Global Atlas of H_2 Potential

Sustainable locations in the world for the green hydrogen economy of tomorrow: technical, economic and social analyses of the development of a global sustainable hydrogen atlas

HYPAT Working Paper 04/2023

Ukrainian Hydrogen Export Potential: Opportunities and Challenges in the Light of the Ongoing War

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Executive Summary

Against the background of the ongoing war of aggression, the working paper analyzes the opportunities and challenges of Ukraine in the topic of hydrogen and Power-to-X products. The main findings are:

- Despite the ongoing war, the EU remains interested in Ukraine as a potential future supplier of hydrogen, to meet European energy demand and support Ukraine’s recovery.
- Ukraine must adopt European standards for hydrogen and comply with European legislation for hydrogen exports to the EU.
- Green steel could become an important export product in the future, generating additional revenues and enabling local value creation in the country.
- Ukraine as well as the relevant transit countries have well-established infrastructure for exporting hydrogen and Power-to-X products to Western Europe via pipelines and seaports, but the repurposing of this infrastructure needs to be further investigated.
- Important energy infrastructures and land for potential renewable energy (RE) deployment are currently occupied by the Russian military. Apart from that, the war's uncertain duration and outcome increase the risks of investing in developing the large RE potential in Ukraine. As a result, low-cost RE might only be sufficient to cover domestic demand.
- Opportunities and obstacles: The development of a hydrogen economy can bring socio-political advantages, such as new jobs. Nevertheless, large-scale hydrogen production in Ukraine might be limited due to water scarcity and competitive water use for the agricultural sector and could imply higher energy costs for households.

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Abbreviations

Abbreviation	Meaning
CO_2	Carbon Dioxide
CSP	Concentrated Solar Power
ENTSOG	European Network of Transmission System Operators for Gas
H2	Hydrogen
HYPAT	Hydrogen Potential Atlas
IEA	International Energy Agency
LCOE	Levelized Cost of Energy
NASU	National Academy of Science of Ukraine
IRE	Institute of Renewable Energy
PtX	Power-to-X
PV	Photovoltaics
RE	Renewable Energy
WACC	Weighted Average Cost of Capital

1 Introduction

The HYPAT project is compiling a global hydrogen potential atlas to assess sustainable production locations based on technical, economic, political and social criteria. The project's findings will contribute to the development of a global hydrogen (H_2) and Power-to-X (PtX) market[1]. Therefore, the aim of HYPAT is to identify important export and import countries for future hydrogen trade, as well as the potential trade quantities, production and transportation costs to derive a hydrogen market price.

Hydrogen is currently considered as an important driver for the transition to a sustainable society that relies significantly on renewable energy sources. The world is actively pursuing the development of the hydrogen economy. In the future, hydrogen produced by electrolysis using wind or solar energy will play a crucial role in various sectors of the economy. To reduce greenhouse gas emissions, particularly carbon dioxide (CO_2), countries around the world are increasingly turning to green hydrogen as a climate-neutral energy resource. To achieve this goal, they are actively formulating and implementing national hydrogen strategies. This also applies to Ukraine, for which the development of the hydrogen economy is particularly relevant in view of Russia's full-scale war conducted on the territory of Ukraine. The European Green Deal provides an opportunity to facilitate the creation and growth of an industry that can help Ukraine achieve energy independence, develop an export-oriented economy, and ensure its national security. Ukraine has a number of competitive advantages (natural potential for renewable energy production and promising options for the low-cost transport of hydrogen to the EU using existing pipeline infrastructure) and possesses the prerequisites for large-scale and export-oriented green hydrogen production. This makes Ukraine attractive for international stakeholders from business, industry and politics who are interested in the development of a Ukrainian hydrogen economy. The HYPAT project therefore considers Ukraine as a potential exporter of hydrogen to the EU, including Germany, and analyzes it in a country study.

The objective of this working paper is to study the hydrogen export potential of Ukraine, including the opportunities and challenges in light of the ongoing war, based on the analyses of national and international sources and literature as well as the modeling and calculations conducted within the HYPAT project.

The structure of this paper is as follows: Chapter 2 presents the current trends and developments of the hydrogen economy in Ukraine, including socio-political dimensions of green hydrogen that might affect stakeholder acceptance of potential hydrogen production and export strategies (subchapter 2.1), and strategic activities in the field of hydrogen (subchapter 2.2). Chapter 3 provides some initial insights from the techno-economic assessment within the HYPAT project, presenting renewable energy potentials (subchapter 3.1), energy demand estimates (subchapter 3.2), and the required infrastructure for exporting hydrogen by pipeline and ship (subchapter 3.3). Chapter 4 examines two aspects of the Ukrainian perspective on the EU hydrogen market: possible hydrogen development paths for Ukraine (subchapter 4.1) and the prospects for Ukraine resulting from the implementation of EU plans (subchapter 4.2). The final chapter concludes with an overall summary.

[1] Further information about HYPAT can be found at https://hypat.de/hypat/projekt.php

2 The Hydrogen Economy in Ukraine – Current Trends and Developments

In comparison to other European countries that have already published national hydrogen strategies, Ukraine is still at the initial stage of formulating its hydrogen policy. With its abundant renewable energy (RE) potential, its proximity to possible import countries in central Europe and the existing natural gas pipeline infrastructure, Ukraine possesses the prerequisites to become a large-scale and export-oriented green hydrogen producer. As a result, national and international stakeholders from business, industry and politics are interested in the development of a Ukrainian hydrogen economy. However, many questions concerning the economic competitiveness of hydrogen production and export in Ukraine are still open. A recent study (Rudolf et al. 2021) has shown that there are insecurity factors that may heavily influence capital costs and as such are crucial to the economic viability of hydrogen production. These are:

- uncertainties in Ukraine's energy and hydrogen policy,
- uncertainties in the business environment for hydrogen, and
- uncertainties concerning hydrogen transport and demand.

Russia's invasion of Ukraine and the ongoing war are delaying Ukraine's development and implementation of its Hydrogen Strategy, which calls into question the country's prospects on the European hydrogen market.

This chapter describes the current events and relevant stakeholders involved in developing a hydrogen economy in Ukraine.

2.1 Socio-political dimensions: opportunities and challenges of green hydrogen in Ukraine

Understanding the socioeconomic and political dimensions of Ukraine's green hydrogen economy is crucial for the development of international cooperative agreements between the Ukraine and potential import partners, such as Germany, especially if the overall objective of such partnerships is to contribute to a stable regional and global hydrogen economy that fosters a socially, politically and environmentally sustainable energy transition at the same time as fulfilling potential import partners' demand for green hydrogen. Social acceptance of the production and export of hydrogen by key political, economic and social stakeholders within Ukraine is an important factor complementing the economic and technical assessments of national conditions, opportunities and challenges. Desk research, complemented by stakeholder interviews, indicate that hydrogen projects can have a positive effect on Ukraine's socio-economic development. However, current research also highlights some potential lines of conflict, which - if not addressed - might have negative impacts on stakeholder acceptance of a green hydrogen economy in the country. These include employment rates, land use conflicts, water scarcity, user costs, and the lack of an updated regulatory framework.

- According to some of the interviewed industry stakeholders, the development of green hydrogen production capacities as well as potential export options could contribute to the revival of territories, for example in the South of Ukraine, where people are currently facing limited employment opportunities. The construction of electrolysis plants, hydrogen production and the creation of 'Hydrogen Valleys' could lead to overall social-economic growth. The creation of both direct and indirect jobs is possible: in hydrogen production, and in the accompanying industries such as transportation, logistics, dispatching, etc. Long-term employment strategies need to be developed, as current projections indicate the need for a high number of workers along the hydrogen supply chain. However, while some of the workforce needed - particularly in the initial phase of building renewable energy plants - include both highly and lower skilled workers, most of the projected jobs will require highly skilled labor. Capacity and skill training strategies to ensure long-term employment will be needed to address the significant reduction in employment after the first few years (Beasy et al. 2023) . Moreover, recent studies predict the biggest employment potential of green hydrogen in road transport and (building) heating, two sectors where the use of green hydrogen remains controversial (van Renssen).

- Potential land-use conflicts need to be carefully assessed. Ukraine is highly dependent on agricultural outputs. Land-use conflicts between agriculture and land needed for renewable energy plants could impede the development of green hydrogen on a larger scale. According to some industry stakeholder interviews, areas to be used for the construction of wind and solar power plants in the country's South have not been used for agriculture for a long time. After gaining independence in the early 1990s, Ukraine embarked on reforms and began the process of economic transformation. As a result of privatization processes, collective farms were liquidated. However, due to local private farmers' lack of sufficient financial capacity and insufficient state support for agriculture, some farmland is now unclaimed and no longer used for its intended purpose. For these reasons, local authorities might welcome the construction of new wind and solar power plants, but potential land-use conflicts should be carefully assessed prior to the development of any new projects.
- Another issue of public concern is the question of freshwater availability and its use for hydrogen production, as Ukraine is one of the most water scarce countries in Europe (Oleg Titamir 2021). This potential water-use conflict (agriculture vs. green hydrogen) could create a powerful narrative in the socio-political context. To reduce the risk of conflict, some industry stakeholders reported in their interviews that they have been conducting environmental feasibility studies assessing the availability of water resources as part of hydrogen pilot projects. Their results show that, particularly in the southern region of Ukraine, sufficient water is available to supply the considered plants. The Institute of Geological Sciences National Academy of Science of Ukraine explored surface and ground water in the region Reni/Ismail, Odesa Region in detail. [1] (NAS 2021). 0.36% of river runoff resources are required to produce the total estimated potential of green hydrogen. Therefore, the available water resources are assumed to be sufficient to realize the achievable potential of green hydrogen production without increasing water intake (MTU 2019). The existing public narrative of potential water scarcity in regard to hydrogen production needs to be carefully assessed and accounted for when planning new green hydrogen projects (Oleg Titamir 2021).
- User costs are an important socio-political dimension in regard to the social acceptance of green hydrogen production in Ukraine. As of now, developing large-scale green hydrogen production in Ukraine would mean significant investments in the country's energy infrastructure (Oleg Titamir 2021). The current public narratives about the possible resulting increases in consumer prices and energy tariffs compared to today's level based on conventional energy resources pose a risk to the acceptability of using green

hydrogen on the domestic market (Zanuda 2021). According to expert interviews with industry stakeholders, in 2025, renewable hydrogen might become competitive with low-carbon hydrogen (€1.5-2.0/kg) or "gray" hydrogen, taking into account the CO_2 price of €50 per ton. It is expected that renewable hydrogen will become competitive with "gray" hydrogen by 2030, at a price of €1.0-1.5/kg.

