogen with carbon to create methane. Creation of synthetic methane can be enormously appealing because it allows for the continued use of current natural gas infrastructure and avoids the need to replace or retire existing natural gas assets. Synthetic methane also has the added advantage of being easier to generate at larger scales and across a wider range of locations than biogas, which has long been seen as a means of "greening" the gas supply.

Only a few pilot projects are currently generating synthetic methane. Most of them extract their carbon from anaerobic digesters linked to agricultural waste or land ll waste. But a pilot in Italy sources its carbon from direct air capture technology, and both options can be considered carbon neutral.

The largest approved project is the Underground Sun Conversion project in Austria, which will combine solar PV with a 13 MW alkaline electrolyzer. The project will produce and store synthetic methane in an underground cavern and will then release the methane directly to customers as needed (McPhy 2017). Two other flagships are in Germany and France. This includes Uniper's "STORE&GO" project in Germany, which uses wind power and electrolysis to produce up to 1,400 cubic meters of synthetic methane a day, or approximately 14,500 kWh of energy (Eckert 2019). In France, the Jupiter 1000 program aims to use a hybrid of alkaline and PEM electrolysis, with carbon capture storage, to create and distribute synthetic methane (Jupiter 1000 n.d.).

2.4. Use of hydrogen in the natural gas industry

Ukraine has a well-developed network of main gas pipelines and a shortage of domestic energy carriers, including natural gas. Hydrogen, as a source of energy, is environmentally friendly. One of the main future methods of hydrogen transportation in Ukraine will be gas pipelines, and underground gas storage tanks can serve as storage for hydrogen.

There are two possible hydrogen delivery scenarios for pipeline transport:

- adding hydrogen to existing pipelines in specified concentrations;
- transportation of 100% hydrogen through new or existing pipelines.

In addition to its main purpose as a mechanism for transporting hydrogen, the use of pipelines can provide a number of additional benefits:

1. *Improving gas supply*: With uncertainty surrounding natural gas supply constraints, hydrogen substitution could provide a shorter-term opportunity to offset growing gas demand.
2. *Power and gas network convergence:* with increase of RES share in power network and reliability/stability requirements, hydrogen provides a new direction for optimizing electricity production: converting surplus renewable energy into hydrogen gas through PEM (proton exchange membrane) electrolysis technology. The hydrogen can then be injected into the natural gas grid. In doing so, the hydrogen can displace natural gas, reducing greenhouse gas emissions and reliance on high-carbon fuels.
3. *Energy storage*: gas pipelines provide an additional option of hydrogen storage by means of a packaging pipeline or "shifting energy in time".
4. *Gas network decarbonization*: the injection of hydrogen into natural gas pipelines increases the opportunities for decarbonization in the energy sector.

One example is in Germany, where experts are already testing hydrogen transport safety parameters to integrate H_2 into the network. The EU's "Hydrogen Strategy for a Climate-Neutral Europe" adopted in July 2020 is the latest in a series of programmes designed to encourage the use of green hydrogen for decarbonization and integration into the power system. Germany, Japan and the G20 have shown considerable interest in developing this technology. Again, in Germany, a report published by the Nowega, Gascade and Siemens Energy pipeline operators stated various requirements for the conversion of natural gas pipelines as central components of the future transition to green hydrogen energy. Although hydrogen can be transported in high-pressure insulated containers as a liquid, or in high-pressure containers as a gas, and in the form of ammonia or methanol after processing, the most viable strategy for its transportation and storage will be through the use of pipeline systems. If these pipeline systems already exist, it will only increase the viability of this green renewable energy source for general use.

A key factor in enriching natural gas with hydrogen is the ability to achieve some decarbonization in the gas sector without the need to upgrade existing infrastructure. A hydrogen concentration of 20% by volume is considered acceptable. The main limitation is the ability of end-use devices to meet higher hydrogen concentrations. In Ukraine, the level of use of natural gas pumped by pipelines is 30-35 billion m^3 per year (in 2018 – 32.4 billion m^3), therefore, the capacity of the hydrogen segment may be 6-7 billion m^3 of hydrogen per year.

The existing network of gas pipelines laid on the territory of Ukraine may be used for hydrogen transportation. These are the main gas pipelines (Torzhok-Dolyna, Urengoy-Pomary-Uzhhorod, Kursk-Kyiv, Ananyiv-Chernivtsi-Bohodzhany, Kremenchuk-Ananyiv, Dzhankoi-Feodosia-Kerch, Donetsk-Mariupol, Ostrozhsk-Shebelynka, Ivatsevychi-Dolyna), gas pipeline branches, gas-distributing stations, compressor stations, underground gas storage facilities, gas metering stations and discharge measurement points. Diameters of main gas pipelines vary from 500 to 1400 mm, operating pressure - from 45 to 75 atm.

One of the notable problems with the inclusion of hydrogen in the natural gas network is the impact it has on the measurements. Traditionally, the measurement and subsequent pricing of gas in pipelines is based on the consumption and energy intensity of the gas used. Thus, pipeline meters should be adjusted to reflect the hydrogen percentage in natural gas, as well as their differences in energy density.

Transporting 100% hydrogen through the pipeline can cause problems regarding the pipes' brittleness depending on the operating pressure and the material of the pipeline. Although this risk increases with increasing operating pressure, the use of polymer-reinforced steel pipes allows to transport hydrogen at pressures of 70-105 bar. In the internal gas distribution network, where the pressure fluctuates within 1-7 bar, the strength limiting risk will be significantly reduced. High density polyethylene is considered the best material for such a pipeline.

In 2019, the Regional Gas Company (RGC) for the first time in Ukraine began test transportation of a hydrogen and natural gas mixture in closed areas of the gas-distributing system in five regions of the country. Experimental landfills are located in Volyn, Dnipropetrovsk, Zhytomyr, Ivano-Frankivsk and Kharkiv regions. These are closed sections of networks that are not connected to external consumers - businesses or individuals. They correspond to the actual condition of real gas distribution networks - there are metal and polyethylene pipes of different diameters, with different service life and different sealing materials. Also, a variety of pressure control technologies and several types of gas-control units were used. It is important to understand how the existing gas delivery system will behave when using hydrogen. At first, hydrogen and natural gas mixtures in concentrations from 2% to 100% are used to test the networks. It is planned to build a hydrogen production plant at one of the landfills. Scientific support of the project allows to receive detailed and comprehensive information on all nuances of use of new, ecological energy carriers. The project is not limited to testing a mixture of hydrogen and natural gas, but also includes work with other synthetic gases such as biogas. Foreign experience is used, but there is a point that makes the RGC project unique in comparison with all foreign ones. In Europe, they gradually increase the concentration of hydrogen in the mixture, starting with 1-3%, and now in some places brought to 20%. RGC plans to carry out tests with transportation of 100% of hydrogen at once that will allow to receive idea of networks conformity with the new energy carrier.

In August 2020, the practical part of the test programme for the use of hydrogen in existing gas distribution networks started. The first experiment was conducted at the landfill in Cherniakhiv, Zhytomyr Oblast, taking into account the prospects of the EU Hydrogen Strategy, with which RGC interacts. For hydrogen testing, the gas system of the landfill in Cherniakhiv was reconstructed by Zhytomyrgaz JSC specialists in such a way that it became a model of the existing gas-distributing system in terms of equipment composition, material selection and degree of wear. During the experiment, the landfill systems were pumped with inert gas and then filled with hydrogen, the concentration of which was increased to 99%. The high concentration of hydrogen in the system allows to obtain unique information about the behaviour of different materials of gas pipelines and equipment. The next stages of the RGC research programme include static and dynamic tests of hydrogen and its mixtures with natural gas at four more specially prepared landfills in the Volyn Oblast.

3. Analysis of hydrogen production methods and their cost-effectiveness

3.1. Mass production of hydrogen using steam methane reforming (SMR)

Hydrogen can be obtained using a number of production methods and technologies. Large-scale production of hydrogen around the world occurs through the processing of natural gas. SMR technology is the conversion of natural gas by reaction with steam and is the most common option.

A standard plant usually has a capacity of 100,000 m³ or 9 tonnes of hydrogen per hour. The process takes several steps, but it can be roughly divided into two stages. During the first stage, natural gas is treated with steam at a temperature from 800 °C to 1000 °C. A synthetic gas is formed, consisting of carbon monoxide (CO) and hydrogen (H_2). The second stage is the water-gas transition, which occurs at a lower temperature. During this stage, the CO from the synthetic gas reacts with even more steam (H_2O), forming CO_2 and more hydrogen. Then the mixture of CO_2 and hydrogen is separated in the gas separation section, a concentrated stream of CO_2 is generated, suitable for capturing and storing CO_2. This is a standard industrial process used in a large-scale production of ammonia and fertilizers, due to the need for CO_2 in the ammonia conversion to urea.

In SMR, part of the natural gas is not converted to hydrogen, but instead is used for steam generation and external heating of the reactor. This is a standard process in which low-CO_2 flue gases are generated. This complicates the capture of 100% CO_2 during SMR. The typical capture rate is 50 to 60%. Although the introduction of process modifications can increase the %age of CO_2 captured by up to about 90%, this reduces the overall efficiency by about 7%.

There are two options, Autothermal Reforming (ATR) and Partial Oxidation (POX), which capture 100% of CO_2. In these two options, the heat of the process increases significantly due to the fact that part of the natural gas reacts with pure oxygen in the reactor. As a result, all CO_2 is stored in a concentrated stream. However, compared to SMR, this process requires a higher level of investment due to the need to use air separators for oxygen. Therefore, to be competitive, processes must work on an even larger scale.

Even so, these methods could be interesting in the future if combined with hydrogen production by electrolysis, as oxygen is generated during the process. The cost of producing hydrogen from natural gas largely depends on natural gas prices. Natural gas accounts for 70-80% of production costs in large-scale production using SMR. Production costs range from approximately € 1 to € 1.50 per kg of H_2.

Small-scale production from natural gas using SMR

Transport costs for hydrogen are relatively high, especially over long distances. The alternative is the production of hydrogen in the customer's premises (at the fuelling station or at the premises of an industrial customer with limited consumption). To this end, various parties are developing small-scale SMR units with a capacity of 100 to 300 Nm³/h, which is equivalent to about 200 to 600 kg H_2 per day. Production in these small units is based on the same principles as in large-scale production. The efficiency is usually from 60% to 65%. It is estimated that in the short term these units could increase production costs to 4-5 euros per kg of H_2, with the prospect of further falling to 3-4 euros per kg of H2 or slightly less in 2030. This level of costs is competitive compared to a combination of large-scale production and transport.

Production units must be used continuously. Thus, the main market is currently in production for small industrial consumers. Strong fluctuations in operating conditions, which can be expected during the refuelling stations start-up, can lead to increased maintenance and operating costs. In addition, hydrogen production occurs at relatively low pressures, which means that the fuelling point will need to provide a significant level of compression. To determine the most practical and cost-effective option, it is necessary to conduct an assessment on a case-by-case basis.

3.2. Hydrogen production by electrolysis

Electrolysis of water is now considered an ideal technology for producing stable hydrogen. This process assumes the use of electricity on an even schedule. However, the current energy mix, which is still largely coal-based in Ukraine, means that hydrogen production by electrolysis is even more energy intensive than SMR production method using natural gas, although the rapid development of wind and solar projects will change this in the coming years.

Electrolysis can be achieved by a number of methods. In all cases, electricity is used to separate water molecules, resulting in the production of hydrogen and oxygen. The best known and most developed options are conventional methods of alkaline electrolysis (AEL) and proton exchange membrane (PEM) electrolysis. Both operate at low temperatures of 60-70 °C. Alkaline exchange membrane (AEM) electrolysis is the third low-temperature option. This option is the least developed, as the technology is still on a laboratory scale.

The fourth option, the solid oxide electrolyzer cell (SOEC), has moved a little further, but is still at a low TRL (Technology Research Level) level. SOEC is associated with high-temperature solid oxide fuel cells (SOFCs) and operates at temperatures of 600-800 °C. Compared to low-temperature options, this technology increases energy efficiency because less energy is required to separate water molecules at these temperatures. AEL and PEM are commercially available on a scale of 1-5 MW unit.

The investment cost for an AEL electrolyzer is currently around € 1,000 per kW. Innovation, optimization and increased volumes can reduce costs to € 370-800 per kW by 2030. It is expected that the systems efficiency, which currently averages 61% (55 kWh/KG, will increase to a minimum of 67% (50 kWh/KG). The investment cost for PEM electrolysis is currently around € 1,400 per kW. Increasing production can quickly reduce costs to € 760 per kW according to market estimates for 2030, although price range widely from € 250 to € 1270 per kW. Power consumption by PEM systems is currently still slightly higher than that of AEL. However, these indicators are improving rapidly, and power consumption is expected to decline to much less than 50 kWh/kg in the near future by 2030 (efficiency above 70%).

With a maximum working hours per year and energy costs of € 70-80 per MWh, current production costs are estimated at € 5-5.5 per kg H_2 and € 6-6.5 per kg H_2 for AEL and PEM respectively. It is expected that by 2030 the costs will be about € 3-3.5 per kg of H_2 on the production site. By this time, large stations with a capacity of 10-100 MW (4-40 tons of H2 per day) will also appear, and possibly more, which will be located in the center. This can reduce production costs to 3 euros per kg H_2 and possibly even to 2 euros per kg H_2. Costs would then be competitive with centralized production using natural gas, especially if natural gas and CO2 prices rise and production has to be combined with CCS. However, if investment costs decrease, production costs will be more driven by energy prices, which are subject to change.

Table 3. Indicators of basic hydrogen production technologies[15]

	Mass SMR	Small-scale SMR	AEL electrolysis	PEM electrolysis
Investment costs, €/kW			1000	1400
Investment costs in 2030, €/kW			370-800	250-1270
Efficiency, %	70-85	60-65	61-67	65-78
Costs, €/kg H_2	1,0-1,5	4,0-5,0	5,0-5,5	6,0-6,5
Costs in 2030, €/kg H_2		3,0-4,0	3,0-3,5	

The main advantages of alkaline and membrane electrolysis are presented in Table 4.

[15] ESMAP. 2020. Green Hydrogen in Developing Countries. Washington, DC: World Bank.

Table 4. Matrix of advantages and disadvantages of electrolysis

	Alkaline	PEM
Advantages	- CAPEX / OPEX - Mature and proven technology in the amount of several MW for steady-state operation - Significant stack service life	- Short response time in dynamic work - Stable solid electrolyte - Appropriate indicator values at partial operation - High level of hydrogen purity
Disadvantages	- Less stable liquid electrolyte - The need for hydrogen purification for final purposes - Longer response time - Long cold start time	- Higher CAPEX / OPEX - Shorter stack service life - The presence of platinum group metals - Less mature and proven technology for use in megawatt equipment

3.3. Other technological options for hydrogen production

Analysis of alternatives for stable hydrogen production, in addition to electrolysis, identified 11 options, of which the following five options may have potential as others still require significant further research and development work:

1) Pyrolysis and gasification of biomass
2) Fermentation of biomass flows into biogas
3) Thermochemical water splitting
4) Photocatalysis (using photoelectrochemical cells - PECs)
5) Supercritical gasification of water with biomass

Biomass is a source of energy for three options, where hydrogen is formed partly from biomass and partly from water. In keeping with discussions about the availability of sustainable biomass and many alternative uses of biomass for applications that require stable hydrogen as well as climate-neutral carbon, it is doubtful that the long-term goal should be to use biomass only for hydrogen production. There is a greater need to use biomass, either directly or through synthetic gas, which also uses carbon, for chemicals and materials, or for sustainable biofuels and synthetic fuels for aviation and shipping.

The other two options use solar energy with all hydrogen produced from water. Thermochemical options require high-temperature heating from concentrated sunlight (using concentrated solar power - CSP). CSP is not possible in many places, but high-temperature heat from CSP can be delivered from other places. The latter option involves the hydrogen production using PECs. This technology is interesting because it combines the functionality of solar panels with electrolysis. This is essentially a type of solar cells immersed in water. Incoming light causes reactions on the surface that directly generate hydrogen. However, materials that combine efficiency, durability and cost-effectiveness at a level sufficient to ensure a viable system have not yet been developed. There is still a long way to go before these systems can surpass the combination of individual solar photovoltaic and electrolysis systems. Such a combined system can be deployed flexibly to convert solar energy into electricity or hydrogen.

These hydrogen production options have a TRL of 3 for photocatalysis, 7 for supercritical gasification of water and 8 for biogas conversion. [16]Production costs in 2030 for different options were estimated

[16] Technology Readiness Levels (TRL) are a type of measurement system used to assess the maturity level of a particular technology. Each technology project is evaluated against the parameters for each technology level and is then assigned a TRL rating based on the projects progress. There are nine technology readiness levels. TRL 1 is the lowest and TRL 9 is the highest. When a technology is at TRL 1, scientific research is beginning and those results are being translated into future research and development. TRL 2 occurs once the

using practical data and mathematical modelling. In the case of small-scale on-site production (0.2-4.0 t H_2 per day), the costs of fermentation in combination with the conversion were estimated to be the lowest, at € 3.5-5.5 per kg H_2. Other uses of biomass are 4.5-6.5 euros/kg.

In the case of large-scale centralized production (more than 20 t H_2 per day), the costs of biomass gasification, photocatalysis and production using thermochemical cycles are 3.0-3.5 euros per kilogram, 4.5-5.0 euros per kilogram and 6.0-6.5 euros per kilogram respectively. Since most options still require a lot of research effort, the costs are very approximate.

Natural hydrogen is uncommon, and its use is associated with certain difficulties. According to the University of Reykjavik and the Sigfusson Research Institute (Iceland), in areas of tectonic expansion of plates and volcanic activity, gaseous hydrogen penetrates the surface and is released into the atmosphere in big volumes and high concentration. Purification of gaseous hydrogen is of paramount importance for further hydrogen utilization in fuel cells. The researchers note that this is a rather difficult task, given the existing gas clean-up technologies.

In Ukraine, there is currently no information on the availability of natural hydrogen sources in quantities suitable for industrial use, which does not preclude the discovery of such deposits in the future.

Table 5. Forecast values of technical and economic indicators of "green" hydrogen production

Production of hydrogen by electrolyzers	Capital costs (EUR/kW)	Operating costs/year, %	System efficiency	Energy cost (EUR/MWh)	Hydrogen cost (EUR/kg)
2020-2025	300-600	1.5 %	75-80 %	25-50	1.5 – 3.0
2025-2030	250-500	1 %	80-82 %	15-30	1.0 – 2.0
Up to 2050	< 200	< 1%	> 82 %	10-30	0.7 – 1.5

3.4. Economic analysis of various hydrogen production methods

Economic analysis of various hydrogen production methods is given in **ANNEX 1**.

basic principles have been studied and practical applications can be applied to those initial findings. TRL 2 technology is very speculative, as there is little to no experimental proof of concept for the technology. When active research and design begin, a technology is elevated to TRL 3. Generally, both analytical and laboratory studies are required at this level to see if a technology is viable and ready to proceed further through the development process. Often during TRL 3, a proof-of-concept model is constructed. Once the proof-of-concept technology is ready, the technology advances to TRL 4. During TRL 4, multiple component pieces are tested with one another. TRL 5 is a continuation of TRL 4, however, a technology that is at 5 is identified as a breadboard technology and must undergo more rigorous testing than technology that is only at TRL 4. Simulations should be run in environments that are as close to realistic as possible. Once the testing of TRL 5 is complete, a technology may advance to TRL 6. A TRL 6 technology has a fully functional prototype or representational model.TRL 7 technology requires that the working model or prototype be demonstrated in a space environment. TRL 8 technology has been tested and "flight qualified" and it's ready for implementation into an already existing technology or technology system. Once a technology has been "flight proven" during a successful mission, it can be called TRL 9.