- The current lack of an updated regulatory framework is regarded as a potential barrier to the development of a green hydrogen economy in Ukraine. The uncertain political landscape causes investment insecurity for both national industries and regional and international investors, according to some of the interviewed industry stakeholders. The development of a green hydrogen strategy and the corresponding policies have been delayed by the current Ukrainian government (see next section). On the other hand, hydrogen production in Ukraine could become key for Ukrainian and European independence from Russian energy supplies and for the rapid transition to the use of green energy.

[1] It was concluded that 2.4% of the approved groundwater reserves is used at the Reni water-intake facility, while 10.5% is used at the Izmail water-intake facility. Additionally, the Danube section of the Reni groundwater deposit has never been used. The maximum possible water withdrawal in the study area (from Reni to Izmail) was determined: It was estimated that the projected groundwater resources of the alluvial aquifer in the Danube River basin between the cities of Reni and Izmail are approximately 2.39 million m^3/day. In conclusion, this aquifer could serve as a reliable source of drinking and industrial water supply. The water consumption for electrolysis from the Danube River was also evaluated. "H2U" received information from the Institute of Geological Sciences National Academy of Science of Ukraine that water consumption from the Danube River for electrolysis to produce green hydrogen does not pose a threat of dewatering the Danube and the Danube lakes and will not affect group water-intake facilities for domestic and drinking water supply of the cities of Reni, Izmail and surrounding localities along and down the Danube. Furthermore, according to the "National Report on the Quality of Drinking Water and the State of Drinking Water Supply in Ukraine in 2019", 11,110 million m^3 of water were withdrawn from natural sources, which is equivalent to 5.3% of river runoff resources (MTU 2019).

2.2 Strategic activities in the field of hydrogen

In recent years, a number of Ukrainian research institutions have helped to develop strategies and technologies to produce, store and use hydrogen. The National Academy of Science of Ukraine has been involved in the program "Hydrogen in Alternative Energy and New technologies" since 2011. This program has a total of 43 projects involving 17 institutions. Their research focuses on the use of RE for hydrogen production.

The "Ukrainian Hydrogen Council" was founded in 2018[2]. It is an energy association engaged in the development of green hydrogen technologies, as well as the dissemination and improvement of energy efficiency in various industry and services sectors. It is the first association from a non-EU country to be granted associate membership in the industry energy agency "Hydrogen Europe".

Although the hydrogen sector in Ukraine is still in its initial phase, a variety of pilot projects have been initiated by both Ukrainian and international stakeholders. These projects include the production of green hydrogen for domestic use and export, and partly hydrogen storage. All projects are still in the development or conceptual stage, although concrete plans concerning project design, costs, and technological options have been developed to some extent already. Industrial and financial partnerships as well as relations to local and federal authorities are already partially established. The next steps would be to secure investments (national and international) and implement the already more advanced projects. However,

[2] More information about the Ukrainian Hydrogen Council can be found at: https://hydrogen.ua/en/home-en

according to the project initiators, investments could not yet be secured. The reasons are the uncertainties surrounding the offtake market, a lack of transport options for hydrogen, and the non-existence of an approved Ukrainian hydrogen strategy. Annex A gives a brief overview of current green hydrogen pilot projects in Ukraine.

There are two recent strategically relevant groundworks related to ramping up a hydrogen economy in Ukraine: A Hydrogen Roadmap (draft version) for the production and use of hydrogen in Ukraine, and the Hydrogen Strategy of Ukraine, which is currently being prepared. They have been developed for the transition to a new clean energy system and to demonstrate a practical program for the sectoral integration of hydrogen into the economy of Ukraine. The main concepts of these two documents will be discussed in the following subchapters.

2.2.1 Hydrogen Roadmap (Dubko et al. 2021)

The "Ukrainian Hydrogen Council" together with the Institute of Renewable Energy (IRE) of the National Academy of Sciences of Ukraine (NASU) is proposing a legislative initiative to integrate hydrogen and energy solutions into the legislative framework, and is developing a practical program for the sectoral integration of hydrogen into Ukraine’s economy.

IRE drafted a roadmap for the development of hydrogen technologies in Ukraine until 2035, which was first presented in April 2019 at the European exhibition dedicated to hydrogen technologies "Hydrogen Europe" in Hannover and then finished as a draft in 2021 (Dubko et al. 2021).

The roadmap outlines a path for Ukraine to integrate hydrogen as a new energy subsector. It identifies four pillars for introducing hydrogen in Ukraine (Dubko et al. 2021):

- Pillar 1: Transformation of the electrical power supply and heating systems
- Pillar 2: Transformation of industrial heat processes
- Pillar 3: Transformation of the transport sector
- Pillar 4: Transformation of the national gas pipelines system and scaling-up of hydrogen manufacturing, storage and transportation.

These four pillars cover the modernization of the Ukrainian energy system including the use of new technologies (digitalization, heat pumps), construction of new infrastructure (transmission lines etc.) and the potential use of hydrogen for each one of these branches.

By introducing new technologies and setting up scientific, transport and production infrastructures, the roadmap will gradually increase the share of clean energy in the Ukrainian domestic and export markets. It aims to prioritize renewable energy, foster hydrogen partnerships, and reduce the consumption of fossil fuels (Dubko et al. 2021; Kudria 2020). The roadmap defines governmental policy, as well as economic, financial, and institutional mechanisms to ensure that the goals of the roadmap are reached.

2.2.2 Hydrogen Strategy (Benmenni et al. 2021)

Ukraine has substantial competitive advantages for the production and export of green hydrogen. In particular, significant renewable energy resources and pipeline infrastructure make the country attractive for domestic and international stakeholders from various sectors, including business, industry, and politics, who have expressed strong interest in developing a hydrogen economy in Ukraine.

The Ukrainian energy policy strongly emphasizes green hydrogen, acknowledging its dual role as an important instrument in decarbonizing Ukraine's economy and a potentially robust export product. In this regard, IRE has formulated a Hydrogen Strategy of Ukraine and published it for wide discussion and engagement (Benmenni et al. 2021).

The Hydrogen Strategy of Ukraine defines the deployment of hydrogen technologies in the country, including relevant goals, key priorities, and required measures to achieve these goals. The formation of a hydrogen economy in Ukraine is expected to be carried out in stages by implementing energy projects of different capacities using different renewable energy sources and hydrogen of various kinds:

Stage 1: Short-term goals (2022–2025)

- Laying the foundation for a hydrogen economy and launching the export market for green hydrogen.
- Establishing the legal framework for hydrogen and strengthening the partnerships with other countries, especially with Germany.
- Preparing the gas transport system.
- Creating the social, economic and political conditions needed for the introduction of clean technologies.
- Revising state policies on GHG emission taxes.

Stage 2: Medium-term goals (2026–2030)

- Diversification of primary energy sources due to the growth of hydrogen production.
- Stimulation of investments to expand hydrogen production in Ukraine up to 12-15 GW will cover in parallel the needs of the export market (10 GW) and the domestic hydrogen demand for i.e. electricity storage or blending with natural gas for in housing and communal heating.

Stage 3: Long-term goals (2031–2050)

- Ukraine is the hydrogen hub for Europe. Rapid expansion of the hydrogen market, including exports.
- Transitioning from a mixture of gas/hydrogen to pure hydrogen in the gas transport system.

Thus, the draft of the hydrogen roadmap primarily emphasizes the initial deployment of hydrogen and fuel cell technologies in Ukraine. It outlines a set of specific applications that could be first deployed in selected locations and subsequently expanded in the future. In addition, the roadmap considers potential technological risks, implementation challenges, and knowledge gaps that currently arise in this context. At the same time, the hydrogen strategy of Ukraine comprises several key goals, including:

- Positioning hydrogen as a fundamental component of Ukraine's new energy system.
- Enhancing Ukraine's energy independence, thereby strengthening its political and economic autonomy.
- Facilitating Ukraine's rapid integration into the political, economic, and security framework of the European Union.

3 Preliminary Techno-Economic Assessment

3.1 Renewable energy potentials

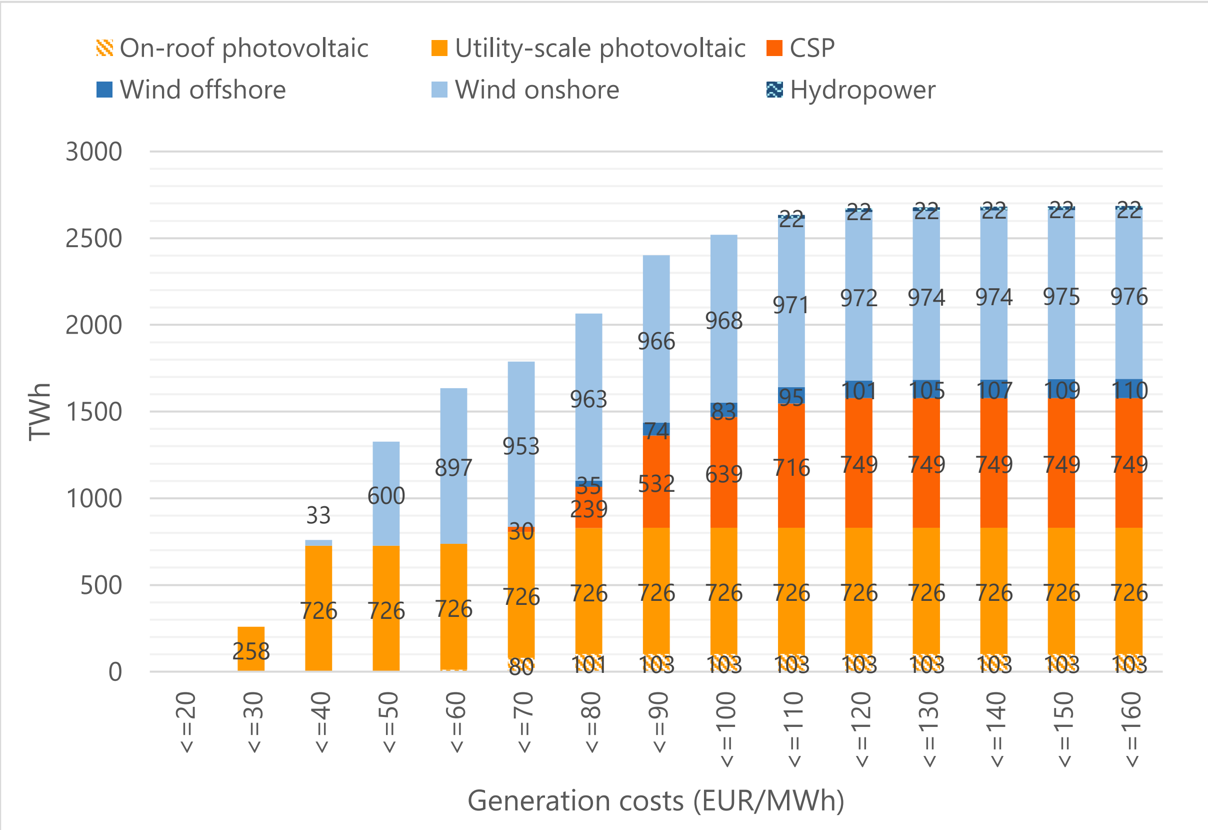
The Renewable Potential Calculator from the model Enertile was used to determine the renewable energy (RE) potentials in Ukraine. The technologies evaluated include utility-scale and on-roof photovoltaic, onshore and offshore wind and concentrated solar power (CSP). The hydropower potential in Ukraine was taken from (Kleinschmitt et al. 2022). Further details about the methodology used to calculate the potentials are given in (Franke et al. 2023; Pieton et al. 2023; Sensfuß et al. 2022).

Three distinct cases using low, medium and high-interest rates were considered to calculate the RES potentials in 2050. The interest rates were determined using historical values according to the methodology of (Breitschopf et al. 2022; Pieton et al. 2023). The calculated interest rates are:

- Low: 4.5%
- Medium: 15.9%
- High: 21.9%

Figure 1 shows the RES potentials for the low-interest rate. This case has 258 TWh pure utility-scale photovoltaic potential at generation costs below 30 EUR/MWh. Utility-scale photovoltaic potential peaks at 726 TWh with generation costs below 40 EUR/MWh. The potential from onshore wind is 600 TWh at generation costs below 50 EUR/MWh and jumps to almost 900 TWh at generation costs below 60 EUR/MWh. Wind onshore potential peaks around 970 TWh at generation costs below 100 EUR/MWh. On-roof photovoltaics potential is 12 TWh at generation costs below 60 EUR/MWh. It peaks at 103 TWh at generation costs below 90 EUR/MWh. CSP potential peaks at 749 TWh at generation costs below 120 EUR/MWh. Wind offshore has a potential of 100 TWh at generation costs below 120 EUR/MWh. The total potential, which amounts to more than 2600 TWh, is achieved at generation costs below 120 EUR/MWh.

Figure 1: **Renewable energy potentials for low interest-rate case**



The high-interest rate case (Figure 2) shows a visible shift toward higher costs. The utility-scale photovoltaic potential reaches its maximum value below 100 EUR/MWh. This represents an increase of 60 EUR/MWh when compared with the low-interest rate value. Onshore wind has a potential of 800 TWh at generation costs below 160 EUR/MWh. This potential is 170 TWh lower than the maximum value of the low-interest rate case at generation costs below 100 EUR/MWh. The total potential in the high-interest rate case is just above 1,500 TWh at generation costs below 160 EUR/MWh. The hydropower potential does not consider an interest rate and is the same for both cases.

Figure 2: Renewable energy potentials for high interest-rate case

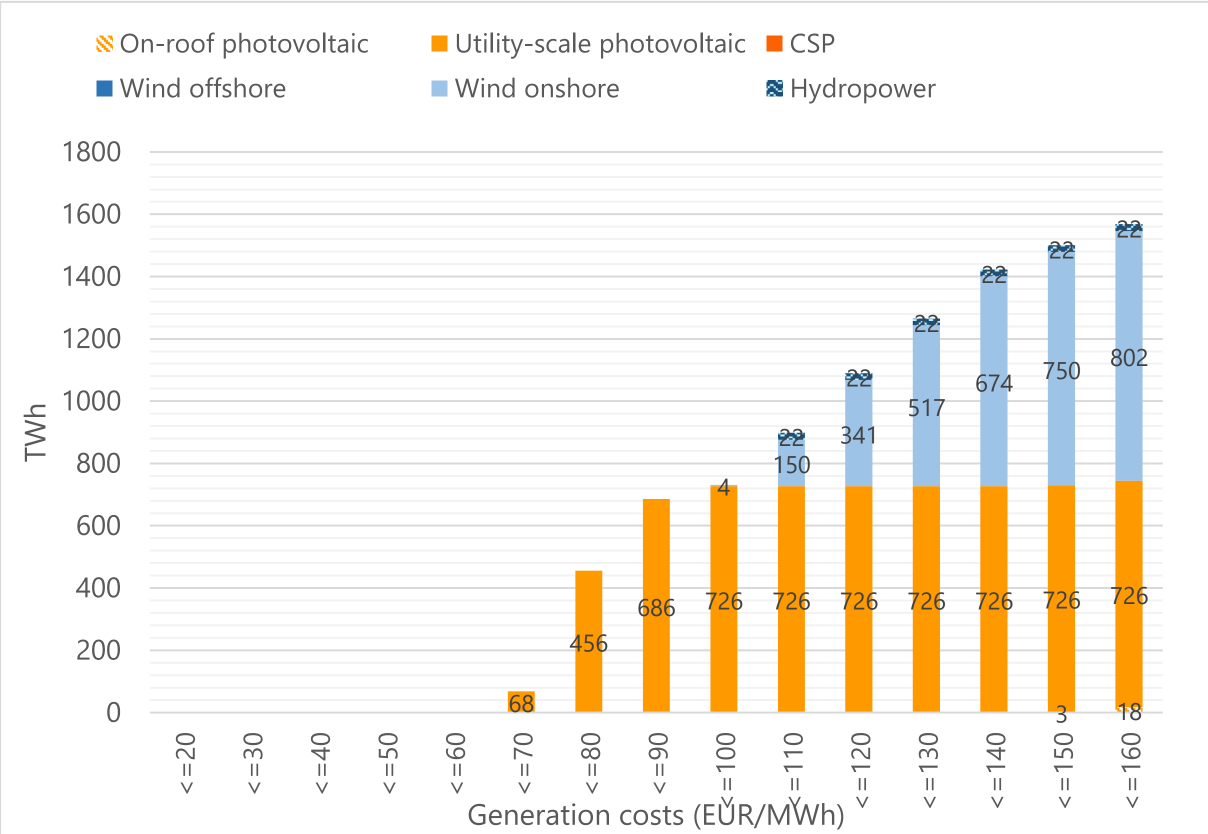
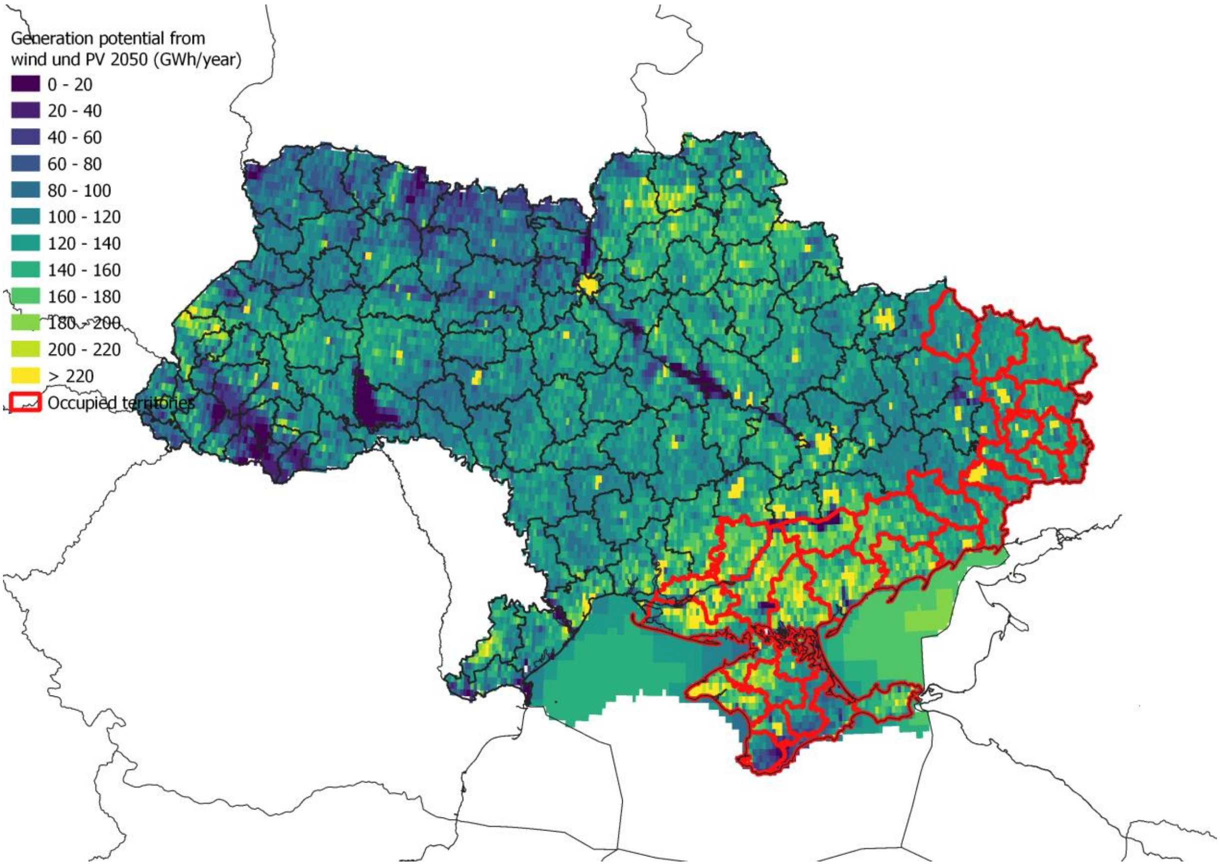


Figure 3: Geographical distribution of RES generation potential in Ukraine in 2050 (GWh/year). Occupied territories (southeast) are outlined in red.