4. Analysis of infrastructure for hydrogen storage and transportation

Storage of hydrogen

Hydrogen may be stored in a liquid and pressurized (compressed) gaseous state. The containers for storing of liquid hydrogen - are stationary ones and transport-related containers, tanks. The compressed gaseous hydrogen can be stored not only in tanks or cylinders/vessels, but also underground in salt caves, depleted oil and gas fields, or water-bearing horizons, as well as in sections of gas pipelines which had been already decommissioned.

The existing salt rooms left after depletion of salt mines are the most promising option for hydrogen storing, taking into account the large-scale plans of the European Union with regard to integration of the hydrogen technologies into various branches of industry, with the aim of decarbonization of the latter. Some of the salt rooms in the territory of the EU countries are already in use for storage of natural gas, compressed air and fuel, while in the UK they use them to store the hydrogen for decades already.

According to the Hydrogen Europe Industry Board, the storage of the hydrogen energy in salt rooms is at least a hundred times cheaper than storing electricity in the energy storage. Apart from the salt rooms, the great potential for new storage reservoirs in salt beds has been proven. Besides, the hydrogen can probably be stored in some depleted gas fields, however such technology requires additional research. Additional information on the storage technologies is given in **ANNEX 2**.

The most advanced technology is storage of hydrogen in electric vehicles being a part of fuel cells or, as alternative, the energy storage.

Transportation of hydrogen

The hydrogen transportation is carried out in special containers designed for the purpose (tanks, reservoirs, vessels/cylinders) and in pipelines both in the pure state and mixed with natural gas, being in a compressed or liquid state.

The pipeline-related transportation of the hydrogen has also the advantage over the transmission of the electric energy when the hydrogen is relatively easy to be accumulated and stored in the underground and on-ground storage facilities under pressure and to be transferred through the gas pipelines to consumers at their request at a pre-determined time and in a controlled amount.

In this respect construction of the hydrogen pipelines is promising. Protection of such transportation routes from a hostile environment requires considerable investments; however, finished hydrogen pipeline is the cheapest way to deliver large volumes of the hydrogen. The development of a network of specialized pipelines could also turn the hydrogen into the cheapest way to transmit the electric energy over the long distances.

Potential of Ukraine in storage and transportation of hydrogen

Same as in the other countries, the natural gas industry of Ukraine is more prepared to receive hydrogen and its mixtures than the other industries. It is in possession of a vast network of pipelines with significantly higher power transmission capacity than that of electric power transmission lines.

The extensive system of mainstream gas pipelines and gas distribution network in Ukraine has a significant potential for using the hydrogen both in the national market and for export supplies.

The Regional Gas Company, which controls near 70% of gas distribution networks in Ukraine, in 2020 has begun to conduct the first field experiments with regard to transportation of mixture of natural gas and the hydrogen. This will make it possible to analyse capabilities of the infrastructure to ensure reliable supplies of gas/hydrogen mixtures to final users in various regions. Preliminary conclusions, according to official reports of the Regional Gas Company, has demonstrated possibility of using 10-15% of hydrogen in a mixture with natural gas for delivery to the company's clients.

The infrastructure of the mainstream gas pipelines of Ukraine can be widely used for export of the gas/hydrogen mixture or the hydrogen alone along various routes and directions, without negative affect on the safety and reliability of the gas supply within the country. Availability of various modes of organizing the work of the GTS (Gas Transportation System) allows to maneuver deploying different transportation scenarios. Such flexibility in operation is an important competitive advantage of the Ukrainian system of gas mainstream pipelines which allows it to remain a notable asset in the European gas market, in spite of the fact of its transformation under the influence of new political and economic factors.

Table 6. General technical characteristics of the gas transportation system of Ukraine[17]

Length of gas pipelines	38.9 thousand km
Length of mainstream pipelines	22.2 thousand km
Throughput capacity at inlet	288 bn m^3 per year
Throughput capacity at outlet	178.5 bn m^3 per year
Throughput capacity at outlet to EU	146 bn m^3 per year
Number of gas transmission units	702 pcs
Number of compressor stations	72 pcs
Electric capacity of compressor stations	5,448.0 MW

Source: PJSC "Ukrtransgas"

The most pressing issue at the moment is the prospects for the Ukrainian GTS after likely termination of the current contract for the transit of Russian natural gas in 2024. Even at the moment the GTS capacities are not fully utilized and may be partially put out of regular operation. However, there is also the possibility of upgrading the gas pipelines for alternative options of their use, associated with supplies of the hydrogen or the gas/hydrogen mixture both to the national market and for export to the EU countries, specifically: Romania, Slovakia, Hungary and Poland.

Arguably, the operation modes of the Ukrainian mainstream gas pipelines allow to arrange not only for export of the hydrogen or the gas/hydrogen mixture from the territory of Ukraine to the EU, but also the reverse-flow supplies from the European market back to Ukraine. It is also possible to implement the investment projects for construction of new dedicated pipelines for the hydrogen transportation.

The potential of capabilities for the hydrogen storage in Ukraine requires further research. This, in particular, relates to capacities of the underground gas storage facilities (USF), which are concentrated in the western regions of the country. The peculiarity of the Ukrainian USF facilities is that they had been created at already depleted natural gas production fields. Whilst most of the USF in the EU are the salt rooms, which have the most suitable characteristics for storing the hydrogen.

The decommissioned mainstream gas pipelines in the flow of upgrading of the Ukrainian GTS can also be used for the hydrogen storage. The geography of their location will become clearer after there is more certainty as to the prospects for cooperation between Ukraine and Russia.

Preliminary, one may conclude that the development of auxiliary services in the electric energy market in Ukraine will not stimulate expansion of the hydrogen storage capacities. This, in particular, will be facilitated by construction of the storage energy facilities based on the fuel cells - those will accumulate the electric energy converted into the hydrogen by the water electrolytic process with the help of renewable energy sources.

In addition, the cylinders/vessels of the types that are currently in use for the compressed hydrocarbon gases or liquefied natural gas in the capacity of the fuel for motor vehicles or household purposes where there is no centralized gas supply, and can be used to store and transport the hydrogen. Under the economy decarbonization trend the demand for the natural gas in these

[17] 1) Situation of the Ukrainian natural gas market and transport system, KPMG Market study, 10 April, 2017 (https://www.nord-stream2.com/media/documents/pdf/en/2017/04/kpmg-situation-of-the-ukrainian-natural-gas-market-and-transit-system-2017-04-10.pdf)
2) PJSC "Ukrtransgas"

consumer segments will continually grow up. Therefore, Ukraine needs to start thinking of expansion of its own production of gas-containing tanks. These tank manufacturing enterprises could produce dedicated tanks for storing hydrogen in liquid and gaseous state under pressure. Such the systems will be in demand both in the national market and for supply of the hydrogen for export.

5. Analysis of potential to produce renewable hydrogen domestically

5.1 Potential for hydrogen production in Ukraine

The application of hydrogen as an intermediary to ensure balancing of the power system of Ukraine while integrating additional RES capacities (wind and solar power) can be navigated by the corresponding volumes of power generation. Targeted volume of production by wind power plants (WPP) and solar power plants (SPP) is determined by the Energy Strategy of Ukraine until 2035. Whereas this Strategy is primarily focused on traditional energy production, the Institute of Renewable Energy of the National Academy of Sciences of Ukraine defined more promising achievable indicators as alternative guidelines for the development strategy of the electric power sector. Since the main obstacle to the large-scale implementation of WPPs and SPPs is the variable nature of their generation, the part of their output can be directed to regulate the energy balance.

In case balancing is performed by means of accumulating and reusing the part of the energy, then, taking into account the efficiency factor of the process “electricity-electrolysis-fuel cell- electric power” at the level of 40% and taking into account the necessity to direct 10-15% of the variable energy output for balancing, the proportion of generation to the grid and for balancing needs should be around 3:1. The volumes of “green” hydrogen, generated for the needs of the electric power generation within the framework of this strategy, are displayed in the Tables 7, 8 and 9.

Potential volume of “green” hydrogen production in Ukraine was calculated by the Institute of Renewable Energy Sources of National Academy of Sciences of Ukraine based on the results of studies of the opportunities for generating electricity by wind and solar power plants. To calculate the potential volume of “green” hydrogen production by the electrolysis method, energy consumption of 4.5 kWh / Nm3 or 50.6 kWh per 1 kg of hydrogen is required.

Table 7. Preliminary forecast of “green” electricity and hydrogen production[18]

	year	*2025*	*2030*	*2035*
Energy strategy	billion kWh per year	**12**	**18**	**25**
	H2 (billion nm^3)	0,6	0,9	1,2
Data from the Institute of renewable energy	billion kWh per year	**21.6**	**35.5**	**52.5**
	H2 (billion nm^3)	1.1	1.8	2.6

Indicated volumes of “green” hydrogen can be used in the power system as accumulating storage systems. The remaining hydrogen, including hydrogen obtained from renewable sources (see table 7), can be directed for other purposes.

Table 8 presents various scenarios of the technically achievable potential of “green” hydrogen on the basis of RES (wind and solar) in Ukraine. These scenarios are based on studies of Ukraine's potential conducted by the International Renewable Energy Agency (IRENA) and the Institute of renewable energy of the National Academy of Sciences of Ukraine and based on the Energy Strategy of Ukraine until 2035.

[18] Atlas of energy potential of renewable energy sources of Ukraine, Instutute of Renewable Energy Sources, 2019; 2035 Energy Strategy of Ukraine

Table 8. Average annual energy potential of RES and corresponding production of "green" hydrogen[19]

Source of information	Type of RES		Power capacity, GW	Electric power, billion kWh per year	Production of H2, billion Nm^3
IRENA	wind power plant	Total, incl.:	466	1,428	317
		terrestrial	320	858	191
		offshore	146	570	126
	PV plant		71	88	20
	Total of RES		**537**	**1,516**	**337**
Institute of renewable energy of the National Academy of Sciences of Ukraine	WPP	Total, incl.:	688	2,174	483
		terrestrial	438	1,190	264
		offshore	250	984	219
	PV plant		83	99	22
	Total of RES		**771**	**2,273**	**505**
Energy strategy	Total of WP and PV plants		**-**	**25**	**5,5**

Since the achievable volume of production of "green" hydrogen is higher that the need for the use of hydrogen to ensure integration of renewable energy sources into the power system, the excess volumes of hydrogen, as indicated in Table 8, can be used to decarbonize energy in general, including use of hydrogen in industry, transport or for export trade.

Use of hydrogen provides for the opportunity to set up on the territory of Ukraine 537-771 GW of RES-based generation capacities with the average annual production of 1,516 - 2,273 billion kWh, which is 10-15 times higher than the annual electricity consumption in Ukraine and which can provide production of 337-505 billion / Nm^3 of hydrogen by electrolysis.

The distribution of the potential opportunities of "green" hydrogen production throughout the territory of Ukraine is outlined in Table 9.

Table 9. Distribution of potential average annual "green" hydrogen production[20]

Oblast (Region)	Million Nm^3	Thousand tonnes
Autonomous Republic of Crimea	14,314	1,274
Vinnytsia oblast	9,055	806
Volyn oblast	5,074	452
Dnipropetrovsk oblast	24,692	2,198
Donetsk oblast	20,516	1,826
Zhytomyr oblast	7,515	669
Vinnytsia oblast	1,170	104
Zaporizhzhia oblast	21,029	1,872
Ivano-Frankivsk oblast	1,968	175
Kyiv oblast	8,263	735

[19] IRENA,2019; Atlas of energy potential of renewable energy sources of Ukraine, Instutute of Renewable Energy Sources, 2019; 2035 Energy Strategy of Ukraine

[20] Atlas of energy potential of renewable energy sources of Ukraine, Instutute of Renewable Energy Sources, 2019

Kirovohrad oblast	13,711	1,220
Luhansk oblast	20,646	1,837
Lviv oblast	5,637	502
Mykolaiv oblast	19,032	1,694
Odesa oblast	22,173	1,973
Poltava oblast	9,818	874
Rivne oblast	5,409	481
Sumy oblast	7,570	674
Ternopil oblast	4,721	420
Kharkiv oblast	17,517	1,559
Kherson oblast	22,021	1,960
Khmelnytsky oblast	7,051	628
Cherkasy oblast	7,138	635
Chernivtsi oblast	1,753	156
Chernihiv oblast	8,598	765
Total	***286,390***	***25,489***
Off-shore	218,742	19,468
TOTAL	**505,132**	**44,957**

The increased opportunities for hydrogen production in the southern regions are stipulated by higher average wind speeds, as well as higher levels of solar radiation throughout the year. Though potentially restrained by a number of technical and economic challenges, the potential for production of “green” hydrogen is quite significant for the domestic market.

5.2 Experience in manufacturing equipment for hydrogen production in Ukraine

The analysis of the production base for hydrogen in Ukraine is performed by using various aspects of hydrogen technologies, in particular: hydrogen production, use of hydrogen, the possibility of its transportation and examples of practical application of hydrogen.

A zirconium-ceramic fuel cell with a lightweight metal carrier for the power systems of automated vehicles has been developed in Ukraine by a group of Institutes of the National Academy of Sciences of Ukraine (Institute for Problems in Material Science named after Frantsevich, Vernadsky Institute of General and Inorganic Chemistry, Institute for Bio-Colloidal Chemistry, Physics and Mechanics Institute of Karpenko, Physical chemistry Institute named after Pysarzhevskyi) as well as samples of a low-temperature fuel cells with a membrane-electrode unit on the basis of the commercial ion-conducting membrane “Nafion”.

The Institute of Mechanical Engineering Problems of the National Academy of Sciences of Ukraine named after A. Podgorny (IMEP of NASU) has developed a technology for manufacturing sophisticated membrane-electrode blocks of various sizes for low-temperature hydrogen-oxygen fuel cells, and batteries based on proton-conducting membranes, and advanced cathode and anode catalysts. Based on this technology, PJSC “ELMIZ” managed to organize a production of demonstration kits for the course “Electrochemical Energy” in higher educational establishments and high schools. These demonstration kits show modern technological principles of creation and work of fuel cells, and they can be used for experiments.

The Institute of Renewable Energy of the National Academy of Sciences of Ukraine has built a demo version of wind power plant VEU-08, which is designed to produce hydrogen by electrolysis. The main elements of the system: wind turbine, control unit, batteries, electrolyzer.

Institute of Mechanical Engineering Problems of the National Academy of Sciences of Ukraine named after A. Podgorny has also developed electrolysis cells and electrolyzers using an active gas-absorbing electrode.

The technology of separation of processes of gas (hydrogen and oxygen) in time is realized in the construction of electrolyzer, thus the process of the electrolytic system work becomes cyclic and consists of periods of hydrogen and oxygen changing evolution. This version of electrolyzer provides hydrogen and oxygen at a pressure of 150 atm. without the use of a compressor.

For the electrochemical process of hydrogen and oxygen generation, a simple design of high-pressure hydrogen cells simplifies installation and operation maintenance. High-pressure hydrogen cells schemes are made on the basis of a single frame and are divided into two main compartments:

- compartment of electrochemical generation of hydrogen and oxygen,
- compartment of power electronics and control.

In order to increase the productivity of high-pressure hydrogen cells, it is necessary to increase the number of electrochemical cells, or to select the appropriate housing of electrochemical cell.

Institute of Mechanical Engineering Problems of the National Academy of Sciences of Ukraine named after A. Podgorny has also developed modular high-pressure hydrogen cells (trademark EVT) which provide the ability to obtain the required performance by combining unified electrolysis cells:

1) EVT 0.2-150, provides productivity of 0.2 m^3 H_2/h and 0.1 m^3 O_2/h;
2) EVT 0.5-150, provides productivity of 0.5 m^3 H2/h and 0.25 m^3 O_2/h;
3) EVT 1.0-150, consists of two cells type EVT 0.5-150, which provides a capacity of 0.5 m^3 H_2 / h and 0.25 m^3 O_2/h.

The National University of Shipbuilding (Mykolayiv) has developed an experimental solar-hydrogen plant for the production of hydrogen using electricity obtained from solar photovoltaic panels. The unit is designed to store the obtained hydrogen, compress it with a metal hydride compressor and fill composite cylinders for further use in power plants with fuel cells. The productivity of the installation is 10.0 kg H_2 per day, purity of hydrogen is 99.97 %, compression pressure is 60-80 MPa, the operating mode is cyclic: daylight production of hydrogen, night time - compression and filling of cylinders.

An experimental plant for the extraction of hydrogen from the gas mixture (synthetic gas, associated and process gases, etc.) using metal hydride technology and its purification has also been developed by this University. Productivity of the plant is 0.5 - 2.0 kg H_2 per day depending on its content in the gas mixture, purity of hydrogen is 99.97 %, supply pressure to the consumer is 3.0-15.0 MPa. Operating mode - continuous.

An experimental installation for transporting hydrogen using a suspension of hydride-forming material in an organic liquid is currently being tested by the University. The liquid suspension, saturated with hydrogen to content of 1.0% is pumped by pipelines to a consumer, where heating releases hydrogen under pressure of 5.0 to 15.0 MPa.

6. Roadmap for the introduction of hydrogen technologies in Ukraine

6.1. Actions and measures at the national level

Ukraine is active in the climate change mitigation process and is a party to the UN Framework Convention on Climate Change (UNFCCC) and its Kyoto Protocol and was one of the first European countries to ratify the Paris Agreement (14 July 2016). The climate change affects Ukraine directly and leads to increased risks to human health and life, natural ecosystems and economy.

The European Union (EU) is in the forefront of the international efforts to combat climate change. The goal of the EU's transition to climate neutral development by 2050, set out in the European Green Deal strategy, will lead to a significant acceleration of energy transformation in the EU countries, which will be reflected in all economic sectors, as well as on cooperation with other countries in Europe and beyond. This transformation will be both a challenge and an opportunity for Ukraine as a country that has the Association Agreement with the EU and is a party to the Energy Community Treaty. Ukraine is fully supportive to the European agreements for 2020, 2030 and 2050 (European policies on climate and energy towards 2020, 2030 and 2050, published February 2019) and strives to comply with its obligations under the Paris Agreement. Ukraine aims to:

1) reduce its total greenhouse gas emissions by 25% till 2020, by 40% until 2030;
2) increase the share of renewable energy up to 25% in the energy mix until 2035;
3) become climate neutral by 2050 in line with the long-term ambition for the EU members (to be synchronized with EU policies).

To achieve these goals, Ukraine intends to apply innovations and become the regional leader in clean energy technologies. This will give the country a competitive advantage. The National Security and Defense Council of Ukraine has made a decision to ensure the revision of the Energy Strategy of Ukraine until 2035 "Safety, Efficiency, Competitiveness", approved by the Order of the Cabinet of Ministers of Ukraine No.605-p of August 18, 2017[21], in connection with which the Concept of "Green Transition" was developed. It provides for the dynamics of industrial gas emissions reduction to move to a climate neutral economy in compliance with the principle of fairness and in the context of achieving the Sustainable Development. In particular, the "green" energy transition is designed to provide incentives for the development of high-tech production in Ukraine, leading to increased domestic demand for goods and services related to clean technologies and enhancing their export potential. The concept of "green transition" will be integrated into National Plan on Energy and Climate Change by 2030. The Energy Strategy of Ukraine until 2035 envisions the decoupling of energy consumption and economic growth: GDP in 2011 USD at PPP is projected to increase by 2.3 times over 20 years, at an average annual rate of 4.2%, while total primary energy supply (TPES) expands just 7%. As a result, energy intensity is projected to drop more than twofold from 0.28 to 0.13. Furthermore, the structure of TPES changes considerably, with the total RES share jumping from 4% in 2015 to 25% in 2035.