The geographical distribution of the RES generation potential (GWh/year) is depicted in Figure 3. The southeast and eastern regions of Ukraine hold the largest generation potentials, which are shaded yellow and light green. This is a good fit with the so-called H_2 valley in Ukraine, where H_2 and green ammonia generation projects are planned. Western and northern Ukraine have a lower RES generation potential, reflected by the darker green and blue shading.

The areas outlined in red in Figure 3 show the areas affected by the Russian invasion according to the BBC map "Territories under Russian control" compiled in July 2022 (The Visual Journalism Team 2022). The affected regions are those with the highest RES potential, the RES potential in these areas accounts for almost 30% of the total potential under 80 EUR/MWh for the low-interest rate case.

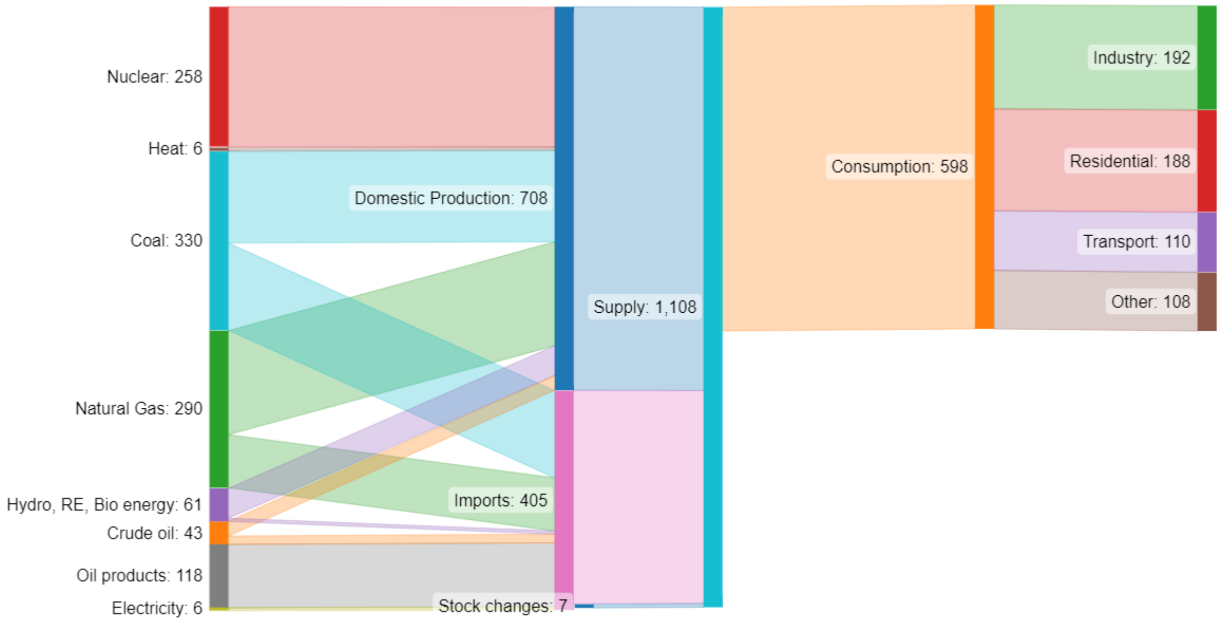
3.2 Energy demand estimation

Total Final Consumption: 2018

In Ukraine, the national Total Final Consumption (TFC) in 2018 amounted to 598 TWh[3] and was dominated by the industrial sector (192 TWh, 32%). The residential sector is the second largest sector of consumption (188 TWh, 31%), followed by the transport sector (110 TWh, 18%) and minor consumers such as services and agriculture. In comparison to other countries, Ukraine has a relatively high share of energy carrier usage for non-energy purposes (31 TWh), such as the production of chemicals (© Enerdata 2022; IEA 2021).

In 2018, the Primary Energy Supply (PES) amounted to 1,108 TWh, including domestic production and imports (IEA 2023). Historically, natural gas consumption has played an important role in Ukraine. However, since 2010, Ukraine has steadily decreased its natural gas consumption in order to reduce its dependency on natural gas imports from Russia (Enerdata 2022; IEA 2015). In 2018, coal (30%) had the highest share in PES, followed by natural gas (27%), nuclear power (24%), and crude oil and oil products (15%). Nearly one third (35%) of the supplied energy carriers were imported (IEA 2021). It is worth mentioning that Ukraine is the seventh biggest producer of nuclear power globally (IEA 2021).

Figure 4: Ukraine Primary Energy Supply (PES) and Total Final Consumption (TFC) 2018 in TWh based on (IEA 2021).



Steel is the second largest Ukrainian export good after agricultural products (OEC - The Observatory of Economic 2023). As Ukraine has 42 Mt of steel production capacity and 21 Mt of steel were produced in Ukraine in 2019, the steel industry is one of the largest consumers in the Ukrainian energy system (Global Energy Monitor 2022). Steel production consumed 60% of the final consumption in the industrial sector and 23% of the overall TFC in Ukraine in 2019 (© Enerdata 2022). The 15.1 Mt of steel exported in 2018 shows the strong orientation toward

[3] Excluding non-energy purposes.

exports in the Ukrainian steel industry, this amounts to roughly three quarters of the steel produced (International Trade Administration 2019). Besides the export of green hydrogen, green steel could in the future become an important downstream product, providing additional export revenues and enabling local value creation in the country. In this respect, Ukraine could have a comparative advantage over other potential green steel suppliers that have neither the existing steel infrastructure nor the industrial knowledge yet. However, it should be noted that many of the Ukrainian iron and steel plants are located in the east of the country, which is currently partly occupied by Russia or has been declared a war zone (see Figure 7).

The residential sector is the second largest sector of energy consumption in Ukraine. More than half of the energy in the residential sector is used for space and water heating(© Enerdata 2022). As natural gas is widely used for both purposes, the residential sector is characterized by a high share of natural gas use: In 2018, 52% of the energy consumed in the residential sector was natural gas for households (IEA 2021). In addition to this, a well-established heat network supplies the heat needed for buildings (© Enerdata 2022). Domestic transportation is the third largest energy consumer in Ukraine, mainly for road vehicles (© Enerdata 2022).

Total Final Consumption: 2018-2050 Scenarios

Within the HYPAT project, the TFC for 2030 and 2050 is estimated for two scenarios: Ambitious Plans and Net Zero. For the Net Zero scenario, high-efficiency measures are applied, processes are highly electrified and new carbon-neutral technologies or processes are introduced. As a result, the TFC can be reduced by 37 % between 2018 and 2050. For the Ambitious scenario, where carbon neutrality is not fully achieved by 2050, mitigation measures are implemented at a lower level than in the Net Zero scenario, so that the TFC can be reduced by 21 % between 2018 and 2050. The results are shown in Figure 5 and Figure 6. Further details on the methodology can be found in (Pieton et al. 2023)

Figure 5: Development of the Ukrainian Total Final Consumption (TFC) in TWh 2018-2050 per sector with historical data based on (© Enerdata 2022; IEA 2021) and future scenarios developed within the HYPAT project.

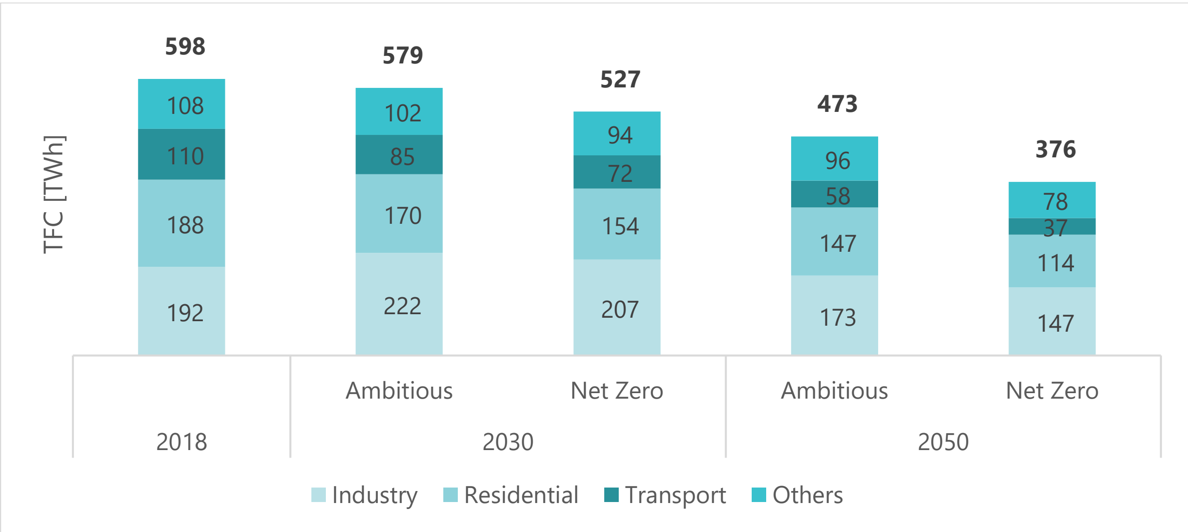
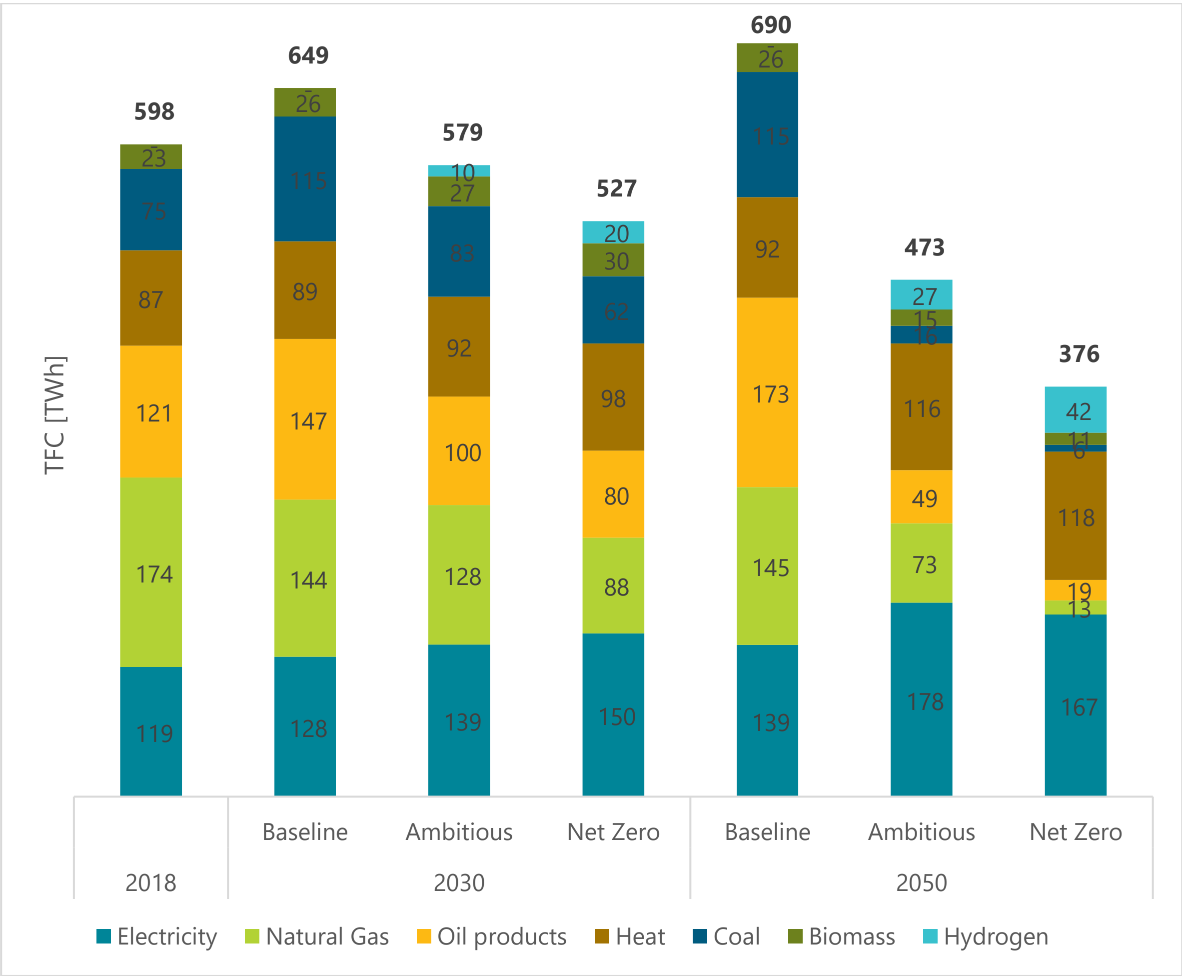


Figure 6: **Development of the Ukrainian Total Final Consumption (TFC) in TWh in 2030 and 2050 per energy carrier[4] with historical data based on (© Enerdata 2022; IEA 2023) and future scenarios developed within the HYPAT project**



3.3 Infrastructure required for export by pipeline and ship

3.3.1 Inland Infrastructure

The existing inland energy infrastructure in Ukraine can be classified using three main categories. They consist of the existing fleet of power generators along with their respective natural gas and electricity transmission networks. In the future, however, Ukraine's energy infrastructure might also incorporate underground hydrogen storage, which would replace current natural gas underground storage, and a hydrogen network.

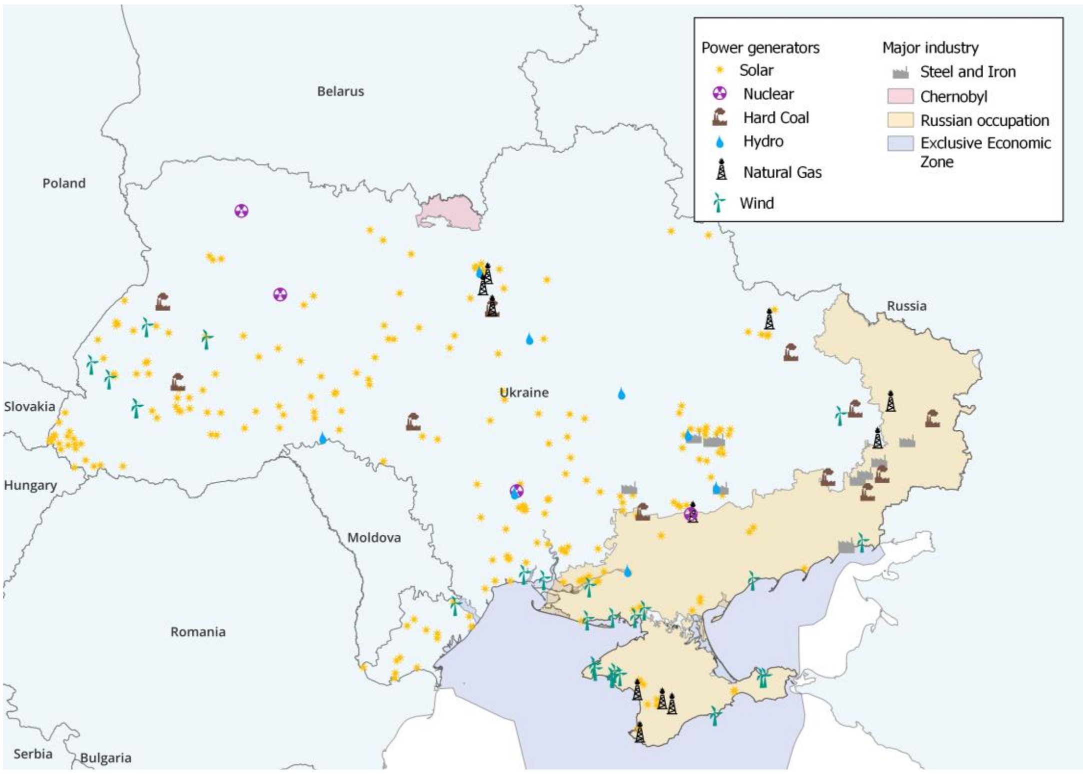
3.3.1.1 Power generators

The main power generators are a mix of renewable and conventional power plants as depicted in Figure 7. In view of the current Russian occupation, Ukraine has lost valuable power

[4] Energetic use only - the chemical use of energy carriers is excluded in this depiction. The energetic use of methanol and ammonia is assumed to be negligible for Ukraine and is therefore not depicted here. Oil includes synthetic oil. Biomass includes biogenic fuels. Heat covers district heating and ambient heat used via heat pumps.

generators, including half of its hard coal plants and most of the wind turbines near the Black Sea coast. In addition to that, Zaporizhzhia the largest nuclear plant in Europe, which has six reactors and generates a total power output of 5,700 MWe, has come under Russian occupation (Armstrong 2022). Moreover, Ukraine was only able to generate 6,000 tons of steel in 2022 compared to 21,366 tons in 2021 (worldsteel.org 2022). This decrease is also due to the Russian invasion, which has affected half of the steel and iron plants in the country as shown in Figure 7.

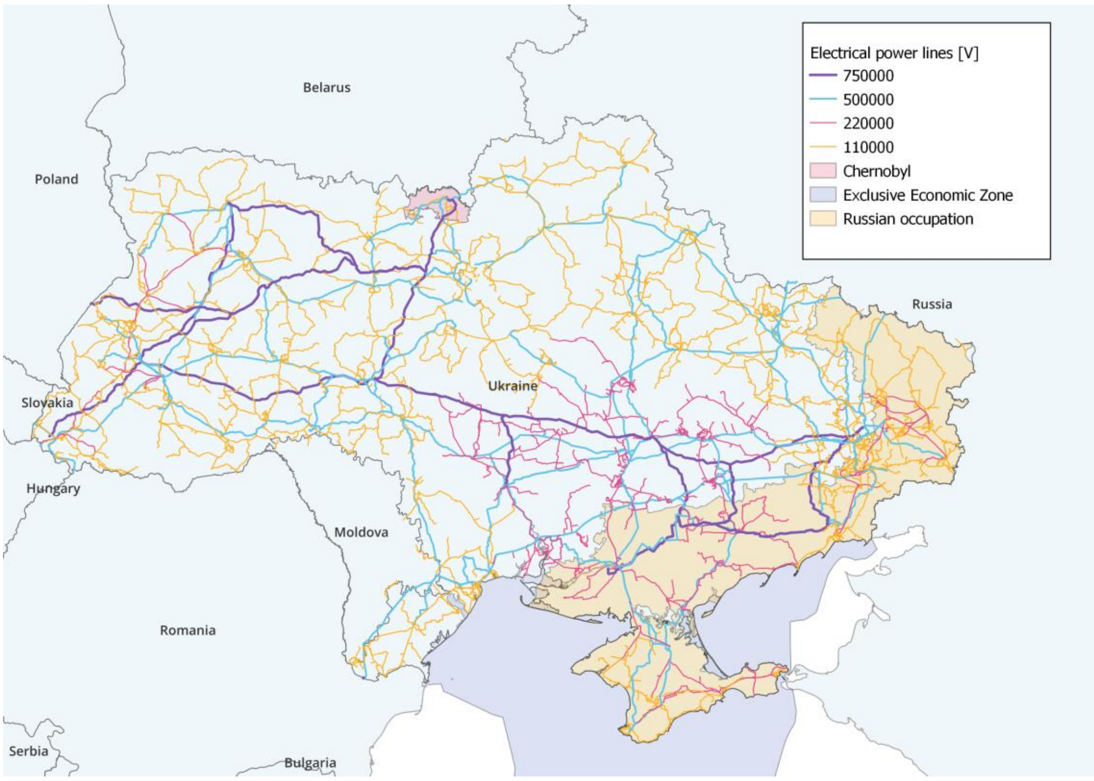
Figure 7: Major power generators and industry in Ukraine (Source: own illustration based on (Gotzens et al. 2019)



3.3.1.2 Electrical network

The national electricity transmission network is well interconnected, especially in terms of high-voltage lines of 750 KV and 500 KV shown in purple and blue, respectively, in Figure 8. This allows electricity to flow from regions with high solar and wind potentials in the south-east to the Ukrainian inland for electrolysis and hydrogen generation, if needed. Unfortunately, the south-eastern regions are currently under Russian occupation.