Energy transition is an ambitious strategic choice of Ukraine, which will determine the main trends and directions of development of the national economy. Implementation of the Concept will contribute to strengthening of intersectoral ties and formation of sustainable clusters in the economy, intensification of innovation and investment activity, creation of new job opportunities, increased competitiveness of Ukrainian companies, advancement of Ukraine in world rankings for significant improvement of investment climate.

Current policies to support renewable energy sources are not sufficient to decarbonize completely, to reduce emissions to stay in line with the Paris Agreement. Most renewable energy sources in Ukraine currently used only to generate electricity, whilst energy transition would boost the usage of RES in transport and industry.

[21] http://zakon3.rada.gov.ua/laws/show/605-2017-%D1%80

In order to achieve the energy transition of such a scale, many new technologies will be needed to replace the current reliance on conventional energy. **Hydrogen technologies** (especially, based on renewable sources) have been considered lately as potentially important to implement ambitious decarbonization plans of national importance. For various forms of final consumption, zero-carbon hydrogen is one of the options that can lead to sustainability improvements. The development of supply and demand for this type of hydrogen should ideally progress in parallel. Strong demand from end users will stimulate rapid development of the market for hydrogen. Once there are clear rules for the market and successful steps have been taken in scaling up production, resulting in cost reductions, this will lead to a clearer picture for potential customers as to what extent hydrogen could be beneficial to them. Improved insights among major potential customers into the cost effectiveness of sustainable hydrogen in reducing CO2 emissions compared to other measures, such as electrification, will in turn provide a better picture of the total potential demand for hydrogen. Step by step, a new market will develop, with hydrogen taking its place as an energy carrier in a zero-carbon energy system.

This Roadmap highlights the hydrogen technologies as a substantial part of a mix of technologies required to transit Ukraine to the climate neutral economy in the second half of this century and is designed to provide a clarity on their adaptation as one of the main technologies capable to support full “green transition” process with great potential to:

- reduce Ukraine’s dependence on fossil fuels;
- decarbonize industry, which is highly dependent on fossil fuels;
- decarbonize the transport sector;
- develop mobility on renewable basis;
- improve energy efficiency and energy saving;
- integrate flexibility options in order to match generation of renewable electricity with demand.

In this Roadmap hydrogen represents a wide range of possibilities and technologies. It can be used to produce ammonia, urea, hydrocarbons and bio and synthetic fuels, in conjunction with other molecules (primarily nitrogen and carbon dioxide). Hydrogen can be stored and transported in various ways: as a liquid, in a gaseous state or bound to other substances. Hydrogen can be produced in different ways. In all of these areas, companies and scientific and research institutes are working on basic and applied research and innovations aimed at making processes and applications more efficient, more sustainable, and cheaper. A considerable innovation drive will be required both in organizational and technological terms in the lead-up to 2030, so that breakthrough hydrogen technologies can be rolled out between 2030 and 2050. Strengthening targeted innovations and providing support for pilot projects will form the core of the joint efforts of the government, the business community and the scientific and research institutes. Government should welcome system innovations that combine energy solutions with alternative raw materials and CCS systems. Finally, government expects businesses to take their responsibility, by investing in those energy-efficient technologies that are already economically viable.

The Roadmap identifies four sectors (Pillars) for introduction of hydrogen technologies in Ukraine.

Pillar 1. Transformation of electrical power supply and heating systems

Why transform?

The energy transition means moving from a fossil fuel-based economy to one based on renewable energy sources with net-zero carbon emissions. In 2018 renewables accounted for only 5% of the energy mix, and for 9% of electricity generation (13.4 TWh in 2019). Although Ukraine’s energy mix is relatively diversified with no fuel representing more than 30% of the energy mix, energy intensity per GDP at purchasing power parity (PPP) is very high: at 0.25 tons of oil equivalent (toe) per thousand2015 USD PPP, it is the second-highest among EU4Energy countries, after Turkmenistan, and over twice the world average (0.11 toe /1000 USD). In 2018, the share of coal (the country’s primary fuel) dropped to 30%, followed closely by natural gas (28%) and nuclear (24%). Ukraine produces all fossil fuels (in 2018: 14.4 million tonnes of oil equivalent [Mtoe] of coal, 16.5 Mtoe of natural gas and 2.3 Mtoe of crude oil), but in quantities insufficient to meet total energy demand.

Currently, natural gas is the primary source of energy for heating of buildings and water heating, with households being the major users of it (8.7 Mtoe in 2018). Most of the coal consumed in the country is used to produce electricity and heat[22].

The electricity sector especially needs not only to be decarbonized, but also to move to new technologies of digitalization, taking into account its current state: the core infrastructure of Ukraine's energy system is still similar to that of 60 years ago highly dependent on fuel imports. Obsolete state of generating capacities, uneven distribution of generation and energy consumption between regions, lack of flexibility of the power system, difficult environmental conditions that limit the possibilities of energy development, – these are only few reasons to name justifying the changes within the energy system. This can be done by integrating digital technologies into all aspects of the energy system, including generation, transmission and demand side technology. There should be parallel processes of modernization, reduction of carbon emissions and gradual reduction of the share of coal generation in compliance with the principle of social acceptability and adaptability of the sector to changes. The share of nuclear generation in the electricity balance of Ukraine will remain at about the same level (~50%) at least until 2030[23] but will decrease later on as some NPPs will be decommissioned (under 2035 Energy Strategy new NPP capacities will be built but not fully replacing decommissioned capacities). Hydropower will also remain at the current level given limited available water resourses for these purposes. Taking into account the political course for the integration of the national power system with the power system of the European Union, the import and export of electricity will provide the necessary technical and market convergency.

What to transform?

1. Electricity sector: The electricity sector of Ukraine today represents centralized generation based mostly on large scale combustion of fossil fuels, and power flowing from supply to demand. After energy transition electricity generation will be based predominantly on renewable energy sources like solar energy. As a result, generation no longer will take place in large industrial plants. It will be dispersed in the system at the places of consumption. The change will be from a system based on large scale, long distance transported electricity into a system with local generation and storage nearby the consumption. To replace the extraction of fossil energy resources there should be the scaled-up production of energy from renewable sources. The transition will result in a sharp increase in use of low-carbon electricity sources, such as the sun, wind and water.

During 2014-2020, 6.2 billion EUR were invested in the construction of 7.7 GW of renewable energy facilities, raising overall capacity from 5.5 to 13.2 GW (of which 4.7 GW are large hydroelectric power plants), including:

- wind power capacity increased from 426 to 1,314 MW;
- solar energy capacity increased from 411 to 6,094 MW;
- the capacity of SPPs of households increased to 779 MW;
- capacity of large hydroelectric power plants increased from 4,547 to 4,716 MW;
- capacity of small hydroelectric power plants increased from 80 to 117 MW;
- capacity of bioenergy facilities increased from 49 to 212 MW.

According to one of the scenarios developed by the NASU (National Academy of Sciences of Ukraine) Institute for Economics and Forecasting already in 2035, 90% of power generation can be provided by renewable energy sources. According to Energy Strategy of Ukraine until 2035 the target for the RES share is only 25% of the final energy consumption. At the same time, according to the above-mentioned scenario, in 2035 it is possible to achieve an increase in the share of renewable sources up to 40% while reducing total consumption by 28% due to energy saving measures and increase in energy efficiency.

2. Residential and non-residential heating: Consumption of energy resources in residential and non-residential buildings in Ukraine is about 40% of all energy consumption, and the amount of

[22] (https://www.iea.org/reports/ukraine-energy-profile)
[23] Generation Adequacy Report by Ukrenergo

energy consumed per 1 m^2 is several times higher than in the EU countries with similar climatic conditions. Heating currently heavily relies on fossil fuels. The heat transition will require changes in the district heating infrastructure. There are the following technologies of carbon-free heating:

a) solar-thermal heating (works only in more southern regions);

b) heat pumps (extract heat from outside or from the ground);

c) electric heating (turning electricity into heat; requires using electricity, presumably mostly generated by RES).

Decision making on a more sustainable heat supply should be coupled with the plans for installing new or phasing out existing infrastructure or plans for restructuring residential areas and non-residential buildings (schools, hospitals, etc.). Decisions on the organization of the heat supply can best be made at the local level based on the local conditions and preferences. In order to facilitate made-to-measure solutions for residential areas, decision making on the heat transition will have to become more of a regional concern than it is today, with a greater role for local authorities, building managers, property developers and residents.

How hydrogen technologies can help?

TASKS	HYDROGEN TECHNOLOGIES AND SOLUTIONS	ACTIONS AND REGULATIONS REQUIRED TO SUPPORT HYDROGEN TECHNOLOGIES
Ukraine's GHG reduction targets	Ukraine must open more sectors to renewable and decarbonized gases. The introduction of power-to-gas (P2G) hydrogen technologies can create an industry for the production of hydrogen and other low-carbon, decarbonized and renewable gases for the needs of the power system. Biomass power plants combined with the introduction of new generating capacities and possibly new nuclear power technologies - particularly on natural gas with carbon capture and storage (in the longer term - based on renewable hydrogen technologies) and biogas, will accumulate and store electricity technologies for balancing in the power system.	• harmonize applied terminology standards with internationally accepted ones in view of future debate on energy transition; • integrate ambitious decarbonization goals in the new gases terminology; • ensure transparency on the gas production processes and their sustainability/GHG reductions; • align different work streams in view of developing new gases markets; • facilitate the distinction between Guarantees of Origin from renewable, decarbonized and low-carbon gas; • trigger demand and investments into plants producing/using renewable, decarbonized and low-carbon gases; • create investment perspective for the needed retrofitting of gas transmission and distribution grids; • carry out a study into the advantages and disadvantages of linking hydrogen production to wind and solar energy via integrated tenders.
Energy transition to transform the electricity system and electricity generation	The large-scale production of renewable electricity will remain important to meet energy demand of residents and businesses If the supply of zero-carbon hydrogen can be scaled up in time, this would offer prospects to achieve CO2 reductions in the electricity sector in the long term with more and more parties, including small customers, playing a role in the provision of flexibility	The government of Ukraine should welcome and support local initiatives. A wide range of policy instruments can be used to support initiatives and to stimulate and facilitate market development. A key process in this context is the revision of the current Ukrainian regulations and norms, as well as the development of new technical safety regulations based on the

		international standards and European Directives. At a local and regional level, initiatives should be undertaken to combine local renewable energy generation with the production, use and storage of hydrogen. As a result, generation no longer will take place in large industrial plants. It will be dispersed in the system at the places of consumption.
Flexibility and stability of the electrical grid	Use of clean hydrogen in natural gas plants offers the opportunity to sustainably realize flexible power capacity. Gas turbine engines with a conventional natural gas combustion system or water injection combustion system can operate on H2 or H2-rich fuels with little or no modifications to the core injectors. Modifications to the fuel delivery system and injectors are required. Small gas turbines, less than 25 MW, can operate on H2 or H2-rich fuels with little or no modification, similar to gas turbines for central power generation. Since H2 can be burned in gas turbines, these turbines could provide an early market for additional H2 production—assuming that the H2 is not generated from natural gas. Turbines located at the site of the hydrogen production could generate electricity, which could be transmitted via the usual electrical transmission and distribution (T&D) system to residential, commercial, and industrial users. Hourly modeling of the operation of the UPS of Ukraine demonstrated that it is possible to achieve stable energy supply throughout the year in all weather conditions in Ukraine on the basis of a combination of existing RES technologies, gas turbine stations (at the intermediate stage) and hydrogen technologies of storage and energy conversion.	There are R&D needs to address issues that include the following: (1) combustion technology to reduce NOx emissions and achieve higher efficiencies, (2) fuel management and controls for operability and safety requirements, (3) cost-and-efficiency trade-offs, (4) material compatibility of components with H2 combustion gas, and (5) systems development and optimization.
Development of the renovated electricity grid	International experience has shown that it is crucial that the development of the electricity grid and the hydrogen grid should be effectively coordinated. The proximity to gas infrastructure, space for the electrolyzers and the space for and capacity of electricity infrastructure are key aspects in that regard. The conversion of electricity to hydrogen is characterized by energy losses that may have an impact on the spatial requirements for the production of energy.	Guidance will be required from the government in consultation with the industrial clusters with regard to the precise locations of electrolyzers.
Sustainability of buildings and districts heating	As the availability of renewable hydrogen is expected to be limited, hydrogen will therefore initially be used for buildings and districts that are difficult to make more sustainable in other ways.	• The starting point will be local heating plans. The government should support the joint efforts and local decision-making process where possible, among others by reviewing the policy and market rules for the supply of alternative energy and the maintenance of the new infrastructure.

		• Update a National Energy Efficiency Action Plan (NEEAP) adopted in 2015, emphasizing on buildings insulation and energy efficiency as the most desirable strategies

It is still difficult to predict at what price renewable fuels will actually become available and whether that price will also lead to an affordable option. It is also difficult to estimate when and which volumes will become available. Therefore, some changes can be made to energy processes during the energy transition. Appliances and lights will need to be made more efficient so that the demand for electricity is reduced. The use of natural gas will need to be drastically reduced in order to make Ukraine's energy supply more sustainable, in the first place *by focusing on energy saving*.

Ukraine has already adopted a National Energy Efficiency Action Plan (NEEAP) in 2015 aligned with the Energy Community Treaty. The NEEAP outlines energy efficiency measures to achieve energy savings of 9% in 2020, compared with average domestic final consumption during 2005-09. However, two major recessions in 2009 and 2013-14 and the loss of government authority over Crimea and part of the Donbass region already reduced total final consumption 29.6% in 2015 compared with the 2005-09 reference average, far exceeding the approved target for 2020. Since this consumption decline can be attributed mostly to structural changes in industry and an overall drop-in activity, the NEEAP energy efficiency targets should be revised to capitalize on Ukraine's significant untapped energy efficiency potential. The approved government's National Action Plan (NAP) therefore prescribes that a new NEEAP and an updated NREAP be drafted, both effective through 2030, assuming that all plans through 2019 (for the NEEAP) and 2020 (for the NREAP) have been implemented. In June 2019 NAP also made the MinRegion responsible for reporting estimated energy efficiency indicator (EEI) values to the SAEE, based on International Energy Agency (IEA) methodology, and publishing the EEIs for industry, agriculture, services, construction and the residential sector by the end of 2019. EEIs are essential to gauge untapped energy-savings potential, set energy efficiency targets and ensure the monitoring of progress.

Pillar 2. Transformation of industrial process heat

Why transform?

Industry is the largest final energy consumer (19.1 Mtoe in 2018) in Ukraine[24]. The energy intensity of GDP of the industrial sector of Ukraine is more than four times higher than the European average, and therefore the competitiveness of domestic goods is much lower compared to the goods produced in the EU. One of the goals of the Green Transition Concept is to reduce the energy intensity of Ukraine's GDP to the average level of the EU countries. Transformation of industrial process heat is an important part of the energy transition. Ukraine has an extensive industrial sector. The main consumers of energy are the refineries and the chemicals, metallurgical and paper industries.

The current state-of-the-art does not allow for large-scale energy saving in these sectors. Often, a complete overhaul of technological processes is required, which takes a lot of time. The first challenge is to organize processes so that less heat or lower-temperature heat is required. Other options include electrification, more efficient use of steam production and use of residual heat in industrial clusters. However, fossil fuels will still be required for the production of some high-temperature heat for the foreseeable future. In time this should be combined with carbon capture and storage systems (CCS). The businesses in these sectors often compete in global markets, where there is sometimes overcapacity, and often with companies from countries with structurally lower energy costs. Many processes in industry rely heavily on carbon-intensive sources, like cement or chemical processing, and it will take a long time to replace these well-developed processing methods. Although replacement methods are being researched, most are still in the development stages.

[24] https://www.iea.org/reports/ukraine-energy-profile

What to transform?

In Ukraine, the industry accounts for approximately 30% of total energy consumption, and more than half of energy resources are consumed by the domestic metallurgical complex. Steel smelting in Ukraine in 2019 was at the level of 21 million tons (in 2013 – 33 million tons). According to Bloomberg, metallurgical plants should produce at least 10-50% of steel and steel products using hydrogen in order to achieve a global goal of zero emissions in 2050 (Bloomsberg Businessweek, Nov.23, 2019). This outlines the potential for hydrogen use in metallurgy. Another direction is production of "green" ammonia fertilizers. Industrial heat is usually produced in the form of hot gases. These gases can be passed through a heat exchanger and/or heat pump to heat water. This water can then be used for district heating in nearby neighborhoods or towns. District heating distributes this heat through a system of insulated pipes to satisfy residential and commercial heating demand. This heating water can either be used for heating of buildings or for water heating. As industrial processes function all year round, this could provide aid to energy saving and efficiency programs and provide a renewable source of heat available to homes throughout the year. Methods to replace traditional heating:

- for medium and low temperatures – electric heating and heat pumps;
- for higher temperature processes – alternative fuels like hydrogen or biogas.

A lot of industrial processes will still produce CO2 even if carbon neutral heating is provided (cement producing or pharmaceuticals). For these carbon intensive processes carbon capture systems should be considered. The collected CO2 may be used in alternative ways such as creating synthetic natural gas. Industrial processes also produce a lot of waste heat and materials that can be re-used under the right government regulations. This will help to improve the circularity and efficiency of these processes.

How hydrogen technologies can help?

TASKS	HYDROGEN TECHNOLOGIES AND SOLUTIONS	ACTIONS AND REGULATIONS REQUIRED TO SUPPORT HYDROGEN TECHNOLOGIES
Decarbonization of carbon intense sectors of industry, particularly, industrial heating	For the Ukrainian economy, the introduction of hydrogen technologies is relevant for the chemical and metallurgical industry for the production of "green" fertilizers and "green" steel. The use of hydrogen as a raw material for industry requires a sustainable source of its production. Currently, hydrogen in Ukraine is mainly received from fossil fuels ("blue" hydrogen). Studies show that as a result of the lower costs, particularly in industry and electricity supply, there are indeed opportunities for "blue" hydrogen. This paves the way for large-scale integration of renewable hydrogen.	Decarbonization Fund funded by CO2 tax revenues may be created to support energy efficient modernization of companies.
Replacement of traditional heating	The use of hydrogen as a combustion fuel source for industrial boilers and process heaters offers the potential for a sizable end-use market for hydrogen. In addition, there could be improvements in efficiencies - 99% thermal efficiency versus 80% for conventional technology (DOE, 2003d). There is experience in the industrial sector using hydrogen blended with other fuels and diluents.	Ukraine should develop and implement a *National Policy for Transition in Supply of Process Heat.*

Pillar 3. Transformation of transport sector

Why transform?