Figure 8: **Ukraine's electrical power network (Source: own illustration compiled using PyPSA-Earth (Parzen et al. 2022))**

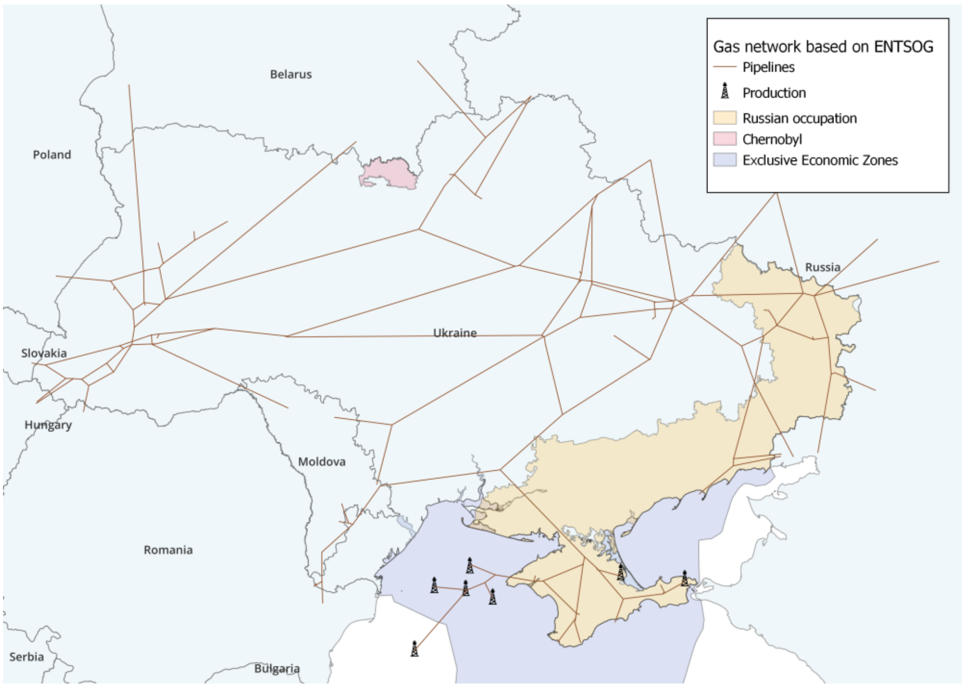


3.3.1.3 Pipelines availability

Ukraine has a dense nationwide natural gas transmission infrastructure (see Figure 9) that, in theory, could be used for hydrogen transport by repurposing the pipeline network or parts of it. Pipeline repurposing represents a great opportunity to cut the costs of hydrogen transport significantly, while avoiding social acceptance issues since the pipeline routes and rights of way are already established. The feasibility of such a process depends on several key characteristics of the network. One decisive factor for short-term repurposing is the availability of parallel pipelines to allow a gradual shift from natural gas to hydrogen without cutting off the natural gas supply. Additionally, due to the different characteristics of the two gases, a few challenges must be addressed for a successful transition. There is the need for new compressors for hydrogen transmission wherever parts of the network are repurposed. The age and material composition of the pipelines are also key aspects that determine the feasibility of repurposing and of avoiding potential damage like hydrogen-induced cracking (hydrogen embrittlement) (ACER 2021).

It is likely that the natural gas transmission network within the Ukraine will not be suitable for the transport of hydrogen, because of its condition and age as well as the materials used in construction (epravda 2020) . Furthermore, damage to the network due to military actions cannot be ruled out. Thus, Ukrainian natural gas networks require thorough research and modernization. The construction of new hydrogen pipelines within Ukraine might be necessary. Given the country’s size, pipeline transport within the country could make up a significant portion of the overall transport costs.

Figure 9: **Natural gas network (Source: own illustration based on ENTSOG)**



The regions Kherson and Zaporizhzhia present a special case, as they have virtually no existing transmission networks. As these two regions have some of the highest hydrogen potentials in Ukraine, it would be necessary to construct transport infrastructure here, either electricity or new hydrogen pipelines.

3.3.1.4 Storage potential

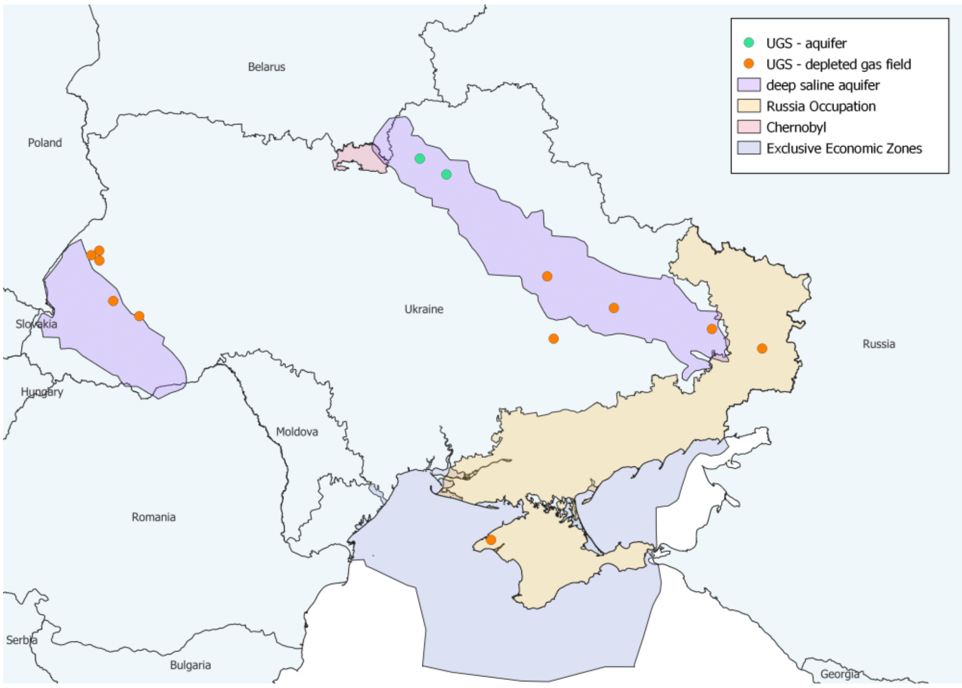
Ukraine has the largest underground natural gas storage (UGS) capacities in Europe with around 327.9 TWh at thirteen storage sites, of which eleven are depleted gas fields and two are saline aquifers (GIE AGSI+ 2022). All of them are currently operational and operated by PSJC Ukrtransgaz, a state-owned company that is part of the Naftogaz Group except for the facility in Hilbovske, which is located in Crimea and operated by PJSC Chornomornaftogaz. Two of the UGS facilities have come under Russian occupation but because these have rather small capacities (with a potential of around 15.56 TWh), the total natural gas storage potential of Ukraine is only slightly reduced. These UGS facilities offer great potential for future hydrogen storage in Ukraine and are already considered future hydrogen storage sites in the drafts of the Ukrainian National Hydrogen Roadmap and the Ukrainian Hydrogen Strategy as well as in the HyUSPRe project. However, it should be noted that the first two only refer generally to the existing UGS facilities in Ukraine and do not examine them in detail in terms of their suitability.

Figure 10 shows the location of all storage sites in Ukraine. The greatest UGS capacity is in the west of the country with around 79 % of the country's total potential. This is also due to the fact that Bilche-Volytsko-Uherske, the largest UGS site in Europe with a capacity of 179 TWh, is located in this area (Cavanagh et al. 2022; Yousefi et al. 2022).

In addition to the existing UGS facilities, there are two saline aquifers that have been discussed for the potential storage of CO_2, for which the presumption can be made that they are also suitable storages for hydrogen: the Dnieper-Donets and the North Carpathian aquifer (Cauchois et al. 2022). In the area of the Dnieper-Donets aquifer, (Caglayan et al. 2020) have additionally identified the occurrence of salt structures suitable for hydrogen storage. However, due to the lack of data for urban and rural areas in Ukraine, (Caglayan et al. 2020) could not calculate the hydrogen storage potential of these salt structures.

The overall underground hydrogen storage potential of Ukraine is estimated at 109 TWh working gas capacity considering all possible future storage sites. However, all these storage options are aquifers or depleted gas fields. Unlike storage in salt caverns, these types of hydrogen storage have a lower technology readiness level and are currently the focus of research projects (Alms et al. 2023). Current areas of concern include the purity of the gas, hydrogen losses due to biological or chemical reactions and diffusion through the cap rock as well as safety concerns.

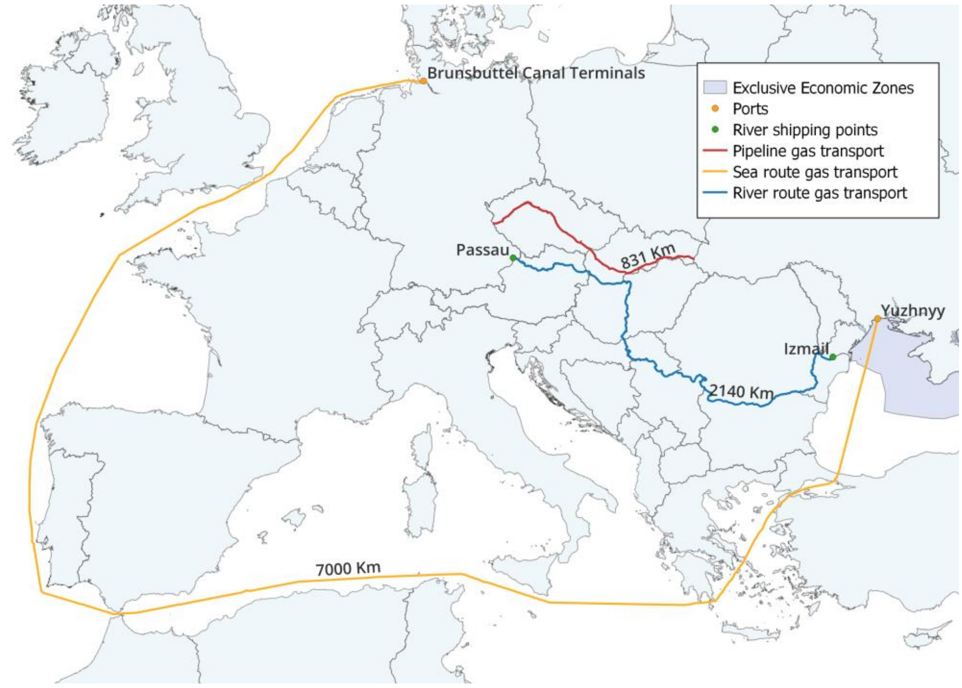
Figure 10: Ukraine's potential underground hydrogen storage sites (Cauchois et al. 2022; GIE AGSI+ 2022)



3.3.2 Export infrastructure to Central Europe

There are various options for transporting hydrogen from Ukraine to Germany and Western Europe. The shortest transport option is by pipeline. In this case the pipeline networks in Slovakia, the Czech Republic, Poland and Austria could potentially be repurposed. If repurposing infrastructure from natural gas to hydrogen proves to be techno-economically feasible, the transmission networks through Slovenia and the Czech Republic make exporting large quantities at low costs possible due to the existence of several parallel, large diameter pipelines. The other options for hydrogen transport are by ship, either via the Black Sea and the Mediterranean to ports in Central Europe or, if suitable river boats are available, via the Danube River. These different transport options are illustrated in Figure 11. At 831 km, the transport distance via pipeline is significantly shorter than the ship transport options with 2140 and 7000 km.

Figure 11: Transport routes between Ukraine and Germany



3.3.2.1 Export via pipeline

There are several large pipeline routes from the Ukrainian border to Germany and Central Europe. The transmission network is well developed with several parallel pipelines. This could enable a gradual transition from the transport of natural gas to hydrogen, if the parallel pipelines are successively repurposed and the compressor stations are fitted with additional compressors. The route with the highest transport potential, called Transgas, passes through Slovakia and the Czech Republic and has a transport capacity of at least 260 TWhH2/yr. Along the 831 km, about 4 compressor stations are required, which results in a power demand of roughly 4 kWh/kgH_2.

3.3.2.2 Export by ship

In addition to transport by pipeline, which needs significant investment in constructing or repurposing pipelines, hydrogen can be transported by ship. This is possible on the Danube River or by sea across the Black Sea, Mediterranean Sea, and North Sea. The sea route is significantly longer, but larger vessels can be used on open waters. Table 1 gives an overview of transport distance and ship capacity for both waterways. The comparison is made for methanol as a possible hydrogen carrier, because ships to transport methanol are already available both for sea and inland waterways. Although ships for the other carriers like liquefied hydrogen or ammonia and larger ships are likely to be available in the next years, the general ratio between inland and seaway transport remains similar. Therefore, sea transport will always be more attractive for large-scale production, although the Danube might be attractive for smaller projects in the medium-term future, as planned in the projects *H2U Hydrogen Valley (Riepkin 2021)* or *Green Hydrogen Blue Danube (Metelko 2020)*.

Table 1: Ship and distance comparison between transport via the Danube River or by sea from Ukraine to Germany

	Route	Distance	Ship capacity (Methanol)	Energy transport per ship
Inland route [5]	Izmayil-Passau	2140 km	3000 t	470 GWh/yr
Sea route [6]	Yuzhnyy-Brunsbüttel	7000 km	75000 t	6575 GWh/yr

Ukraine has multiple ports along the Black Sea coast that are potentially able to export hydrogen or other energy carriers[7]. The ports are depicted in Figure 12.

Figure 12: Seaports in Ukraine. Regions affected by the Russian Invasion as of June 2022 are marked in red. Yuzhne as an ammonia terminal is marked in green. Own illustration based on (Argus 2023; Maritime Safety Information 2020)

The port of Yuzhnyy already has an existing ammonia terminal (Argus 2023), and is therefore likely to be used as export hub. It is marked in green and was used for the distance calculation in Table 1. It must be pointed out that the ports of Kherson in Crimea and those along the Sea of Azov are affected by the Russian invasion as of June 2022; the latter are further affected by frequent freezing of the Sea of Azov during the winter months.

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5 (Lahmann 2021).

6 (epravda 2020; odfjell 2023). (epravda 2020; odfjell 2023)

7 Minimal size "S" according to the World Port Index.

3.4 Summarizing the preliminary techno-economic results

Ukraine has a high potential for generating renewable electricity. RE potentials are estimated to be around 2,100 TWh (<80 €/MWh) in an optimistic scenario in the longer term. Almost 30 % of Ukraine's RE potentials would not be available at present, as these are located in areas currently occupied by Russian forces. The same areas are home to 56 % of the existing steel production capacities, which hampers the potential to export green steel from Ukraine.

In an optimistic scenario, with strong economic development until 2050 (low interest rates assumed) and a climate-neutral, highly electrified and efficient energy system, it is feasible that over 30 EUR/MWh_{el} of electricity would be available for export or for producing exportable hydrogen. In a conservative scenario, with weak economic development until 2050 (high interest rates assumed) and a nearly climate neutral and largely electrified energy system, over 90 EUR/MWh_{el} electricity would be available for export or for producing exportable hydrogen. However, these strongly simplified initial results are based on RE potentials and the TFC. They consider neither energy transformation nor distribution losses. These will be further elaborated in a detailed techno-economic evaluation within HYPAT, which assesses an optimized national energy system as a whole.

Ukraine has well-developed infrastructure for exporting hydrogen or other energy carriers to Western Europe in the form of pipelines and seaports. In particular, the pipeline network in the Ukraine and the transport pipelines in Slovakia and the Czech Republic that lead to Germany have a high potential to be used for hydrogen. Within Ukraine, thorough investigations are necessary to establish the condition of the pipelines. Potentially, new construction of hydrogen pipelines will be necessary if repurposing proves unfeasible or not economic.

Furthermore, Ukraine has an estimated potential of 109 TWh of underground hydrogen storage, which is remarkably high. However, most of the UHS sites are located in the north-east of the country, which is far away from both the potential export ports for ship transport and the regions with the highest hydrogen production potentials. This could result in either higher transport costs or in higher storage costs if other, more expensive storage options are employed.

Finally, pipeline and port infrastructure as well as storages are likely to be affected by the Russian invasion. Nevertheless, the assessed infrastructure and export routes will be used as input for the detailed techno-assessment of PtX exports within HYPAT.

4 The Prospects for Ukraine on the EU Market for Hydrogen.

4.1 Possible hydrogen development pathways for Ukraine

A review of the main program documents of the EU aiming at the hydrogen development - "Green Hydrogen Investment and Support Report" (Hydrogen Europe 2021) and "Green Hydrogen for a European Green Deal A 2x40 GW Initiative" (van Wijk 2020) - reveals that the EU acknowledges the importance of Ukraine in advancing the hydrogen economy.

According to "Green Hydrogen for a European Green Deal A 2x40 GW Initiative" in Ukraine, 10 GW of new capacity for the production of green hydrogen could be created. This seems reasonable considering that experts from the Institute of Renewable Energy of the National Academy of Sciences of Ukraine, the "Ukrainian Hydrogen Council" and "Hydrogen Europe" associations estimate that Ukraine has the second largest renewable energy potential in Europe (wind, solar and biomass energy) (Kudria 2020) (IEA 2021b). Four regions in Ukraine are able to provide half of the energy demand of the EU countries. Thus, according to the data of the Ukrainian Hydrogen Council, these regions are the most promising: Odesa (4 GW of solar energy and 34 GW of wind energy), Mykolaiv (3 and 30 GW, respectively), Kherson (3 and 34 GW) and Zaporizhia (3 and 33 GW). EU plans assume the development of 11 GW of wind power plants and 11 GW of solar plants in Ukraine, which could power electrolyzers with a capacity of 10 GW for the production of green hydrogen (ECOBUSINESS magazine 2020).

At the same time, the European Commission states that Ukraine will not be transformed into a “raw material” annex for the purpose of producing and supplying green hydrogen. The EU is ready to contribute financially and organizationally to the creation of an internal market for green hydrogen in Ukraine, so that the country can also integrate innovative technologies into its economy and industry. The volume of planned EU investments in the implementation of the above mentioned plans is about EUR 20 billion (ECOBUSINESS magazine 2020). Ukraine has to provide the right conditions for using hydrogen in transport, and in the metallurgical and chemical industries. Ukraine has already taken the first steps in this direction, for example, the construction of the first hydrogen filling station in partnership with Denmark. Germany is providing key assistance in developing a hydrogen market in Ukraine. Both countries signed a "Joint Statement on the Beginning of Energy Partnership". The announced partnership will include, in particular, cooperation in the field of hydrogen supplies from Ukraine to Germany (NFU 2020). Ukraine is also discussing pilot projects with Germany on a scale of 100 MW and up, similar to the 100 MW solar-hydrogen plant project in Morocco. In addition, the Czech company Witkowitz - one of the largest machinery and engineering companies in Eastern Europe - is negotiating with "Pivdenmash" on the construction of a plant to produce equipment for hydrogen production (NFU 2020). Hydrogen production also represents an opportunity with respect to Ukraine's surplus power generation. Ukraine's nuclear-industrial complex could make good use of this opportunity. Nuclear hydrogen can be competitive for realizing the European Commission's intentions to deploy electrolyzers for hydrogen production with a total capacity of 40 GW in the Eastern and Southern Partnership countries by 2030. However, it remains highly uncertain whether importing hydrogen produced using nuclear energy will be a viable option for the EU in terms of sustainability.

4.2 Perspectives for Ukraine from the implementation of EU plans

Despite the war, the EU continues to be interested in Ukraine in terms of a hydrogen economy. In particular, in early January, Ukraine was visited by Frans Timmermans, Executive Vice-President of the European Commission. The main topic of the meeting was the *Action Plan for Ukraine's recovery*. The "Timmermans Recovery Plan" includes 10 measures of strategic importance for Ukraine (UHC 2023). On February 2, 2023, Ukraine and the European Commission signed a Memorandum of Strategic Partnership in the field of renewable gases. This represents a big step and a new stage in synchronizing the efforts between Ukraine and the EU on green transformation (Oleksandr Riepkin 2023). Analyzing the consequences of implementing the specified EU plans to develop a hydrogen economy revealed the following opportunities for the Ukrainian economy:

- In addition to geopolitical advantages, *the implementation of the policy of energy independence* will significantly improve the state of the country's balance of payments due to a decrease in imports.
- *Demonopolization of the production and distribution of electricity in the country*. Demonopolization could contribute to the emergence of competition, increase investments in the development and reconstruction of the existing infrastructure, undermine the monopoly positions of Ukrainian financial and industrial groups on the energy market and thus have a positive effect on the market price.
- *Reduction of harmful emissions* from the energy, metallurgical and chemical industries and in certain areas of the transport sector.
- *Creation of a new export industry with financial and technological support by the EU*: the installation of 10 GW capacity of wind and solar power plants is expected, 7.5 GW of which will produce green hydrogen to meet EU demand (van Wijk 2020).
- *Creation of the internal hydrogen market with the help of the EU.* According to the "Green Hydrogen for a European Green Deal A 2x40 GW Initiative" strategy, the EU is ready to provide assistance to develop the internal market for the production, storage and use of hydrogen (the installation of 2.5 GW of wind and solar power plants is expected to cover the needs of the domestic market) (van Wijk 2020).
- *Creation of new jobs in energy supply and infrastructure as well as the supplier industry.* According to the calculations of international organizations, such as the Global Wind Energy Council, 1 million dollars spent on the creation of renewable energy sources creates 7.49 permanent jobs, which, when compared to the equivalent figure for conventional energy of 2.66 jobs, is 3 times higher (GWEC 2021). However, it should be considered that some of these jobs are only short term. Other estimations carried out as part of the EU initiative "Green Hydrogen for a European Green Deal A 2x40 GW Initiative" also envisage the creation of new jobs for the maintenance of electrolyzers, power plants and the necessary infrastructure (van Wijk 2020; Zelenko 2021).
- *Reconstruction of steel infrastructure based on new decarbonized processes.* As mentioned in Figure 9, most of the steel infrastructure is in the currently occupied area and has been affected by the war. This offers the opportunity to rebuild infrastructure using decarbonization technologies (e.g., direct reduction of iron using hydrogen).