Transport has significant share of total energy consumption in Ukraine. In 2017, transport (including pipeline) accounted for more than 20% of final energy consumption. More than half of passenger traffic is carried by buses. The railway carries 390 million passengers per year, while road transport carries 7.5 times more – more than 3 billion passengers. According to the statistics, every resident of Ukraine uses buses on average 70 times a year. The operational length of the main railway tracks is 19.8 thousand km, of which electrified tracks - 9.9 thousand km as of 2018 (47.4%). The vast majority of fuels used in the sector are petroleum products (diesel and gasoline), due to which transport is one of the largest sources of pollution and greenhouse gas emissions. At the same time, this sector plays a key role in ensuring movement of goods and passengers, creating and providing appropriate services for the development of the country's economy. In Ukraine, the need to transition to the use of sustainable technologies in the transport sector is critically important for both environmental and economic reasons.

What to transform?

Several segments of transport sector require decarbonization technologies to be implemented during the first phase of the Hydrogen Roadmap: light road vehicles, heavy-duty trucks, buses, railroad transportation, maritime shipping.

Ukraine is committed to the implementation of stricter CO2 emissions requirements for road transport, shipping and aircraft emissions. Moreover, it should aim to implement a European biofuel blending obligation as it will be considered as the first significant step towards alternative fuels wide-spread on the market. Use of biofuels in the EU varies by Member State, depending on how countries choose to meet their targets for renewables in transport and for reduction of greenhouse-gas intensity of fuels under the Fuel Quality Directive. Some Member States set an overall biofuels incorporation target; some set separate targets for biofuels in petrol or diesel or both; others rely solely on targets for the reduction of carbon intensity in fuels. More far-reaching energy savings can only be made by changing the types of vehicles and fuels used. Electric motors are already available for smaller vehicles and relatively short distances. Liquid biofuels and biogases are the best alternative for heavier and longer distance transport by road, water and air.

The creation of infrastructure of vehicles on fuel cells at long distances, in medium and difficult conditions of operation, is a trend in the development of the logistics industry. In addition to refueling infrastructure at the main Ukrainian transport axes, roll-out will also be required in adjacent regions.

How hydrogen technologies can help?

TASKS	HYDROGEN TECHNOLOGIES AND SOLUTIONS	ACTIONS AND REGULATIONS REQUIRED TO SUPPORT HYDROGEN TECHNOLOGIES
Decarbonization of road transport	In Ukraine, electric transport consumed 7.0 billion kW-h of electricity in 2018. This identifies a potential for hydrogen fuel cell transport market. Special attention should be paid to the use of fuel cells and hydrogen (FCH) in road transport. Hydrogen transport can overcome the shortcomings of electric cars with low mileage range and the need for frequent charging. Vehicles on fuel cells can reach mileage of 350 to 1,200 km between refueling, and the total resource reaches 500,000 km. In Ukraine there are a number of routes of	• *A Renewable Fuels Long-term Plan* should be created with the involvement of relevant stakeholders; • Subsidy schemes for zero emissions urban logistics and heavy-duty transport should be developed; • The further roll-out of refueling stations will be encouraged.

	considerable length, where hydrogen buses could compete with traditional ones. More innovative solutions like hydrogen technologies are required to facilitate the deployment of the alternative fuels at a greater scale.	
Decarbonization of rail transport	Regarding rail transport, hydrogen fuel cell powered trains represent an environmentally friendly and economically feasible alternative to existing technologies in low-electrified networks.	
Decarbonization of maritime sector and river transport	In the maritime sector, ships with fuel cells are at the stage of demonstration projects. Hydrogen fuel cells can also be used to replace onboard and coastal power to reduce polluting emissions and avoid significant costs of installing electrical connections in the harbor. In Ukraine, the use of hydrogen on water transport has its prospects. The potential of river transport is mastered by only a third, in general it is able to reach 20% with the volume of traffic in 10-12 million tons per year.	
Reduction of total transport sector emissions in 2050 to at least 60% of the emissions of 1990	Development of the market for sustainable hydrogen for the mobility sector. The European Green Deal and Initiative 2X40GW Electrolyzers will contribute to providing incentives for the use of hydrogen in the shipping industry (maritime transport and inland waterways) and in the ports of Ukraine as produced clean hydrogen is planned to be shipped for the export.	*The National Plan on Energy and Climate Change by 2030* should include long-term agreements with the sectors for transportation of specific groups (e.g. disabled), waste collection vehicles, zero emissions urban logistics and a strategy for long-distance transport for hinterland connections should provide further support for the roll-out of hydrogen. This should be reflected in the procurement programs of the national government and local authorities.

Pillar 4. National gas pipelines system and scaling-up of hydrogen manufacturing, storage and transportation

Ukraine has a well-developed network of main gas pipelines and a shortage of its own energy sources, in particular natural gas. Part of the existing gas grid can be used for the transport of blended-in hydrogen. Physical blending up to 2% is already achievable with minor adjustments, and with further adjustments, the percentage could gradually be increased to approximately 10-20%. Currently, studies are still underway to determine the optimal hydrogen share in the mix that can be used in Ukraine's GTS.

Converting electricity produced locally into hydrogen and blending it into the gas grid will increase the opportunities for decentralized production of energy in places where the electricity grid has insufficient capacity. The feasibility of various options for physical and administrative blending will be explored in the near future in consultation with NaftoGaz, regional network operators and natural gas users, while, in addition to technical, practical, regulatory and safety aspects, also considering the price effects for end users. A key factor for adding hydrogen to natural gas is the ability to achieve some level of decarbonization in the gas sector without the need to modernize the existing infrastructure. The use of pipelines can provide a number of additional advantages, for example, energy storage: gas pipelines provide an additional option for storing hydrogen using a packaging pipeline or "transferring energy in time".

One of the most important problems with the addition of hydrogen to the natural gas network is the impact of such a mixture on measurement. Traditionally, the measurement and subsequent pricing of gas in pipelines is based on the consumption and energy capacity of the gas used. Thus, pipeline meters must be adjusted to reflect the percentage of hydrogen in the gas mixture, as well as their differences in energy density.

Various national and international studies have shown that significant cost savings in production of renewable hydrogen of around 50-60% can be achieved in the next ten years. In order to achieve such a reduction of cost, a major scaling up of green hydrogen production is required by 2030. This will allow a more industrialized production method and unlock economies of scale. In addition, innovation may also lead to higher electrolysis efficiency and therefore lower costs. It is primarily the use of cheaper materials (for electrodes and membranes) that is crucial in that regard and still requires a great deal of research. However, it is expected that significant volumes of renewable hydrogen will only become available beyond 2030.

The development of hydrogen infrastructure should take into account the development of European hydrogen market, which is relevant with a view to the potential hub function played by Ukraine for provision to neighbouring countries. The connections with the partners in the 2x40GW Initiative are of particular interest. Identifying the potential demand, supply and storage capacity required will be part of this review. In this context, the ports of Odesa, Kherson and Mykolaiv Oblasts will be identifying the potential export supply (to overseas territories). In an international context, Ukraine will promote exploring hydrogen cooperation, among others as part of the *Danube Hydrogen Valley project*. In this regard, installation of green hydrogen production facilities in southern Ukraine, namely, in Odesa, Zaporizhya, Kherson and Mykolayiv Oblasts is highly important. Given the geographical location of the main production facilities, it is important to take into account the strategy of developing hydrogen logistics throughout Ukraine using the Dnieper River and road transport. The identification of potential consumers of green hydrogen on the territory of Ukraine and the development of domestic hydrogen pipelines are also important.

How hydrogen technologies can help?

TASKS	HYDROGEN TECHNOLOGIES AND SOLUTIONS	ACTIONS AND REGULATIONS REQUIRED TO SUPPORT HYDROGEN TECHNOLOGIES
Development of infrastructure for sustainability, decarbonization of the gas network	• Pumping hydrogen into natural gas pipelines increases opportunities for decarbonization in the energy sector. One option to increase demand for renewable hydrogen is through an obligation for its blending in the natural gas grid.	• The option of blending hydrogen in the natural gas grid should be developed as a cost-effective and flexible way to support the scaling up of green hydrogen. Ukraine needs to explore the policy, legal and market aspects on this issue.
Improving the efficiency of gas supply	• With uncertainty around the restrictions of natural gas supply, hydrogen could provide a shorter-term opportunity to compensate for the growing demand for this fuel.	• A blending obligation may be able to offer greater offtake security to green hydrogen projects. • The government should indicate that it intends to play a key role in the development of the hydrogen infrastructure. Alongside the national network operators and network companies NaftoGaz and National Gas Transmission System Operator, the government should review whether and under which conditions part of the gas grid can be used for the transport and distribution of hydrogen. The regional network operators and network companies will be involved in this process.

The Three Phases and Design Principles Matrix of the Roadmap

The Roadmap of Implementation of Hydrogen Technologies in Ukraine can consist of the three phases in a sequence of steps. The phases mostly coincide with the three stages of the updated Energy Strategy of Ukraine (ESU) adopted in August 2017, though this Strategy will need to be updated again during Phase 1 of the Hydrogen Roadmap in order to reflect the newest developments towards hydrogen economy.

Currently, the Energy Strategy implementation is divided into three following stages:

1. The first stage (2021-23) aims to create liberalized, competitive energy markets and minimize state inference in their performance.

2. The focus of the second stage (2024-26) is on developing energy infrastructure and integrating it with the European system and attracting necessary energy sector investments.

3. Finally, the third stage (2027-29) is concerned with sustainable development: meeting greenhouse gas (GHG) emissions reduction commitments; rapidly developing renewables; and ensuring energy security by further boosting gas production, including unconventional gas and offshore drilling, after achieving gas self-sufficiency in the second stage.

In these 3 phases of development, it is crucial that the relevant laws and regulations will be developed and implemented as soon as possible. A review of the use of the existing gas grid needs to be pursued, as well as the regulation of the whole value chain. In the short term, the focus should be on building the first scaled-up hydrogen production plants. Gaining experience with the production of renewable hydrogen in Ukraine and abroad and its use in different sectors will also lead to a better understanding of the cost reductions that can be achieved and of the potential size of the market. The basic conditions for the growth of hydrogen market will be shaped in the period leading up to 2025.

The three phases of the implementation of the Roadmap for assisting in the hydrogen technologies introduction and acceptance by the Ukrainian economy within the frame of production, storage, transportation and use of hydrogen help to pinpoint where an energy demand comes from and so focus the efforts for the energy transition. It will enable Ukraine to determine which sectors need to take action to facilitate the transition to renewable energy supply. They contain the following tasks:

- creation of a world-class hydrogen energy equipment database;
- development of scientific and technical projects based on samples of world-class hydrogen energy equipment, approbation and development of recommendations for their implementation;
- creation of basic demo samples;
- performing of scientific and technical research on the creation of national equipment and technologies;
- creation of a harmonized regulatory, technical and industrial base necessary for the production of devices and equipment, its certification, as well as installation, operation, repair and maintenance.

International hydrogen strategy outlined in the Roadmap

An international strategy has long been part of the Ukrainian approach to getting on track with systematic decarbonization of the economy. The principal focus is on Europe, with Ukraine also actively taking part in global partnership initiatives. The Ukraine's European strategy consists of the following tracks:

a. The Ukrainian government signed and ratified the Association Agreement with the European Union in 2014, and the Deep and Comprehensive Free Trade Agreement between Ukraine and the European Union entered into force on 1 January 2016: Direct contact with the European Commission at every conceivable level. The key goal in this regard is to make clear to the Commission what Ukraine regards as desirable hydrogen policy in terms of issues such as common standards for sustainability, safety, quality, blending of hydrogen in gas grids, flexible market regulations that provide enough flexibility for market creation, and adequate innovation support (compared to China, Japan and the US); Multilateral Forums and Consultations with EU countries in which Ukraine will be taking the initiative to develop common approaches to critical issues such as standards, market incentives and market regulations ahead of the discussions in an EU context.

b. Bilateral cooperation with neighboring EU states: IPCEI (Important Projects of Common European Interest) is a European instrument for the rolling out of projects with significant value to society in which governments are able to provide more support than within the usual frameworks. *The National Climate Agreement* should set out that, in the context of the IPCEI, Ukraine will be focusing on a strong role in *EU 2x40GW Electrolyzer Initiative* and *Blue Danube IPCEI Project.*

c. Ukraine as an Observer to the Energy Community Treaty in November 2006 and a full Member in September 2010: adopting and implementing the energy acquis, namely the legislative frameworks for the electricity and gas sectors and requirements in the areas of renewable energy, competition and the environment.

In addition, Ukraine positions itself as an active participant in international initiatives such as the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), IEA, IRENA.

Trade policy should explicitly take into account the opportunities to export Ukrainian hydrogen, knowledge and skills. Policy aimed at attracting foreign investment needs to explicitly showcase the appeal of Ukraine as a location for companies in the hydrogen value. The significant interest of foreign companies in hydrogen projects in Ukraine highlights that its favourable starting position is already recognized. Bilateral foreign policy needs to specifically focus on developing potential export relationships with countries that emerge as potential net importers of clean hydrogen, such as Germany in Europe and Japan in Asia.

Public Awareness for the energy transformation and hydrogen economy

Ukraine is taking part in a global effort to develop a low-carbon energy economy that is safe, reliable and affordable. Therefore, the society-wide *Energy Agreement for Sustainable Growth* should be concluded with industries, non-governmental organizations and municipal governments as major first step. The Energy Agreement should include targets for energy efficiency savings to 1.5% of our final energy consumption and for an increased share of renewable energy. For that, *The Energy Dialogue* should be announced in Ukraine. This is an extensive public consultation, during Phase 1 formally lasting for three months. During this consultation all parties will have the opportunity to share their views on the future energy system and to contribute to the design of the policy agenda. Findings from this consultation will be presented by the end of the Phase 1 in a so-called *Energy Policy Agenda*. The Energy Dialogue will also be instrumental in fostering the awareness of the energy transition in Ukraine.

For the energy transition to succeed, the public, businesses and NGOs must be constructively involved at an early stage in the discussion on the spatial accommodation of the energy infrastructure. Wherever possible, all stakeholders should be involved in weighing the benefits of an energy supply initiative against the hindrance or risks it involves for the local people and businesses. This will require all parties to help with identifying spatial alternatives for energy generation, storage and transport. Agreements can then be reached with these parties on the accommodation of these initiatives in the region and the division of the responsibilities, benefits and burdens. This process requires a clear division of roles in the development of energy projects. The relevant municipality will bear the main responsibility for the spatial planning process, while the national government is the competent authority for initiatives of the national interests. The initiator has primary responsibility for the cooperation with the public, businesses and NGOs, and is supported to this end by the competent authority.

The Hydrogen Roadmap of Ukraine

First phase (2021-2023):

Assessment of the Ukrainian economy for “green transition” and launch of the hydrogen economy

Assessment of the structure of the economy and sources of emissions, which can help highlight priority areas of focus. Recommended: evaluate emission impacts of different options.

***Energy sector governance*[25]**

The **Cabinet of Ministers (CoM)**, the ultimate decision-making body, is responsible for policy co-ordination and the oversight of state energy companies. Energy policy is high on its political agenda, with the parliament and the president involved in decision-making. Several main national-level institutions have energy policy responsibilities:

- The **Ministry of Energy (MoE)** is responsible for most energy supply policies, sustainable energy policy and climate change policy, and for co-ordinating energy policies across the government and advising the parliament.
- The **Ministry of Ecology and Natural Resources (MENR)** is responsible the state policy in the field of environmental protection, including preservation of ozone layer, ecological safety, treatment of waste, hazardous chemicals, performance of the state ecological expertise.
- **The Ministry for Development of Economy, Trade and Agriculture (MDETA**) is responsible for the implementation of state policy for technical regulations.
- The **Ministry of Infrastructure (MoI)** is responsible for air, road, rail, sea, river and urban electric transport, issues related to the use of Ukrainian airspace, subway systems, roads, transportation safety, merchant shipping.
- The **Ministry of Finance (MoF)** is responsible for taxation relevant to the energy sector.
- The **Ministry for Communities and Territories Development (MCTD or Minregion)** is responsible for coordination of the development processes to ensure the implementation of reforms aimed at regional and local development.
- The **State Agency on Energy Efficiency and Energy Saving (SAEE)**, under Ministry of Energy, is the central government body responsible for advancing and promoting energy efficiency and renewable energy developments and technologies.
- The **National Commission for State Regulation of Energy and Public Utilities (NEURC)** supervises the natural gas and electricity markets as well as the heat sector. The NEURC is subordinate to the President and accountable to the parliament.
- **The State Labor Service of Ukraine (SLS*)*** is responsible for state supervision and control in industrial safety, labor protection.
- The **Anti-Monopoly Committee** (**AMC**) is responsible for preventing excessive concentration of market power.

[25] functional description and abbreviations for further use in Roadmap Design Principles Matrix Tables below

<table>
<tr><th></th><th></th><th colspan="2">Document type</th><th>Responsible Agency</th><th>Partner Agency</th></tr>
<tr><td>I</td><td>II</td><td colspan="2">III</td><td>IV</td><td>V</td></tr>
<tr><td rowspan="7">LEGISLATION</td><td>Identification of necessary legislative changes in the field of hydrogen technologies</td><td colspan="2">1. Analysis of legislation and formation of a list of legislative changes (to introduce changes to the relevant laws and by-laws) in order to promote the development of hydrogen technologies.
2. A study into the advantages and disadvantages of linking hydrogen production to wind and solar energy via integrated tenders.
3. Analysis of policies and mechanisms of EU countries on the introduction of hydrogen energy. Analyze the European Union context and its requirements:
o RED II requirements for renewable energy in transport
o Access to European grant funding schemes
o Touchpoints with European Union and national European hydrogen strategies
o Opportunities from bilateral partnerships with European countries
o Sectoral decarbonization
o Integration of renewable energy
o Energy security</td><td>• MoE
• MENR
• MCTD</td><td>– Ministry for Development of Economy, Trade and Agriculture;
– The Ministry of Infrastructure;
– National Academy of Science of Ukraine;
– The Institute of Renewable Sources of Energy;
– NASU Institute for Economics and Forecasting;
– Industry Professional Organizations</td></tr>
<tr><td rowspan="6">Policies and Strategies</td><td>Sectors</td><td>Document type</td><td rowspan="6">• CoM
• MoE
• MENR
• MCTD
• MoI</td><td rowspan="6">– Ministry for Development of Economy, Trade and Agriculture;
– NEURC;
– SAEE;
– National Gas Transmission System Operator;
– NASU Institute for Economics and Forecasting</td></tr>
<tr><td colspan="2">1.Decarbonization of the economy</td></tr>
<tr><td>1.1. Overall strategy</td><td>1. Development of a National Hydrogen Strategy</td></tr>
<tr><td>1.2. Energy efficiency and saving</td><td>1. Energy Saving and Energy Efficiency Policies</td></tr>
<tr><td>1.3. Renewable Energy Sources (RES)</td><td>1. National Hydrogen Program: Development of the Concept of production and use of “brown”, “grey”, “blue” and "green" hydrogen by 2050 with the involvement of ITA (international technical assistance) projects, specialized associations and scientific institutions;
2. Developing and amending legislation and regulations to ensure the use and extension of the list of alternative energy sources in all sectors of the economy, including the hydrogen value chain; 2035 Energy Strategy update</td></tr>
<tr><td>1.4. Waste Management</td><td>1. Development of the Roadmap for the Circular Economy Principles</td></tr>
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<tr><td colspan="2">2. Decarbonization of the energy sector</td></tr>
<tr><td>2.1. Supply of energy resources</td><td>1. Forecasting of needs for infrastructure development and optimization of existing transportation systems, distribution, storage of hydrogen fuels, electricity, heat.
2. Launch of the Energy Infrastructure Program;
3. Integrated 2021-2030 National Plan on Energy and Climate</td></tr>
<tr><td>2.2. Electricity</td><td>1. Development of Policy on increased share of highly effective cogeneration;
2. Audit of economic feasibility of the policy of increasing the share of highly effective cogeneration and its introduction in the regions of Ukraine</td></tr>
<tr><td colspan="2">3. Decarbonization of the residential and non-residential heating</td></tr>
<tr><td></td><td>1. Development of the Program for large-scale thermal modernization of buildings to achieve specific energy consumption per square meter at the level of the average of the EU countries
2. Development of Local District Heating Plans</td></tr>
<tr><td colspan="2">4. Decarbonization of the industrial process heat</td></tr>
<tr><td></td><td>1. Industry Memorandum 2030
2. Establishing a National Policy for a Transition in the Supply of Process Heat
3. Establishing an Industrial Modernization Policy</td></tr>
<tr><td colspan="2">5. Decarbonization of the transport sector</td></tr>
<tr><td></td><td>1. Action Plan on Improvement of the transport network and public transport routes planning
2. Development of the Plan on use of environment friendly transport and micro mobility in cities;
3. Optimization of the structure of passenger and cargo flow by increasing the share of passenger traffic by public transport, and the share of cargo flow - by rail and water transport
4. Alternative (Renewable) Fuels Action Plan</td></tr>
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<td></td>
<td>Standards, Regulations, Certification and Monitoring</td>
<td>1. Formation of the list of required international (national) technical Standards and requirements in the field of production, transportation, storage and use of hydrogen;
2. Development of new and adjustment of existing national technical standards and requirements with their further harmonization with international and</td>
<td>• MoE
• MENR
• MCTD
• SAEE</td>
<td>– Ministry for Development of Economy, Trade and Agriculture;
– The Ministry of infrastructure;</td>
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</table>

		European standards and requirements in the field of production, transportation, storage and use of hydrogen[26]; 3. Implementation of the National Emission Monitoring, Reporting and Verification System; 4. Development of emissions standards for coal power plants; 5. Development of fuel economy standards for vehicles; 6. Hydrogen power generation regulations as a power supply and backup power source required for expanding renewable energy; 7. Development and implementing of the National System of technical regulation on "green" construction; 8. Development of the technical standards for improving the efficiency of individual heating and air conditioning of buildings, substitution of carbon-intensive energy resources (coal, gas) by environmentally friendly ones – electric and thermal energy from renewable sources (solar, wind, geothermal energy, biofuels); 9. Monitoring compliance of the advancing hydrogen technologies with operational safety standards of the power system of Ukraine; 10. Standardization and certification of equipment for the production of hydrogen, equipment that uses hydrogen or works on hydrogen, in particular: standards for the share of hydrogen, safe use of mixtures with hydrogen, the use of GTS; international, long-distance transport, etc.; 11. Development of a mechanism to monitor the key performance indicators implementation to address climate change and reduce greenhouse gas emissions across all sectors of the economy		– Ukrainian Research and Training Center of Standardization, Certification and Quality; – Technical committees for standardization; – National Academy of Science of Ukraine; – National Aviation University; – Kyiv Polytechnical Institute; – Industry Professional Associations
ECONOMIC MEASURES	**State mechanisms to support measures and projects for the hydrogen production and use of hydrogen technologies**	1. Development of mechanisms of state support for hydrogen technologies and relevant legislation; 2. Development of proposals for equipment mass production, including feasibility studies and technical documentation; 3. Launch of the pilot projects of energy facilities based on hydrogen and RES, analysis of their effectiveness and recommendations for further development of hydrogen energy; 4. Promotion of technological development and cooperation with relevant organizations; 5. Development of Concept for the economically affordable, environment and climate friendly energy sectors to avoid a price shock for consumers, socio-economic and political resistance; 6. Development of mechanisms for protecting vulnerable consumers: targeted social support for certain categories of such consumers. Any benefits and subsidies must be monetized, and charges should be made based on the cost of energy resources (including taxes and fees);	• MoE • MENR • MCTD • MoF • SAEE	– The Ministry for Development of Economy, Trade and Agriculture; – The Ministry of infrastructure; – National Academy of Science of Ukraine; – The Institute of Renewable Energy Sources – NASU Institute for Economics and Forecasting

[26] see **ANNEX 4** for the list of current regulations related to hydrogen in Ukraine

		7. Perform the audit of existing programs to support socio-economic development and economic diversification in order to create new financing mechanisms; 8. Development of a Sustainable Procurement Program; 9. Decisions on optimal mechanisms of state support for hydrogen technologies and development of relevant acts of legislation; 10. Determining technical potential for hydrogen production, creating appropriate databases and choosing promising technologies and directions for implementation, elaborating various development scenarios and assessing their economic efficiency: - Identify logistic opportunities of Ukraine; - Define relevant domestic applications and associated hydrogen volumes; - Determine hydrogen price ranges (domestic and export); - Identify several most suitable locations for hydrogen production and determine suitable plant sizes; - Identify potential production volumes, resulting hydrogen cost, potential national offtakers accessible from the plant (including usage type and quantity); - Quantify renewable energy (RE) production potential to understand the potential for hydrogen production in Ukraine; - Assess possibilities for hydrogen transport and its cost to suitable domestic offtakers and to customers in the European Union, leveraging in particular the existing gas transport infrastructure; - Analyze opportunities for use of hydrogen in industry: clean transport (road, rail, maritime, aviation), clean chemicals (incl. ammonia production), clean mining industry, manufacturing, construction, agriculture		
	Digitalization of economic processes in energy system	1. Development of the Concept of a fundamentally new technological platform for energy resources; 2. Ensuring cybersecurity and personal and industrial data control with regards to the energy transition	• MoE • MENR • SAEE	– The Ministry of Digital Transformation
	Market development	1. Involvement of international technical assistance (ITA) for the implementation of pilot projects: on production, transportation and demand management of hydrogen from renewable energy sources; 2. Development of a database of potential projects in the area of production and use of "green" hydrogen; 3. Decisions on construction of transport infrastructure, as well as local pilot projects (hydrogen re-fueling stations, scaled-up electrolyzers for renewable hydrogen); 4. Modeling the development and sustainable functioning of energy markets with a high degree of openness and competition, which will stimulate participants to optimize costs, market pricing, and consumers – to rational energy consumption, and the provision of balancing services; 5. Introduction of technology of accumulation of electrical energy at the level of industrial enterprises and ensuring their active participation in the market of electrical energy;	• MoE • MENR • MCTD • SAEE • AMC	– The Ministry for Development of Economy, Trade and Agriculture; – The Ministry of infrastructure

		6. Conducting preliminary consultations and negotiations on diversification of sources of supplies of equipment for hydrogen technologies in Ukraine and its export to foreign markets; 7. Development of legislative incentives for investments into infrastructure and economics improvement of systems of production, supply and usage of hydrogen; 8. Organization and participation in activities aimed at promoting the development of hydrogen production and use, raising awareness of local authorities about the benefits and prospects of its use. Conducting preliminary consultations and negotiations with international partners on diversification of sources of supplies of equipment for hydrogen technologies in Ukraine and its export to foreign markets.		
	Economic incentives	1. Foster domestic applications, e.g. in transport and heating; intellectual property protection in hydrogen technologies; 2. Development of methods for strengthening the role of consumers in terms of their active participation in the market, in particular in the activities of electricity production, -development of the concept and implementation of legislative initiatives on coal, non-digitalization of international and transparent access in third parties to the energy infrastructure (electricity, gas networks and storage facilities), which should be significantly modernized; 3. Creation of incentives for the introduction of innovations in energy-efficient technologies, including measures for electrification of industrial processes; 4. Development of the use of technologies that will improve the efficiency of heat supply systems, including the use of highly efficient cogeneration and trigeneration. New cogeneration plants for centralized heating should, in particular, focus on the use of biomass and biogas as well as hydrogen technologies	• MoE • MoF • MCTD • SAEE • NEURC	– The Ministry for Development of Economy, Trade and Agriculture; – The Ministry of infrastructure
SUPPORT FOR R&D	**Increasing the share of scientific research in the climate sphere**	1. Support for the integration into existing research projects, creation of consortiums (e.g., long-term EU programs, USA, Japan, etc.); 2. Support for the interaction of Ukrainian scientists with the leading scientific institutions of the world; 3. Construction of research installations using renewable energy sources (wind & solar power plants, other sources of electrical and thermal energy) and installations for hydrogen production, processing of co-production technology	National Academy of Science of Ukraine	– MoE – SAEE
	Strengthening and deepening cooperation between science, policy makers and business	1. Identification of areas for action to overcome potential hurdles; 2. Creation of mechanisms for the development of internal potential of innovative energy technologies and equipment; 3. Creation of the Concept of systematic integration of education, science and business. Such integration is critical for sustainable personnel, financial and technological support of innovation activities in energy and energy engineering, will contribute to the emergence of innovative and production clusters, improve employment, especially among young people; 4. Development of a framework to attract sustainable investments as well as to support green technologies for a fair transition to a green economy including a public-private partnership policy to ensure the development of innovative green technologies.	• MoE • National Academy of Science of Ukraine	– SAEE

PUBLIC AWARENESS		1. Public awareness campaign on the safety of hydrogen and the significance benefits of hydrogen use is shared among citizens; 2. Changes in the approach in government communications from traditional information campaigns "for all" to the target approach aimed at "agents of change" – market players, investors, active consumers, local self-government organizations; 3. Launch of public consultations in the form of Energy Dialogue and findings from this dialogue presented in Energy Policy Agenda. The society-wide Energy Agreement for Sustainable Growth should be concluded with industries, non-governmental organizations and municipal governments as a major first step	• MoE • MCTD • Local Authorities	– SAEE

Second phase (2024-2026):

policies prioritization, hydrogen market and supply chain development and demonstration, scale-up

Policy selection criteria include emission abatement potential, cost and other considerations. Above all else, policies should be prioritized based on their potential to reduce greenhouse gas emissions, because this is the primary goal of climate policy. After this, the economic impact of a particular policy is the most important criterion to consider. It’s important to consider two types of impacts: direct economic and macroeconomic. Other considerations: political feasibility, energy security, public health and other co-benefits, social equity, CO2-free hydrogen (brown coal combined with CCS, utilizing renewable energy).

		Document type	Responsible Agency	Partner Agency
I	II	III	IV	V
LEGISLATION	**Identification of necessary legislative changes in the field of hydrogen technologies**	1. Development of normative/legal acts in the field of production and use of renewable hydrogen; 2. Inclusion of provisions on the production and use of "green" hydrogen in the development and/or revision of strategic state documents and initiatives in the field of energy, energy efficiency (including buildings and structures) and climate, taking into account the provisions of the Hydrogen Program; 3. Identification of required normative/legal acts on transport, use of airspace of Ukraine, roads and ports taking into account the provisions of the Hydrogen Program; 4. Development of regulations on transportation safety, merchant navigation and navigation and hydrographic support of ships with regards to the goals for the development of hydrogen technologies according to the Hydrogen Program; 5. Development and adoption of legislation and market rules for new players on the energy market: pro-sumers (consumer producers), energy cooperatives, aggregators, condominiums management and others	• MoE • MoI • MoF • MCTD • SAEE • NEURC	– The Ministry for Development of Economy, Trade and Agriculture; – The Ministry of infrastructure; – National Academy of Science of Ukraine; – The Institute of Renewable Sources of Energy; – Industry Professional Organizations; – NASU Institute for Economics and Forecasting
	Policies and Strategies	<table><tr><th>Sectors</th><th>Document type</th></tr><tr><td colspan="2">***1.Decarbonization of the economy*** 1. Development and approval of the National Environmental Action Strategy 2. Development and approval of the Fair Transition Strategy, which should combine both overcoming negative socio-economic consequences and investing in creating new opportunities, primarily in small and medium-sized enterprises (including startups and new businesses) that contribute to the diversification of the local economy.</td></tr><tr><td>*1.2. Renewable Energy Sources (RES)*</td><td>1. 2035 Energy Strategy update; 2. Development and Adoption of Mayors Agreement and the transition of cities to 100% RES; 3. Developing the Policy of increasing the share of independent players in the energy markets of Ukraine, including foreign ones.</td></tr><tr><td>*1.3. Waste Management*</td><td>1. Adoption of the Policy on the different types of waste disposal (e.g., the recycling of waste in landfills, agricultural waste and forestry);</td></tr></table>	• CoM • MoE • MENR • MCTD • MoI	– Local municipalities; – The Ministry for Development of Economy, Trade and Agriculture; – SAEE; – NEURC; – Association of Energy Efficient Cities of Ukraine; – Industry Professional Associations; – National Gas Transmission System Operator;

			2. Adoption of Circular Economy Action Plan which will boost the re-use of valuable materials in waste and improve the way municipal and packaging waste is managed thus making the circular economy a reality. It further will strengthen the "waste hierarchy" by placing prevention, re-use and recycling clearly above landfilling and incineration.		– The Anti-Monopoly Committee
		2**. *Decarbonization of the energy sector***			
		2.1. Supply of energy resources	1. Development of the Principles of Application of power-to-gas technology, which can create a scaled-up industry of hydrogen production and other low-carbon gases for the needs of the power system (accumulation of energy, displacement of peaks of production and consumption) and/or transport; 2. Development of Modernization Policy for the main network and distribution networks, localization of energy supply, etc.; 3. Adoption of plans (schemes) for the development of local power systems and other use of hydrogen technologies, regional programs for proper modernization of municipal thermal power; 4. Development and implementation of policies and measures aimed at improving the efficiency of energy resources and energy saving with improvement of the quality of energy services and supply of energy resources; 5. Development and implementation of the Policy of integration of Ukraine's energy markets with European ones, in particular the synchronization of the United Power Systems (UPS) of Ukraine with ENTSO-E[27]; 6. Development of the Program for hydrogen usage in the energy sector for the gradual replacement of nuclear power plants and coal-fired thermal power plants.		
		2.2. Electricity	1. Introduction of Principles for new generating capacities for hydrogen and/or synthetic gas produced through RES; 2. Development of the Principles for solar and wind generation, biomass power plants in conjunction with the introduction of new generation capacities – in particular, natural gas and biogas, technologies of accumulating and		

[27] Agreement on the conditions for the future unification of the UESI with ENTSO-E, which came into force on July 7, 2017, has to be readjusted in terms of phases syncronization

			storing electricity for balancing in the power system and possibly new technologies of nuclear energy			
		1.3. Heat supply	1. Introduction of Government Program for development of effective district heating systems; 2. Under conditions of economic feasibility, in some regional communities, partial transition to the use of decentralized systems and electrification of heating			
		3. Decarbonization of residential and non-residential heating				
			1. Introduction of National and Municipal Programs of energy accumulation technologies development at the domestic level (hydrogen technologies); 2. Programs for development of centralized heating, air conditioning and hot water supply systems, especially in cities, based on renewable energy sources; 3. Development of the Transition Policy to cover biomass or hydrogen technologies in the boiler systems in public and private buildings			
		4. Decarbonization of industrial process heat				
			1. The Policy on Large-scale use of renewable energy sources (biofuels and waste, electrical and thermal energy from RES) in industrial processes for the replacement of carbon-related resources; 2. Adoption of the Strategy on the increase in industrial production and use of hydrogen, other synthetic energy resources produced from RES			
		5. Decarbonization of transport sector				
			Introduction of the intermodal freight transport technologies;			

	Standards, Regulations, Certification and Monitoring	1. Development of new and adjustment of existing national technical standards and requirements for the design of hydrogen infrastructure objects; 2. Introduction of the Standards for gas mixtures; 3. Standardization and certification of equipment for the production of hydrogen, equipment that uses hydrogen or works on hydrogen, in particular: - standards for the share of hydrogen, safe use of mixtures with hydrogen, the use on international, long-distance transport, etc.; - fuel stations for hydrogen electric vehicles; - production and use of fuel cells that operate on hydrogen; - hydrogen electric vehicles. 4. Development of Standards for construction of new energy efficient buildings - "passive houses", buildings with close to zero energy consumption.	• MoE • SAEE • MENR • MCTD	– The Ministry for Development of Economy, Trade and Agriculture; – The Ministry of infrastructure; – Ukrainian Research and Training Center of Standardizatio, Certification and Quality; – National Academy of Science of Ukraine; – Industry Professional Organizations
ECONOMIC MEASURES	**State mechanisms to support measures and projects for the hydrogen production and use of hydrogen technologies**	1. Implementation of stimulation measures for the entire hydrogen supply chain (equipment manufacturers, infrastructure operators, users). Stable and supportive policies to encourage private investments. Complete exploitation of renewable sources with hydrogen production facilities should be facilitated by implementation of certification for hydrogen from renewable energy; 2. Development of the New reform for the social assistance system in the energy sector; 3. In the medium term, renewable energy support schemes will include determining the cost of generating electricity/heat/cold on a competitive basis and moving from monetary support (preferential prices and/or tariffs) to other forms (e.g., preferential connectivity, priority access to networks, etc.). By 2050, renewable energy should become a major source of energy without the need for any support; 4. Targeted energy efficiency programs and energy efficiency fund products will be improved and extended, including simplification and greater differentiation for scaling up projects of comprehensive thermal modernization of both multifamily anď individual houses; 5. Gradual minimization of state subsidization of fossil fuels. assistance on fossil fuels; energy decarbonization measures and/or measures that will contribute to the achievement of strategic goalš on ensuring energy security and achieving Ukraine's energy independence, with a mandatory assessment of compliance with the legislation of Ukraine and the EU principles. The approach to the use of State aid for fossil fuels should be developed in the medium term, in particular by determining the relevant criteria by the Cabinet of Ministers of Ukraine; 6. In the form of direct subsidiesˇ and fiscal incentives, there should be a promotion of the energy efficiency in buildings (in particular, public),"green" transport, research developments, support for export of services, etc. Some funds and programs will be introduced to co-finance municipal energy transition initiatives, in particular within the framework of the Mayors Agreement. All	• CoM • MoE • SAEE • MENR • MCTD • MoF	– The Ministry for Development of Economy, Trade and Agriculture; – The Ministry of infrastructure; – National Academy of Science of Ukraine; – The Institute of Renewable Energy Sources

		programs and projects where budget funding is envisaged must necessarily provide for performance indicators and independent verification of results; 7. Creation and implementation of public-private partnership support programs, stimulation of investments in the field of infrastructure development for the production and use of hydrogen; 8. Developing International Technical Assistance Plan for the implementation of the pilot projects		
	Digitalization of economic processes in energy system	1. Development of the Concept for the implementation of Smart Grids in Ukraine for the period up to 2035; 2. Introduction and use of modern technologies related to demand management, distributed generation and accumulation of renewable energy	• MoE • NEURC • SAEE	– The Ministry of Digital Transformation – Transmission system operator; – Distribution system operator
	Market development	1. Launch of commercial implementation of hydrogen technologies in transport. Construction of local (regional) pilot transport networks, including the purchase of vehicle fleet and construction of re-fueling stations and their technical maintenance; 2. Strategic hydrogen stations development project, regulatory reform, technological development; 3. Approbation of pilot projects in the gas industry using hydrogen as an additional component	• MoE • MoI • SAEE • MENR • MCTD	– The Ministry for Development of Economy, Trade and Agriculture; – National Academy of Science; – NASU Institute for Economics and Forecasting
	Economic incentives	1. Introduction of specific instruments at the legislative level for risky investments into infrastructure and improvement of the economics of hydrogen supply chain systems. Specifically, access to income of the energy and carbon markets as an important element in achieving bank adaptability of infrastructure investments in the middle-term horizon, which correspond to the long-term vision of the role of hydrogen and implementation of flexible pricing systems; 2. Implementation of effective mechanisms for managing consumer demand; 3. Development of a system to stimulate the introduction of new technologies of geothermal energy, heat pumps, etc.; 4. Stimulating the development and use of carbon capture, storage and utilization technology at large burning facilities, in order to comply with Ukraine's international obligations and improve the energy efficiency of the economy; 5. Advanced training and professional reorientation of workers, employment and technical assistance programs	• MoE • MoF • MENR • MCTD • SAEE	– The Ministry for Development of Economy, Trade and Agriculture; – The Ministry of infrastructure

SUPPORT FOR R&D	**Increasing the share of scientific research in the climate sphere**	1. Ensuring appropriate support at the state level of scientific research in the field of finding ways, technology˘, methods, means in the field of combating climate change; 2. State funding for research and innovation˘ should gradually grow and be based on competitive principles with the simultaneous introduction of an effective system for assessing the effectiveness of the use of funds; 3. Special programs to support startups and scientific projects. Particular attention will be paid to young scientists whose research contributes to achieving the goals of the Hydrogen Program	• National Academy of Science of Ukraine	– MoE – SAEE
	Strengthening and deepening cooperation between science, policymakers and business	1. Innovations is a key driver for the energy transformation. Introduction of Innovative solutions to make the power system more flexible, allowing for a higher, cost-effective use of renewables (see ANNEX 3 of the current Report for details); 2. Encouraging the cooperation of business and research institutions will take place both by changing the mechanisms of public-private partnership, as well as the continuation of the reform of higher education, since the main research centers, around which complexes of technological entrepreneurship can be created, will be universities and other institutions of higher education	• National Academy of Science of Ukraine	– MoE – SAEE
PUBLIC AWARENESS		1. Conduct extensive awareness raising program at the level of local communities, since the "green" transition should create incentives for efficient and responsible energy participation in the production/consumption of energy at the local level, mechanisms for demand management, as well as stimulate the development of new forms and types of economic activities related to the implementation of the Roadmap	• CoM • MoE • Local Authorities	– The Ministry of Culture and information policy

Third phase (2027-2029):

put together a Smart Portfolio of Policies and Strategic hydrogen projects development, regulatory reform, technological development

		Document type		Responsible Agency	Partner Agency
I	II	III		IV	V
LEGISLATION	**Policies and Strategies**	**Sectors**	**Document type**	• CoM • MoE • MENR • MoF • MoI • MCTD	– The Ministry for Development of Economy, Trade and Agriculture; – SAEE; – NEURC; – National Academy of Science of Ukraine; – The Institute of Renewable Sources of Energy; – Industry Professional Organizations; – NASU Institute for Economics and Forecasting
		1.Decarbonization of the economy 1. Search for ways to further use the material and technical base and property of decommissioned enterprises during the transformation of the respective regions; 2. Development and implementation of respective emission reduction plans for major polluting cities			
		1.2. Renewable Energy Sources (RES)	1. 2035 Energy Strategy update; 2. Development of policies and principles of integration of sectors (sector coupling) of electricity, heat supply and air conditioning, transport, industry and agriculture		
		1.3. Waste Management	1. Further development of a framework legislation for waste management		
		2.1. Supply of energy resources	1. Changing the structure of Ukraine's economy: the Program of gradual "green" transition and replacement of the share of extractive industries in the economy with new sectors, Increasing the use of RES which will cause a reduction in the need for traditional fossil fuels and the curtailment of certain extractive industries, primarily the coal sector; 2. Utility business model reform		
		2. Decarbonization of the industrial process heat	1. Industrial process emission Policies: livestock measures, prevent methane leaks from natural gas and petroleum systems, cement clinker substitution, cropland and fertilizer management, preventing methane leaks from landfills, eliminating refrigerants with high global warming potential, controlling methane leaks from coal mining, reducing methane emissions from wastewater treatment, reducing metallurgical coke production for iron and steel; 2. Carbon pricing policies;		

			3. Policies to promote industrial energy efficiency (1) equipment standards, (2) education and technical assistance, (3) financial incentives, (4) mandatory targets		
		3. Decarbonization of the transport sector	1. The Program for modernization and increasing the number of the river ports; 2. Hydrogen and electric vehicle promoting policies; 3. The Program for maximum re-equipment of the fleet of vehicles with internal combustion engines for electric, hydrogen vehicles and cars on fuel cells or others that meet the criteria for sustainability and environmental friendliness; 4. The Program for maximization of the use of biofuels, biomethane and other carbon-neutral fuels, primarily in the field of public transport; 5. Urban mobility policies, such as parking restrictions (congestions charges)		
	Standards, Regulations, Certification and Monitoring	1. Renewable portfolio standards; 2. Vehicle performance standards; 3. Vehicle feebates; 4. Building codes and appliance standards; 5. Encouraging adoption of Energy Management systems; 6. Ensuring digital standardization and certification in the field of production and use of "green" hydrogen, taking into account European standards and norms; 7. Improvement/implementation of the system of collection, systematization and publication of statistical information on hydrogen technologies, emissions monitoring		• MoE • MoF • SAEE • MENR • MCTD	– The Ministry for Development of Economy, Trade and Agriculture; – The Ministry of infrastructure; – National Academy of Science of Ukraine
ECONOMIC MEASURES	**State mechanisms to support measures and projects for the hydrogen production and use of hydrogen technologies**	1. Organization of industrial production of equipment for hydrogen production; 2. Implementation of renewable electric power at the level of up to 25% of the total generation with parallel provision of shunting capacities according to the “electrolysis-hydrogen-fuel cells” scheme; 3. Deployment of large-scale demonstration projects of energy production from hydrogen with the construction of a combined heat and power (CHP) plant on fuel cells; 4. Development and launch of a pilot project for decarbonization of the gas transmission system; 5. Replacement of natural gas by hydrogen in municipal utilities up to 10%; 6. Ukraine's access to Blue Danube Initiative		• MoE • SAEE • MCTD • Local authorities	– The Ministry for Development of Economy, Trade and Agriculture; – The Ministry of infrastructure; – National Academy of Science of Ukraine; – The Institute of Renewable Energy Sources

				– Technical committees for standardization
	Digitalization of economic processes in energy system	1. Development of measures for the implementation of smart energy grids in Ukraine (ensuring cybersecurity of smart energy grids)	• MoE • NEURC • SAEE	– The Ministry of Digital Transformation – Transmission system operator; – Distribution system operator
	Market development	1. Organization of a national network of gas refueling stations for hydrogen vehicles with a centralized supply of hydrogen, capable of providing up to 10% of transportations, including up to 15% of passenger traffic; 2. Developing international hydrogen supply chains and domestic Power-to-Gas for renewable hydrogen supply; 3. Creation of integrated networks of waste disposal and disposal facilities, which will enable the state or region to ensure the and disposal of their own waste; 4. Transition to a sustainable cycle economy model, in which the volume of products, materials and resources is used as long as possible, and waste formation is minimized	• MoE • SAEE • MCTD • Local authorities	– The Ministry for Development of Economy, Trade and Agriculture; – The Ministry of infrastructure
	Economic incentives	1. Developing tools for the introduction of "green public procurement" criteria; 2. Review and improvement of mechanisms of social protection of consumers: free access to consultations and information on energy efficiency, preferential lending and/or subsidies to replace inefficient energy consumption devices, consumer protection, including the introduction of the Energy Ombudsman Institute; 3. Conducting a large-scale thermo-modernization of state-funded institutions and organizations and mandatory public procurement, taking into account the criterion in energy efficiency and environmental friendliness ("green" procurement), which will provide an example of high priority of these measures for Ukraine; 4. Funds, saved as a result of energy efficiency measures, such as thermal modernization of educational or healthcare institutions, should be directed to support the development of education and public health. This will have a stimulating effect and support the interest of local communities.	• MoE • MoF • SAEE • Local authorities	– The Ministry of Economy; – The Ministry for Communities and Territories Development; – The Ministry of infrastructure
SUPPORT FOR R&D	**Increasing the share of scientific research in the climate sphere**	1. Sequence in scientific researches on the development and certification of national equipment.	• National Academy of Science of Ukraine	– Private businesses

PUBLIC AWARENESS		1. The key focus of communications, along with strengthening the role of consumers, should be the effect of economic growth and improvement of the welfare of citizens - in particular, opportunities for employment, development of entrepreneurship	• MoE • SAEE • Local Authorities	– The Ministry of Culture and information policy

6.2. Actions and measures at the oblast and municipal level

The development of local hydrogen supply chains is crucial to the Ukrainian economy for several reasons:

- an affordable, reliable and sustainable energy supply is a key factor that may influence the decisions of companies on where to locate and is needed to help energy-intensive industries located in the regions of Ukraine to become more sustainable. The Ukrainian economy has a large percentage of energy-intensive industries. In order to retain these kinds of industries in the regions, it is crucial that companies should be able to purchase zero-carbon energy carriers at internationally competitive prices;
- the development of hydrogen supply chains in the regions of Ukraine will lead to opportunities for Ukrainian companies and knowledge institutions, which will also benefit employment. Ukraine had a large number of companies in the manufacturing industry, which have the potential to grow into key players in the development of regional and international hydrogen supply chains based on their knowledge in fields, such as industrial gases, advanced materials and chemical processes. Ukrainian local municipal authorities have to develop the maps of the potential position of the local manufacturing industry in the area of hydrogen to identify the potential companies with operations in the hydrogen sector. A strong cluster of companies should be formed in each region to operate in the field of hydrogen technology in the vicinity to the main ports and gas transportation system hubs;
- specifically, with regard to ports and the Ports of Odessa, Mykolaiv and Kherson regions in particular, retaining the current hub function within international energy flows is crucial from a strategic perspective. Hydrogen has the potential to become a globally traded commodity. Given the significant expected demand for sustainable hydrogen in industry in Europe, it would therefore be highly advantageous for Ukraine to become the linchpin in that supply chain and to use existing regional infrastructure for that purpose.

Regions across the country should be developing hydrogen clusters, cooperating internationally with such organizations as the Fuel Cells and Hydrogen Joint Undertaking of the EU. Odessa region is already forming the first Hydrogen Valley in Ukraine cooperating with Danube Hydrogen Valley company in the frame of the 2x40GW Electrolizers Initiative. An integrated approach is also being developed in regions, such as Kherson, Zaporizhzhia and Dnipropetrovsk.

On a smaller scale, various groups of stakeholders – municipalities, small and medium businesses, citizens, system network operators, agricultural establishments, among others, should be working on innovative hydrogen applications. These efforts will have economic opportunities linked to local sustainability strategies. The local governments should develop these initiatives and use them as an essential part of how it is intended to shape the energy transition together with the central government in the years to come.

6.3. Identification of pilot projects

Development of a project proposal for technical assistance to support legislative reforms and attracting direct investments and other financing for a hydrogen economy.

Project proposal 1 – Development of the hydrogen strategy of Ukraine.

The overall objective of the project is to support the implementation of reforms in Ukraine's energy sector in line with the EU acquis for energy and taking into account the provisions of the EU Hydrogen Strategy. The main activities will be focused on building up a sustainable case for use of hydrogen in transmission, storage, distribution and dispensing.

<u>The project activities will be designed to develop the hydrogen strategy of Ukraine, which should inter alias include:</u>

- Overview of EU hydrogen production – volumes, growth, recent changes, new sources & technologies, transportation and mobility, prospects for development;
- Overview of EU regulations and support programs aimed at decarbonization and desulphurization (e.g., CO2-taxes and emission trading schemes like EU-ETS) support carbon-neutral business activities;
- Overview of EU prospective for hydrogen use – recent changes, further developments (methane substitute, energy production etc) and export potential;
- Summary of key strategic priorities in hydrogen development globally, strategic initiatives, opportunities and risks;
- Overview of current power and energy system of Ukraine with gap analysis (shortages/ surpluses), capacity utilization, potential for internal hydrogen use;
- Formulation strategic goals and prerequisites of strategy implementation (what and when should be achieved);
- Analysis of the potential for hydrogen production from nuclear power in Ukraine: global experience and recent developments, projects implemented, production profile (key efficiency and economy indicators, investment cost and feasibility), potential for scaling production in Ukraine (volumes, costs, transportation and consumption);
- Green hydrogen production potential in Ukraine – analysis of green tariff versus hydrogen production economic profile, investment cost and feasibility, key recommendations;
- Overview of other hydrogen production sources: pros and cons, cost of use and construction benchmarking, high level assessment of economic feasibility (blue, grey, turquoise other);
- Summary of key finding outlining: the benefits for Ukraine from the hydrogen production; application and profile of technologies to be used for hydrogen production; investment cost and profitability; potential consumers of hydrogen; a list of pilot projects including the profile of potential investor; the scope of governmental support.
- Development of roadmap and action plan for implementation of the hydrogen strategy.

Indicative budget and duration: EUR 2 million, duration 24 month.

Implementation modality: Service contract/ international open tender.

Project proposal 2 – Analysis of various aspects of introducing hydrogen economy in Ukraine.

The overall objective of the project is to support the implementation of reforms in Ukraine's energy sector in line with the EU acquis for energy and taking into account the provisions of the EU Hydrogen Strategy. The main activities will be focused on building up a sustainable case for use of hydrogen in transmission, storage, distribution and dispensing.

<u>The project activities will be designed to achieve the following results:</u>

- Analysis of investment costs for hydrogen production technologies;
- Analysis of physico-chemical parameters of hydrogen and characteristics of impact on various type of metals used in existing gas pipelines in EU;
- Analysis of marginal ranges of mixing hydrogen with the natural gas for further transit to the EU;

- Analysis of EU practice of mixing the hydrogen and natural gas in case of transfer of significant volume of gas (more than 1 mcm) and its industrial use (technology);
- Principles, methods, and technologies for separating hydrogen from a mixture with natural gas (with examples);
- Assessment of existing legal framework (including regulatory) in EU on hydrogen aiming to identify the areas and ways for improvement of Ukrainian legal framework on the basis of the best EU practices and legislation.

Indicative budget and duration: EUR 1 million, duration 12 months.

Implementation modality: Service contract/ international open tender.

6.4. Implementation of the Roadmap tasks – monitoring and verification

The Roadmap provides for the implementation of a large amount of research and development works, research, development, test and evaluation works, processing of regulatory and technical documentation for pilot industrial construction, the introduction of the most effective projects into industrial operation, as well as the use of standard methods of administrative control by the system of work organization and control of program implementation adopted in the country this level, considering the inter-sectoral nature of some of the Roadmap's tasks.

Organization of work related to the regional aspects of the Roadmap shall be performed by the relevant central and local executive authorities. Their functions and duties are defined by the Energy Strategy of Ukraine. Governmental authorities and national regulatory authorities shall provide:

- keeping the provisions and objectives of the Roadmap while developing regulatory legal acts for regulating activities in the resources market, in hydrogen technologies and related services;
- the balance of interests of the country, natural monopolies and consumers of goods (services);
- displaying of the provisions and objectives of the Roadmap in the implementation requirements for licensed activities in the market of hydrogen technologies and related services.

The Ministry of Energy (MoE) along with **the State Agency for Energy Efficiency and Energy Saving of Ukraine (SAEE)** subordinated to it as an implementation arm should perform overall coordination of the activities provided for by the Roadmap.

The Ministry for Development of Economy, Trade and Agriculture (MDETA) while forming and implementing the state economic policy ensures that the provisions of the Roadmap are considered by means of:

- creation and implementation of support programs to business entities and public-private partnerships;
- coordination of foreign economic policy, determination of priorities of economic cooperation during the dialogue with trade partners;
- improvement of the system of collection, systematization and publication of statistical information on hydrogen technologies;
- coordination of the activities of the national standardization body on the implementation of the national standardization program for the adoption / harmonization / actualization of standards on hydrogen technologies.

The Ministry for Communities and Territories Development (MCTD or Minregion) ensures implementation of the provisions of the Energy Strategy of Ukraine by means of:

- formation and implementation of state policy in heat supply sphere, confirmation of regional programs for modernization of municipal heating system;
- approval of plans (schemes) for the development of local heating system;
- coordination of investment plans of municipal energy companies;
- development of strategic initiatives in the sphere of energy efficiency of buildings and structures.

The Ministry of Ecology and Natural Resources provides (MENR):

- keeping the provisions and objectives of the Roadmap in Ukraine's foreign policy in negotiations, concluding international agreements and Ukraine's participation in international initiatives on climate change and environmental protection;
- keeping the provisions and objectives of the Roadmap in developing of a low-carbon development strategy of Ukraine to implement the provisions of the Paris Agreement;
- ensuring the fulfilment of Ukraine's obligations in achieving the objectives of the Paris Agreement and other international agreements on climate change.

The Ministry of Infrastructure of Ukraine (MIU) will be involved in following tasks as to introduction of hydrogen technologies:

- formulation and implementation of state policy on issues related to transport, the use of Ukrainian airspace, roads and ports;
- formulation and implementation of state policy on issues related to transportation safety, merchant shipping and navigational/hydrographic support for vessels;
- participating, within the limits of our authority, in the formulation and implementation of state tariff policies and public procurement policies in the transportation field;
- the Minister of Infrastructure coordinates with the State Aviation Administration, the National Sea and River Transport Inspection Agency, the National Land Transport Inspection Agency and the National Automotive Road Agency.

Local government authorities ensure the implementation of the Roadmap within their competence, namely:

- development and approval of plans (schemes) for the development of local energy systems and other use of hydrogen technologies, regional programs for the proper modernization of municipal heat power engineering;
- approval of investment plans of municipal energy and transport companies;
- realization of renewable energy potential locally.

Civil society exercises public control over the activities of executive authorities to implement the Roadmap by means of:

- conduct evaluation of projects of regulatory legal acts;
- participate in the work of public councils under the executive authorities who deal with implementation of the energy policy and informing society about the executive authorities' activities on the implementation of the Roadmap.

Supervision from the side of the Ukrainian society can be performed by the NGOs active in the sectors of energy and environmental protection and by professional associations, e.g. Energy Association "Ukrainian Hydrogen Council".

It is advisable to delegate the scientific, technical and information support of the Program to the specialized institutions of **the National Academy of Sciences (NAS),** namely, the **Institute of Renewable Energy of the National Academy of Sciences of Ukraine (IRE of NAS)**, Ukrainian technical committees for standardization.

7. Conclusions and recommendations

Hydrogen is a flexible energy carrier that can be produced from a variety of domestic energy resources and used in all sectors of the economy. An energy system based on domestic energy resources, using hydrogen as a carrier and deployed on a large scale, if accomplished, could improve energy security, air quality, and greenhouse gas management. Such a system will require development across a spectrum of complementary technologies for hydrogen production, transportation, storage, and use. The transition to a hydrogen economy has begun in all developed countries of the world and could take several decades to achieve. Hydrogen energy could play an increasingly important role in Ukraine's energy future, as it has the potential to help reduce dependence on energy carriers imports and lower pollution and greenhouse gas emissions.

Ukrainian central and local governments will need to implement and sustain consistent energy policies that elevate hydrogen as a priority. Strong public-private partnerships will need to focus on finding new ways to collaborate on the development and use of hydrogen energy. A logical next step will be the development of a National Hydrogen Strategy and Programme, which will need to address research, development, testing, outreach, and codes and standards related to the production, delivery, storage, and use of hydrogen.

KEY DRIVERS AFFECTING HYDROGEN TECHNOLOGIES DEVELOPMENT IN UKRAINE

Supportive of further development:

- National security and the need to reduce oil imports;
- Global climate change and the need to reduce and ultimately eliminate greenhouse gas emissions and pollution;
- The need for new, clean energy supplies at affordable prices;
- Air quality and the need to reduce emissions from vehicles and power plants;
- Rapid pace of technology developments supporting hydrogen and competing energy carriers.

Suppressing further development:

- The difficulties in building and sustaining national consensus on long term energy policy priorities;
- Lack of a hydrogen infrastructure and the substantial costs of building one;
- Lack of commercially available, low-cost hydrogen production, storage, and conversion devices;
- Hydrogen safety issues;
- The need for additional demonstrations of carbon sequestration and lower-cost sequestration methods;
- The current availability of relatively low-cost fossil fuels exacerbating the inevitable depletion of these resources;
- Simultaneous consumer preferences for both a clean environment and affordable energy supplies.

Major findings from this study include the following:

1) <u>HYDROGEN PRODUCTION</u>

- **Hydrogen production costs are high relative to conventional fuels.** With most hydrogen currently produced from hydrocarbons, the cost per unit of energy delivered through hydrogen is still higher than the cost of the same unit of energy from the hydrocarbon itself. This is especially the case when the comparison is made at the point of sale to the customer, as delivery costs for hydrogen are also higher than for hydrocarbons. The large-scale, well-developed production and delivery infrastructures for natural gas, oil, coal, and electricity keep energy prices low and set a tough price point for hydrogen to meet.

- **Low demand inhibits development of production capacity**. Although there is a healthy, growing market for hydrogen in refineries and chemical plants, currently there is no demand for hydrogen as an energy carrier. Demand growth will depend on the development and implementation of hydrogen storage and conversion devices, and on a demand pull from products such as hydrogen-powered cars and electric generators. Without demand for high-quality hydrogen in the merchant energy carrier market, there is little incentive for industry to completely develop, optimize, and implement existing and new technologies.
- **Advanced hydrogen production methods need development.** While wind, solar, and geothermal resources can produce hydrogen electrolytically, and biomass can produce hydrogen directly, other advanced methods (i.e. pyrolysis) for producing hydrogen from renewable and sustainable energy sources without generating carbon dioxide are still in early research and development phases. Renewable technologies such as solar, wind, and geothermal need further development for hydrogen production to be more cost-competitive from these sources.
- **Public-private partnership production demonstrations are essential**. Stakeholders need a basic understanding of the different sources of hydrogen production before they will be willing to embrace the concepts. Demonstrations are the best way to gain the needed confidence. The large scale of some production processes, however, makes them particularly difficult and expensive to demonstrate.

Recommendations

- **Research, development, and demonstrations are needed to improve and expand methods of economically producing hydrogen**. Production costs need to be lowered, efficiency improved, and carbon sequestration techniques developed. Better techniques are needed for both central-station and distributed hydrogen production. Efforts should focus on electrolyzers. The specific needs and actions required differ for each of the hydrogen production technologies. Various combinations of the production technologies are likely to be used for different applications.
- **Enact policies that foster both technology and market development**. Government support for research and development should focus on developing advanced renewable and low-carbon-emitting methods plus carbon dioxide capture and sequestration technologies. Improve gas separation and purification processes.
- **Develop and demonstrate small hydrogen plant based on renewable energy sources with electrolyzer**. The technology also needs further refinement for improved reliability and integration with storage systems and fuel cells. Optimize and reduce costs of electrolyzers. Efforts to improve the efficiency and lower the costs of electrolyzers must continue, as this production method is ideal for distributed generation and could offer early market opportunities. Although electrolysis is currently more expensive than thermal production, a better understanding of high temperature and high-pressure electrolysis could bring costs down. In distributed hydrogen systems, the hydrogen produced on-site often requires compression (to pressures as high as 5,000 psi) for storage; high-pressure electrolysis could remove the need for this additional compression. A near-term study should be conducted to develop measurable goals for electrolysis in terms of production efficiency, capital cost, and price. Specific goals will help to align and focus development efforts. Develop advanced renewable energy methods that do not emit carbon dioxide.
- **Develop advanced nuclear energy methods to produce hydrogen**. Research is needed to identify and develop methods for economically producing hydrogen with nuclear energy, which would avoid carbon emissions. Thermochemical water splitting using high-temperature heat from advanced nuclear reactors could be included in future nuclear plant designs.
- **Develop methods for large-scale carbon dioxide capture and sequestration**. A cost-effective way to capture and sequester carbon dioxide would facilitate the production of vast quantities of hydrogen with low carbon emissions. Demonstrate production technologies in

tandem with applications. Demonstrations are expensive, especially since there may be little initial demand for the hydrogen produced. Demonstrations that integrate production technology with other elements of the hydrogen infrastructure, including a market use, will be more cost effective. These demonstrations should highlight safety and other benefits to stimulate market interest. Demonstrations of hydrogen generation, purification, storage, dispensing, and fuel cell electricity generation should be pursued in the short term in major metropolitan areas. For technologies that need larger-scale testing and demonstration, an industrial-scale testing location should be developed to alleviate difficulties in finding acceptable sites;

2) HYDROGEN DELIVERY

Current delivery systems will need to expand significantly to deliver hydrogen to all regions of the country in a safe and affordable manner. Distributed hydrogen production is likely to play a significant role, but alternative delivery systems tailored to consumer applications (such as the transport of hydrogen in safe, solid metal alloy hydrides, carbon nanomaterials, and other chemical forms) need to be developed to transport hydrogen to end-use sites on an as-needed basis.

Recommendations

- **Develop a demonstration rollout plan**. A hydrogen delivery infrastructure needs to be started in several regions of Ukraine. Government-sponsored pilot testing of refueling systems, similar to those for compressed natural gas, would help establish a basis for certifying components of fuel stations. Demonstration programs would stimulate development of delivery and end-use technologies. Regional delivery networks in a number of states would be a good approach to build out the systems.
- **Develop a consensus view on total costs of delivery alternatives**. Analyses of the total costs of delivery alternatives need to be conducted. Analyses should weigh options that address all potential fuel delivery points, the cost of maintaining existing fuel infrastructure, and the suitability of the existing infrastructure for future hydrogen use.
- **Increase research and development on delivery systems**. Improvements are needed in areas such as hydrogen detectors; odorization; materials selection for pipelines, seals, and valves; and transportation containers for hydrogen. Technology validation should address research and development needs for fueling components such as high pressure, breakaway hoses; hydrogen sensors; compressors; on-site hydrogen generation systems; and robotic fuelers. Researchers need to test the feasibility of delivery methods from centralized and distributed hydrogen production plants as well as compressors, storage systems, and other components integrated into complete delivery systems. Testing and validation should be ongoing. An organization should be established to perform testing and certification and to identify components that require validation and testing protocols. The organization should include representatives of insurance companies, government agencies, National Laboratories, and industry;

3) HYDROGEN STORAGE

The lack of low-cost and lightweight storage devices as well as commercially available and cost-competitive fuel cells interferes with the implementation of hydrogen as an energy carrier. For a “hydrogen economy” to evolve, consumers will need to have convenient access to hydrogen, and storage devices will be one of the keys. Better hydrogen storage systems will offer easy access to hydrogen for vehicles, distributed energy facilities, or central station power plants.

Recommendations

- **Develop a coordinated national programme to advance hydrogen storage materials.** A fully funded national program is needed to improve the performance and reduce the cost of hydrogen storage. Advanced storage materials that show promise for hydrogen storage include alanates, carbon structures, chemical hydrides, and metal hydrides. Storage technologies are integral to the production, transport, delivery, and application of hydrogen as an energy carrier

- **Initiate a program to support development of high-risk technologies.** None of the currently known technologies satisfy all the desired hydrogen storage attributes sought by manufacturers and end users. Each has its advantages and disadvantages.
- **Develop a mass production process for hydrogen storage media**. Currently, no market force is driving efforts to reduce raw material costs and develop efficient mass production processes. Even the more mature compressed and liquid hydrogen storage technologies are expensive due to an absence of high-volume demand. Emerging technologies still in the laboratory, including hydrides, alanates, and carbon adsorption materials, have further to go along the path to commercialization and mass production. Fundamental improvements in hydrogen storage processes remain to be fully understood and optimized. Once the materials have been optimized in the laboratory, practical integrated storage systems must be developed and demonstrated. At that point, design and scale-up for production and cost must be addressed.

4) FUEL CELLS

Engines, combustion turbines, and fuel cells can convert hydrogen into useful forms of energy. Research and development are needed to lower costs and enhance manufacturing capabilities for fuel cells and to develop higher-efficiency and lower-cost designs for engines and turbines. Industry should focus its efforts on developing profitable business models for distributed power systems, optimizing fuel cell designs for mobile and stationary applications, and expanding tests of hydrogen-natural gas blends for combustion. Government should assist in developing better information on the fundamental properties of hydrogen combustion and improving fundamental understanding of advanced materials, electrochemistry, and interfaces for fuel cells.

Fuel cells require enhanced materials, membranes, and catalysts to meet both engineering and cost criteria. For all types of fuel cells except phosphoric acid, reliability of performance and durability over extended hours of operation remain to be proven. Phosphoric-acid fuel cells are the only type of fuel cells with substantial commercial experience, but efforts to bring down their manufacturing cost have not yet paid off. Questions also remain about the performance of all types of fuel cells under diverse climatic conditions and geographic locations. Manufacturing scale-up issues and the associated need to establish high-volume demand are major barriers in achieving cost reductions. Research is needed to fill in critical knowledge gaps.

Researchers require better information about the flame characteristics of hydrogen combustion and the impacts of conversion technologies on reciprocating engine and turbine designs. Better knowledge is also needed to guide the use of advanced materials in hydrogen combustion systems. Existing databases need to be populated with more performance data for hydrogen-burning engines and turbines operating over extended periods; performance data needs include efficiency, emissions, and safety, for both mobile and stationary applications. Market and institutional barriers hinder development of cost-competitive hydrogen conversion devices. Customers do not see a robust value proposition that convinces them to choose hydrogen conversion products. Substantial cost reduction will be essential—particularly without a bridging incentive or government mandate fostering use of hydrogen conversion products rather than lower-cost conventional fuels and products. In the absence of such policies, conventional fuels and conversion devices will continue to be the only practical option for consumers. Fuel cell manufacturers also face problems in developing innovative safety technologies and achieving profitable operations prior to the development of large-scale markets.

Recommendations

- **Enhance manufacturing capabilities for fuel cells**. Techniques are needed for handling high fuel cell production volumes and achieving better consistency and quality control. Advancements in this area are one of the surest means to achieving the large cost reductions needed to move fuel cells from niche to mass markets. Improvements are also needed in the cost and integration of balance-of-plant components, such as power conditioning, thermal storage and management, water management, and fuel processing equipment.

- **Collect more and better information on operating performance at existing demonstration sites.** Improved instrumentation and expanded data collection efforts are required to facilitate analysis of the full range of cost, efficiency, and emissions parameters for all mobile and stationary applications under a wider range of environmental conditions. More extensive tests of the reliability and durability of advanced materials are also needed, particularly for polymer-electrolyte membrane and solid-oxide fuel cells. At the same time, better market analysis is needed to provide the financial community with an improved understanding of the potential for fuel cells and hydrogen-using engines and gas turbines.

5) APPLICATIONS

The ultimate aim is to enable consumers to use hydrogen energy devices for transportation, electric power generation in cities and homes, and portable power in electronic devices such as mobile phones and laptop computers. Once the cost and performance issues associated with hydrogen energy systems have been addressed, the next challenges will involve customer awareness and acceptance. Safety, convenience, affordability, and environmental friendliness are key consumer demands. Industry should focus its efforts on understanding consumer preferences and building them into hydrogen system designs and operations. Government should identify opportunities to use hydrogen systems in facilities for distributed generation, combined heat and power, and vehicle fleets.

Fuel applications of hydrogen will need to meet much lower economic cost targets than those for current industrial markets. Since scale is critical to cost reductions, care should be taken to build the necessary scale into all government policy and demonstration programs. Efforts should focus on the development of better components for existing delivery systems, including hydrogen sensors, pipeline materials, compressors, and high-pressure breakaway hoses. Demonstration projects should emphasize testing the hydrogen infrastructure components in applications such as fueling stations and power parks.

Recommendations

- **Conduct research and development to address critical challenges to a hydrogen economy**. Transportation and stationary applications will require development of low-cost and durable fuel cell stacks and systems. Development needs include high temperature membranes for fuel cells; low-cost, fast-response, and low-power consumption sensors and controls; low-cost, reliable, subsystem components such as compressors, pumps, and power electronics; and low-cost, reliable, hybrid batteries and ultra-capacitors. In transportation applications, research should be directed to enable near-term end use of hydrogen prior to the development of a nationwide hydrogen delivery system. Hydrogen storage research for vehicles should focus on systems that have the capability to match the driving range of equivalent gasoline vehicles. Development should focus on systems that are safe, have low weight and small size, and are cost competitive. Storage systems will have to be compatible with the fueling infrastructure, and the safety of storage system designs should be ensured through the development of codes and standards. Combustion strategies and after-treatments must be optimized to maximize power densities and thermal efficiencies while minimizing tailpipe emissions. Challenges in engineering design include developing flow handling and engine management systems for a commercial-ready device. Research is needed to develop better control strategies that will help hydrogen and hydrogen-enriched hydrocarbon fuels gain wider acceptance.
- **For the near term, research is needed to address such issues as durability, cost of the fuel cell stack, system integration, system architecture**. Demonstrations should showcase the near-term availability of multiple alternative technologies for distributed generation power parks. This effort could include the development of hydrogen-based mini economies around an existing hydrogen infrastructure. Conventional conversion devices need to be

demonstrated in stationary, transportation, and hybrid stationary-mobile applications, and should be designed to promote the creation of hydrogen clusters. As the number of demonstration projects grows, so will the hydrogen clusters. This will help jumpstart the creation of the hydrogen infrastructure for both stationery and transportation applications. Relationships should be built and expanded beyond current demonstration activities. Public-private partnerships to demonstrate early vehicles and the associated fueling infrastructure will be necessary to minimize economic risks. Institute regulations, codes and standards to foster customer acceptance of the hydrogen vision. Standard nationwide interconnection agreements are needed to enable connection to the current electrical grid without punitive costs, policies, or actions. Standard agreements and educational materials should be prepared for use by fire, insurance, and building code officials. Develop public policies that encourage use of hydrogen as a fuel. Convincing Ukrainians to use hydrogen applications will require incentives such as cost sharing demonstrations, policies for price parity, and "rights-of-way" for hydrogen infrastructure (similar to those in the natural gas industry). The government should adopt national interconnection standards, require utilities to treat stationary hydrogen customers in a manner similar to others in the same rate class, and ensure that distributed generation options are valued for their ability to utilize waste heat and achieve high efficiencies. Strategies might include development of emissions trading that reaches the small size level, assigning value to externalities via a "carbon tax," or other such measures. Government could also provide incentives for investing in new technologies, such as tax credits for transportation, stationary, and portable hydrogen systems and for hydrogen infrastructure development.

6) EDUCATION AND PUBLIC AWARENESS

Education and outreach on the many benefits of hydrogen is a vital element of this Roadmap. It will require a long term, coordinated commitment by diverse stakeholders to effectively communicate key hydrogen messages to a wide and varied audience. A broad-based education and outreach program — including public relations, media campaigns, demonstration activities, and policy initiatives — must start immediately. Education is an ongoing process impacting all aspects of the hydrogen roadmap and its prospects for success. Specific actions must be taken to overcome the barriers and achieve the vision for a hydrogen economy.

Innovative ideas and creative incentives are needed to prime the population for migration toward a hydrogen economy. Consumers need to feel compelled to learn more about hydrogen and must be clear about how a hydrogen economy can benefit the environment and energy security of the nation. Hydrogen needs to be "branded" and "personalized" for the consumer; safety needs to be stressed.

Recommendations

- **Establish regional, state, and local networks.** Networks should be developed to include code officials, building engineers, energy regulators, and consumers in hydrogen technology demonstrations. These networks should provide public education on installation, codes and standards, and safety issues.
- **Create a broad coalition to influence Ukrainian energy policy on hydrogen**. A hydrogen advocacy coalition could be created to support public policies that encourage the development of hydrogen production, storage, and utilization technologies; the removal of key regulatory and market barriers; the development of education curricula; and the creation of public policies that would make hydrogen an important component of a secure, efficient, and environmentally acceptable energy mix. The coalition could reach out to public and private decision makers regarding the need to implement consistent and sustainable policies and procedures that support hydrogen systems. It could also encourage regional hydrogen initiatives and partnerships, establish packets produced. Other public relations and outreach activities would include: Construction of traveling exhibits on hydrogen; Expansion of online hydrogen

databases and information center; Creation of Internet marketing materials; effective consumer messages, awareness campaigns, and media outreach.

- **Develop a comprehensive public education and outreach program.** Hydrogen needs to get "on the map" and in the minds of consumers. Getting the message out will require a coordinated effort by government, industry, and businesses to develop a broad-based education and outreach program. This program, which should be developed as soon as possible, should include public relations and advertising campaigns. Public spokespersons need to be identified and media briefing
- **Create a public demonstration hydrogen village**. Homebuilders, architects, lending institutions, realtors, technology manufacturers, and related associations should lead an effort to launch a community model or hydrogen village that identifies stakeholders, products, and the infrastructure of a hydrogen economy.
- **Commit resources for long-term education of students at all levels**. Student education is a key component to broadcasting the hydrogen message and developing a knowledgeable, involved hydrogen support network. Without a targeted technology (and applications-level) education program for students and teachers, our past will continue to define our future. Long-term resources should be committed to educate all students. Easy-to-integrate curricula should be developed for kindergarten to grade 12, vocational, four-year engineering, and advanced-degree students. Hydrogen education packages should be created, including lesson plans, videos, demonstration hardware, and experiments to help educate science teachers and their students. Educator training should be made available to all interested teachers through summer workshops and in-service training. Prizes could be offered for college-level engineering theses and projects on vehicle systems, stationary applications, and storage technologies. In addition, a hydrogen fellowship program should be created to encourage interest in the industry at the graduate-level.

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ANNEX 1 - Economic analysis of various hydrogen production methods

Table 1. KPIs Hydrogen production from raw biogas

No.	Parameter	Unit	SoA (State of Art)		Targets		
			2017	2020	2024	2027	2030
SYSTEM*							
1.	System energy use	kWh/kg	56	56	55	54	53
2.	System Capital cost	€/(kg/d)	3800	3100	2400	2000	1550
3.	System operational cost	€/kg	1.35	1.35	1.32	1.30	1.28

*Table 2. KPIs Photocatalytic water splitting**

No.	Parameter	Unit	SoA (State of Art)		Targets		
			2017	2020	2024	2027	2030
SYSTEM*							
1.	H2 production by energy**	kWh/(m2year)	-	30	100	300	500
2.	System cost	€/m2	-	300	210	185	110
3.	System capital cost	€/m2	-	125	40	20	12
4.	System lifetime	years	-	0.3	3	5	10

*photo electrochemical cell
** These values are valid for a global solar irradiance of 2000 kWh/(m2a)

Table 3. KPIs Biological production

No.	Parameter	Unit	SoA (State of Art)		Targets		
			2017	2020	2024	2027	2030
SYSTEM*							
1.	System carbon yield	H2/C	0.62	0.64	0.65		0.65
2.	Reactor production rate	€/m2	10	40	100		200
3.	Reactor scale	€/m2	0.5	1	10		>10

Table 4. KPIs Solar thermal

No.	Parameter	Unit	SoA (State of Art)		Targets		
			2017	2020	2024	2027	2030
SYSTEM*							
1.	Hydrogen production rate	Kg/m2	0.8	1.13	2.16	3.26	4.11
2.	System Capital cost	€/(kg/d)	33.9	29.9	15.2	9.7	7.4
3.	System operational cost	€/kg	1.39	1.17	0.59	0.38	0.30
4.	Hydrogen prod.cost	€/kg		8.42	4.26	2.71	2.07

Table 5. KPIs Hydrogen production via pyrolysis

No.	Parameter	Unit	SoA (State of Art)		Targets		
			2017	2020	2024	2027	2030
SYSTEM*							
1.	Hydrogen conversion rate*, [a, b, c, f, h]	kgH2/kg	0.262	0.29	0.32	0.34	0.355
		%HHV	49	50	52	54	56
2.	System carbon yield**,[c,b,f]	H2/C	0.27	0.28	0.30	0.31	0.32
3.	System capital cost***,[a,b,e,d]	€/(kg/d)	1550	1442	1299	1192	1085
4.	System overall operational cost****	€/kg	1.6	1.5	1.4	1.3	1.2
5.	System operational cost*****	€/kg	0.01	0.01	0.009	0.008	0.008

Table 6. KPIs Hydrogen production via waste/biomass gasification

No.	Parameter	Unit	SoA (State of Art)		Targets		
			2017	2020	2024	2027	2030
1.	System carbon yield**,[g]	H2/C	0.11	0.15	0.22	0.27	0.32
2.	System capital cost***,[g]]	€/(kg/d)	7654	7124	6417	5887	5357
3.	System overall operational cost****[g]	€/kg	4.2	3.9	3.5	3.2	2.9
4.	System operational cost*****[g]	€/kg	0.057	0.053	0.048	0.044	0.040

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Methodology:
* Estimated by linear fitting of the value available in the literature
** For 2017, the carbon yield was estimated as mass ratio based on the outlet composition reported in “Hydrogen from biomass gasification” IEA Bioenergy: Task 33: December 2018. To estimate the expected increase of the carbon yield by 2030 it has been assumed that 50% of conversion would be reached by 2030. This assumption is considered reasonable with respect to the maximum theoretical conversion is 88%. A conversion of 50 % results in a carbon yield of 0.32. Therefore, given the carbon yield estimated for 2017 and the value expected by 2030, the time evolution of the parameter was considered to be linear.
*** Gasification: the capital cost has been estimated from the data reported in “Hydrogen from biomass gasification” IEA Bioenergy: Task 33: December 2018. The capital cost has been estimated as (total investment)/(kgH2/d) considering the lower heating value (LHV) of hydrogen for the 1MW plant. The system capital cost for the 50 MW plant @ 2017 was 1806 €/(kg/d) and @ 2030 it was estimated to be 1200 €/(kg/d). Pyrolysis: capital cost from ref [a] for the plant 2.7 of ton H2/day. The temporal evolution of the capital cost (gasification and pyrolysis) was estimated using a learning curve and assuming a linear doubling of the number of plants by 2030. The "Learning Curve" approach with the doubling of power plants by 2030 shows a reduction of the capital cost of approximately 15%. Moreover, taking into account the breakthrough of new technologies by 2030, an additional 15% of capital cost reduction is expected by 2030, resulting in the overall reduction by 30% by 2030. Therefore, assuming the goal of reaching a reduction by 30% of the capital cost by 2030, a linear reduction from 2017 to 2030 was hypothesized.
**** The overall OPEX was estimated based on the data reported in the “Hydrogen from biomass gasification” IEA Bioenergy: Task 33: December 2018 for the 1 MW plant. The feedstock cost was included in the estimation. The decrease of the OPEX by 2030 was estimated with the same approach used for the capital cost by hypothesizing 30% CAPEX reduction by 2030.
***** The OPEX was estimated considering a plant life of 20 years and including only operation and maintenance costs.

ANNEX 2 - Hydrogen storage technologies

The most important hydrogen storage methods that have been tested over a long period of time include physical storage methods based on compression or cooling or a combination of both (hybrid storage). In addition, a large number of new hydrogen storage technologies are being developed and researched. These technologies can be grouped together by material-based storage technologies. They may include solids, liquids or surfaces.

Liquefied hydrogen. In addition to storing gaseous hydrogen under pressure, it is also possible to store cryogenic hydrogen in a liquid state. Liquid hydrogen (LH_2) is in demand today in areas that require a high level of purity, such as the chip industry. As an energy carrier, LH_2 has a higher energy density than gaseous hydrogen, but it requires liquefaction at -253 °C, which involves a complex technical process and additional economic costs. When storing liquid hydrogen, tanks and storage rooms should be insulated to check for evaporation. Tanks for LH2 are used today mainly in space travel.

Cold and cryocompressed hydrogen. Separate compression and cooling can be combined. The cooled hydrogen is then compressed, which leads to further storage of hydrogen for mobility. The first installations are already working. The advantage of cold or cryogenic compression is a higher energy density compared to compressed hydrogen. However, cooling requires additional energy.

***Material storage of H_2*.** An alternative to physical storage methods is the storage of hydrogen in solids and liquids and on surfaces. Most of these storage methods are still under development. Moreover, the achieved storage densities are still inadequate, and the costs and time associated with charging and unloading hydrogen are too high and/or process costs are too expensive. Material carriers for hydrogen storage can be divided into three classes:

1) hydride storage systems;
2) liquid hydrogen carriers;
3) surface storage systems that remove hydrogen by adsorption.

Hydride storage systems. In metal hydride storage systems, hydrogen forms compounds with metals. Here, molecular hydrogen is first adsorbed on the surface of the metal, and then embedded in the elementary form (H) in a metal lattice with heat output and re-released using heat. Metal hydrides are based on elemental metals such as palladium, magnesium and lanthanum, intermetallic compounds, light metals such as aluminium, or certain alloys. Palladium, for example, can absorb a volume of gaseous hydrogen up to 900 times of its own volume.

Liquid organic hydrogen carriers. Liquid organic hydrogen carriers are another option for hydrogen chemical binding. These are chemical compounds with high water absorption capacity. They currently include, in particular, a carbazole N-ethylcarbazole derivative, as well as toluene.

Surface storage systems (sorbents). Hydrogen can be stored as sorbate by means of attachment (adsorption) on materials with a high specific surface area. Such sorption materials include but not limited to microporous organometallic cage compounds (organometallic bases (MOF)), microporous crystalline aluminosilicates (zeolites), or carbon nanotubes. Adsorbent materials in powder form can acquire high density storage volumes.

Underground storage. When it refers to industrial storage of hydrogen, there can be used salt rooms, depleted oil and gas fields, or water-bearing horizons as underground storage. Although its expensiveness, salt rooms are considered as the most suitable storage for hydrogen. Underground storage facilities have been used for many years for natural gas and oil/oil products in order to balance seasonal demand / supply fluctuations or to prepare for a crisis.

Today the experience of hydrogen storage rooms operating exists in only a few locations in the United States and in Europe. Particularly underground gas storage facilities in Europe and North America can be used as large reservoirs for hydrogen, which is generated from remaining renewable energy sources. However, only a relatively small part of them are the storage rooms. The most common form of underground storage is depleted gas reservoirs, moreover, the natural gas reserves are unequally distributed in regions.

Gas network. Another option for storing of remaining excess renewable energy in the form of hydrogen is to supply it into the natural gas grid (hydrogen-rich natural gas).

Before early 20th century hydrogen-rich municipal gas or coke oven gas with hydrogen content above 50 vol.% was distributed to households in Germany, the United States and England via gas pipelines, for example, - although not for the long distances.

Infrastructure elements installed at that time, namely pipelines, gas-fired plants, gas apparatus, etc. were designed for hydrogen-rich gas and later they were changed to a natural gas. Many countries considered the possibility of adding hydrogen to existing natural gas networks. Thus, volumes from 5 to 15 vol.% of hydrogen in the USA could be implemented without significant negative impact on final users or pipeline infrastructure. Meanwhile large hydrogen applications in some cases require expensive re-equipment of instruments. The mentioned limit in Germany was established a bit lower up to 10 vol.%. Basically, concentrations of gas with up to 10 vol.% of hydrogen can be transported in current natural gas network without risk of damaging gas installations, and distribution infrastructure, etc.

It is possible to assume that many of the gas transmission networks, distribution lines and storage facilities, which were operated in the past, are still used. Thus, for example in Leeds (Great Britain) the studies of possibility of current natural gas network re-equipment (used mainly for municipal heating) totally to hydrogen were taken place. Considering the length of large gas networks in many industrial countries there can be kept a significant amount of hydrogen.

Costs. Hydrogen storage is a key component in hydrogen supply. The choice of the most appropriate storage technology is a balancing solution between the amount of hydrogen, its storage (for example tank size) and energy use.

In general ***compression*** of hydrogen gas is the most attractive variant for permanent storage considering its relatively low cost and better availability. Together with possible improvement in compression efficiency, hydrogen storage is expected to add $ 0.3 per kg to the cost of hydrogen produced until 2025.

Another storage technology, including liquefaction and storage media as ammonia, have better densities along with higher price. Thus, these technologies become more financially viable when storing (or transporting) large quantities of hydrogen, where there are severe restrictions. Together with possible improvement in liquefaction, it is likely to add additional $ 1.59-1.94 per kg to the cost of hydrogen produced until 2025.

Summary data on the prime costs of various technologies of hydrogen production and storage are given in the table below (based on Australia's National Hydrogen Roadmap, 2018).

Table 1. Achievable and expected cost of hydrogen technology

Technology	Given cost	2018	2025
Black coal gasification with CCS	LCOH, $/ kg	2,57-3,14	2,02-2,47
Compression and storage in tanks (35/150/350 bar)	LCOH, $/ kg	0,48/0,34/0,38	0,41/0,26/0,27
Compression and storage in salt rooms	LCOH, $/ kg	0,22-0,26	0,16-0,20
Production and storage of ammonia with hydrogen reduction	LCOH, $/ kg	1,39-1,68	1,10-1,33
Liquefied hydrogen production and storage	LCOH, $/kg	2,57-3,14	1,59-1,94
Fuel cells	LCOE, $/MW h	330-410	120-150
Fuel cell electric vehicles	$LCOT_{automobile}$, $/ tonne-kilometre	1,29-1,57	0,63-0,77
	$LCOT_{bus}$, $/ tonne-kilometre	2,66-3,25	1,66-2,02

The usage of gas pipelines is the best solution for consumers connected to the gas network, meanwhile for autonomous consumers the delivery in cylinders is a better possible variant, as delivery for vehicles. It can be used directly as fuel or together with fuel cells for autonomous power supply, therewith it reduces limitations in gas pipelines with high hydrogen concentration in the fuel gas composition. One better solution is a local production of hydrogen using electricity from renewable energy sources, which allows to achieve a balanced energy supply.

The hydrogen technologies play essential role in solving specific problems connected with a stable operation of energy sector and the industry as a whole. The hydrogen production by the water electrolytic process with utilization of the electric energy obtained from the renewable sources makes it possible to accumulate excessive energy for further storage until the time when it is highly needed to the users, as well as to transport it over long distances.

The **Hydrogen Insights 2021** report[28] by Hydrogen Council, McKinsey & Company analyzes the competitiveness of hydrogen applications across sectors through 2030 compared with conventional and low-carbon alternatives. Lower hydrogen production and distribution costs across all regions will improve the cost competitiveness of all end applications, as reflected in the shift to the right in the cost competitiveness matrix compared to Hydrogen Council Study 2020, "Path to hydrogen competitiveness: a cost perspective".

In addition to hydrogen's role as an overarching cost driver, the Hydrogen Insights report identifies three additional cost drivers with implications for individual end applications. They include optimized routes for green steel through the combination of DRI and scrap, which help green steel achieve cost competitiveness; improvements in battery technology that influence hydrogen breakeven with low-carbon alternatives in the transport sector; and new applications for hydrogen or hydrogen-based fuel usage (**see Exhibit 17, p.26** of the Report).

At a hydrogen production cost of USD 1.6-2.3/kg, most road transportation applications and hydrogen feedstock for industry are "in the money" (see **Exhibit 18, p.27** of the Report). With hydrogen costs between the blue and green hydrogen cost targets for 2030 and without any costs for carbon emissions, hydrogen is only competitive in heavier road transportation applications (not including passenger cars). A cost of carbon at USD 100/t of CO2e could push industry feedstocks for applications like steel, ammonia, and refining to breakeven and beyond. Other forms of transportation like shipping or aviation only break even at higher costs of carbon (> USD 70/tCo2e) but require hydrogen-based fuels as the only zero-carbon fuel possibility that can realize decarbonization ambitions.

[28] https://hydrogencouncil.com/wp-content/uploads/2021/02/Hydrogen-Insights-2021-Report.pdf

ANNEX 3 - Innovative solutions

The integration of solar and wind power poses specific challenges as system operators pursue low-carbon investments and long-term energy sustainability. As these variable renewable energy (VRE) sources reach high shares of power generation, power systems must be increasingly flexible to maintain the balance of supply and demand over each day or year. A large number of innovations that can be used to integrate high VRE shares are emerging and are being implemented worldwide.

Innovations are emerging across four key dimensions of the world's power systems:

- **Enabling Technologies**: Technologies that play a key role in facilitating the integration of renewable energy.
- **Business models**: Innovative models that create the business case for new services, enhancing the system's flexibility and incentivising further integration of renewable energy technologies.
- **Market design**: New market structures and changes in the regulatory framework to encourage flexibility and value services needed in a renewable-based power energy system, stimulating new business opportunities.
- **System operation:** Innovative ways of operating the electricity system, allowing the integration of higher shares of variable renewable power generation.

Innovation is a key driver for the energy transformation. Innovative solutions can make the power system more flexible, allowing for a higher, cost-effective use of renewables. IRENA's 2019 Innovation Landscape study outlines 11 solutions to create reliable, efficient future power systems using large shares of solar and wind power:

- Solution I: Decreasing VRE generation uncertainty with advanced weather forecasting
- Solution II: Flexible generation to accommodate variability
- Solution III: Interconnections and regional markets as flexibility providers
- Solution IV: Matching renewable energy generation and demand over large distances with supergrids
- Solution V: Large-scale storage and new grid operation to defer grid reinforcements investments
- Solution VI: Distributed energy resources providing services to the grid
- Solution VII: Demand-side management
- Solution VIII: Renewable energy mini-grids providing services to the main grid
- Solution IX: Optimising distribution system operation with distributed energy resources
- Solution X: Utility-scale battery solutions
- Solution XI: Power-to-X solutions

The proposed solutions make use of 30 innovations – see the table below:

ENABLING TECHNOLOGIES	BUSINESS MODELS	MARKET DESIGN	SYSTEM OPERATION
• Utility-scale batteries • Behind-the-meter batteries • Electric-vehicle smart charging • Renewable power-to-heat • Renewable power-to-hydrogen • Internet of Things • Artificial intelligence and Big Data • Blockchain • Renewable mini-grids • Supergrids • Flexibility in conventional power plants	• Peer-to-peer electricity trading • Energy-as-a-service • Community-ownership models • Pay-as-you-go models	• Increasing time granularity in electricity markets • Increasing space granularity in electricity markets • Innovative ancillary services • Re-designing capacity markets • Regional markets • Time-of-use tariffs • Market integration of distributed energy resources • Net billing schemes	• Co-operation between transmission and distribution syste m operators • Advanced forecasting of variable renewable power generation • Innovative operation of pumped hydropower storage • Virtual power lines • Dynamic line rating

ANNEX 4 - Ukrainian norms and regulations applicable to hydrogen technologies

Hydrogen is classified as a hazardous fuel gas and, as a result, activities related to the design, construction, manufacture, operation of technological facilities, systems and equipment, the production and use of hydrogen, are regulated in Ukraine by a number of regulations (norms, rules, technical regulations) and related standards of different levels. The main regulatory requirements include:

1. Technical regulations:

- equipment and protective systems intended for use in a potentially explosive environment (harmonized with Directive 2014/34/EC of 26.02.2014
- pressure running equipment (harmonized with Directive 2014/68 / SS of 15.05.2014
- simple high-pressure vessels (harmonized with Directive 2014/29 / EC of 26.02.20214)
- water heating boilers running on liquid or gaseous fuels
- gaseous fuel devices (harmonized with EU Regulation 2016/426 of 09.03.2016)
- mobile pressure equipment (harmonized with Directive: 1999/36 / EC of 29.04.1999)
- requirements for automobile gasoline, diesel, ship and boiler fuel (harmonized with Directives 98/76 / EC of 13.10.1998 and 2005/33 / EC of 06.07.2005)

2. Safety rules, rules of labor protection, safety rules during operation:

- fire safety rules in Ukraine (NABB A.01.001-2014)
- safety rules in the production of hydrogen by electrolysis of water (NPAOP 24.11-1.03-78)
- safe operation of piston compressors operating on explosive and toxic gases (NPAOP 0.00-1.14-76)
- safety of gas supply systems (NPAOP 0.00-1.76-15)
- labor protection during operation of pressure equipment (NPAOP 0.00-1.81-18)
- safety during operation of means and systems of automation and control in the gas industry (NPAOP 11.1-1.07-90)
- electrical installations (NPAOP 40.1-1.32-01)
- safe operation and maintenance of automobile gas filling compressor stations (NPAOP 63.2-1.06-02)

Regulatory technical safety requirements for used equipment, devices, systems and their components are established, as a rule, by standards. Since the state of the national hydrogen technology regulatory framework does not meet the current international standards, the introduction of national standards harmonized with international ones will eliminate existing administrative and technical barriers caused by outdated Ukrainian regulatory documents that do not comply with a number of EU Directives and the current legislation of Ukraine in the field of standardization (Law No. 114-IX of September 19, 2019).

The development of standards at the state level is carried out by technical standards committees, which include manufacturers and consumers of products, research and public organizations, regulatory authorities, etc. In Ukraine, in 2020, the technical committee for standardization of TC 197 "Hydrogen Technologies" was established (Order of the State Enterprise "UkrNDNC" No. 130 of 22.06.2020), which operates in hydrogen technologies in accordance with the adopted international classification of standardization. Due to the fact that hydrogen technologies cover various industries, TC 197 also coordinates the activities of national technical committees, whose activities are related to the design, construction, manufacture, operation of technological objects, systems and equipment, the production and use of hydrogen:

- TC 8 "Pipes and steel cylinders"
- TC 21 "Dynamic and volumetric pumps"

- TC 25 "Fire Safety"
- TC 26 "Operation of aircraft"
- TC 28 Compressors
- TC 38 "Refined and petrochemical products"
- TC 55 "Methanol, synthesis products"
- TC 80 "Road transport"
- TC 108 "Pipe Fittings"
- TC 133 "Gas natural"
- TC 146 "Materials, equipment, technologies and facilities for the oil and gas industry"
- TC 187 "Explosion-proof equipment"
- TC 318 "Construction of oil and gas production, transportation and storage facilities"