The opportunities described above show that hydrogen could play an important role in the reconstruction of the Ukrainian economy after the war, especially since the Ministry of Energy and Coal Industry of Ukraine has expressed the desire to develop green hydrogen production together with partners from the EU. The partnership with the EU foresees investments of about 20 billion euros in the Ukrainian economy to create a complex for the production, storage and transportation of green hydrogen (epravda 2020a). However, in addition to the ongoing war, the investment climate and economic policy in Ukraine may significantly affect the speed of implementing EU plans.

5 Summary and Conclusions

Despite the ongoing war, the EU remains interested in Ukraine as a potential future supplier of hydrogen, to meet European energy demand and support Ukraine's recovery.

- From an economic point of view, the production of green hydrogen is currently too expensive and requires significant financial support to become cost-competitive. With the financial and technological support of the EU, 11 GW wind and 11 GW photovoltaic plant capacity could be installed in Ukraine by 2030 to produce green hydrogen (10 GW electrolysis) for export and the domestic market.
- The recently published national Hydrogen Roadmap and Hydrogen Strategy of Ukraine lay the foundation for this partnership (see chapter 2.2). The development of green hydrogen production capacities as well as exports could contribute to the revitalization of territories and the creation of additional jobs.
- Germany plays a major role in the development of a hydrogen market in Ukraine, as the "Joint Statement on the Beginning of Energy Partnership" includes cooperation in the field of hydrogen supplies from Ukraine and Morocco to Germany.

Ukraine should harmonize with European hydrogen standards and follow European rules when exporting hydrogen to the EU.

- Consequently, there is a necessity to create and implement a Ukrainian hydrogen standardization system that would comply with European standards and norms.

Green steel could become an important export product in the future, generating additional revenues and enabling local value creation in the country.

- The established steel production know-how, existing infrastructure and long experience in exporting steel could give Ukraine a competitive advantage over other potential suppliers of green steel, which are not yet players on the steel market.

Ukraine as well as the relevant transit countries have well-established infrastructure for the exporting hydrogen and PtX products to Western Europe via pipelines and seaports, but repurposing needs further investigation.

- In particular, the pipeline network from Ukraine through Slovakia and the Czech Republic to Germany has a high potential to be used for hydrogen. New construction of hydrogen pipelines may be necessary if repurposing is neither technically feasible nor economical.
- The estimated underground hydrogen storage potential in Ukraine of 109 TWh is remarkably high, although most sites are located a long way from both export ports and pipelines, as well as from the most favorable hydrogen production sites. This could increase storage and transportation costs. Furthermore, it is as of now uncertain if hydrogen storage at these locations is indeed feasible.
- The most significant techno-economic obstacle to the development of a hydrogen economy in Ukraine is the critical state of the gas transport infrastructure within Ukraine.
- Considering the existing state of certain gas pipelines, the government would need to formulate a comprehensive program aimed at modernizing the gas transformation

network. This program should include various sources of financing, such as budgetary allocations, private investments, international grant programs, and loans.

Important energy infrastructures and land for potential RE deployment are currently occupied by the Russian military. Apart from that, the war's uncertain duration and outcome increase the risks of investing in developing the large RE potential in Ukraine. As a result, low-cost RE might only be sufficient to cover domestic demand.

- Half of the coal-fired power plants and most of the wind turbines near the Black Sea coast, as well as Zaporizhzhia - Europe's largest nuclear power plant - are currently under Russian occupation.
- Ukraine was only able to produce 6,000 tons of steel in 2022, down from 21,366 tons in 2021, due to the invasion of Russia, which controls half of the country's steel and iron plants.
- Ukraine harbors a relatively large potential for solar PV and wind within Europe. When calculating the levelized cost of electricity from wind and solar, the political, social and economic situation of the country is reflected in the interest rate: The assumptions are 4.5% for a rapid and positive development, 21.9% for a slow development after the war until 2050.
- The RE potential in the war-affected regions accounts for almost 30% of the total potential below 80 EUR/MWh for the low interest scenario.
- Investment risks play an important role when estimating the cost of future renewable electricity. If investment risks are high, so too are interest rates. This could reduce the RE potential at 80 EUR/MWh from ca. 2,100 TWh (4.5%) to ca. 500 TWh (21.9%), which would barely be sufficient to meet domestic demand.

Opportunities and obstacles: The development of a hydrogen economy can bring socio-political advantages, such as new jobs. Nevertheless, large-scale hydrogen production in Ukraine might be limited due to water scarcity and competitive water use for the agricultural sector and could imply higher energy costs for households.

- Job creation in the hydrogen sector could be important for the recovery of the Ukrainian economy. The production of green hydrogen will come with a significant number of renewable energy installations that might require 27,000 - 50,000 job per year.
- Producing large amounts of green hydrogen using electrolysis requires significant volumes of deionized water. Ukraine is currently one of the European countries with the lowest supply of drinking water (except for the southern region of Ukraine), and the global warming of the climate implies increasing water shortages. This challenge could be overcome, as using desalinated water would increase hydrogen production costs by only a small margin.

In summary, developing green hydrogen production in Ukraine is a long-term goal that requires active government involvement and significant investments.

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	Project 1: Kakhovka Project / River Wind	Project 2: Danube Hydrogen Valley	Project 3: H2 Production Region Sumy	Project 4: Transcarpathian Green H2 Project	Project 5: Kyiv Green Data Centre	Project 6: Energy Project "European Galicia"
Brief description/Goal	H2-Hybrid-Plant based on PV- and wind energy plants on Ukrainian inland waters	H2-production and transport along the Danube	Production of green H2 from wind power. Transport via main gas-pipeline from Russia through Ukraine to EU	Green H2 production from PV and transport via pipeline. Production of green H2 in biomass gasifiers in winter	H2-production from PV	Green hydrogen and Ammonia Production based on PV
Location/Region	Northwestern part of the Kakhovka Reservoir. It is located on the Dnieper River in Southern Ukraine and covers a length of 240km an area of 2155 km^2	Danube Mouth, Region Odessa	Region Sumy, City of Bilopillya, North East from Kyiv	Transcarpathia Region, located in Western Ukraine at the border to Romania. Village of Gudya. The main pipeline for gas to Romania crosses the site	Makariv District, Kyiv Region. 136 ha land owned by "Solar Energy" LLC	Kamianka-Buzka, Lviv Region in Western Ukraine. Proximity to Polish border: 36km. Distance to existing gas pipeline is 500 m
Products	H2, Ammonia	H2, Ammonia	Hydrogen	Hydrogen	Hydrogen	Hydrogen, Ammonia
Planned installed capacity (RE)	Phase 1: 150-250 MW wind power , 50 MW PV Phase 2: 600-800 MW wind power , 400 MW PV	Phase 1: 50 MW PV Phase 2: 2 GW PV, 3 GW wind power	120 MW (mix PV and wind power)	100 MW PV	100 MW	Total: 400 MW PV 4 Phases with 100 MW each
Planned installed capacity (Elektrolyzer)	Phase 1: 200 MW Phase 2: 1.1 GW	Phase 1: 50 MW Successive increase up to: 3 GW	110 MW 2.5-3 tons H2 per hour	30-35 MW	30 MW	Total: 200 MW 50 MW per Phase
Projected timeline	Phase 1: 2021\2022	Expected 2025		Design 6-8 months, construction and installation 1.5-2 years	Design, 6 months, construction 1.5 years	Plant construction: 3 years First Phase: 1.5 years
Investment volume	Phase 1: €400 m Phase 2: over €2 bn	Phase 1: €100 m Up to €14 bn.	€280 m	€130 m Discounted payback period 5-6 years	€125 m	€400 m Payback period 5 years
Usage of hydrogen	Export/Local	Local/Export	Export	Export	Local/Export	
Transport	Pipeline	River transport, technical possibility for direct pipeline transport to Germany via existing gas transport system (additional research required)	Pipeline, also railway transport possible	Pipeline, road, and rail	Either by das carriers of by pipeline. Solution expected in the next 2-3 years.	Rail and road. Pipeline transport at a later stage of the project
Scalability	Up to 1.2 GW installed power capacity (RE) and 1.1 GW electrolyzers capacity	Up to 5 GW installed power capacity (3 GW Wind, 2 GW PV) with 3 GW electrolyzer	Scaling up possible. High wind potential, sufficient land and water resources			
Positive Side Effects	Stabilization of the power grid (no feeding into the grid intended)	Connection to the European power transmission grid	Economic strengthening of the region	Environmental protection measures planned for stabilization of ecological condition of the region	4-5 hydrogen fueling stations planned in the area. Support the sustainable social and economic development of the Kyiv Region	
Consortium	- River Wind Ukraine - East European Association for the development of hydrogen economy, - Federation of employers Ukraine - Naftogaz Ukraine - Expressions of interest: SIEMENS, Linde und ThyssenKrupp	- Danube Hydrogen Valley - Reni electolysis plant - Reni solar cluster - Safyan solar cluster - Kilia solar cluster - Danube Offshore Wind - Danube electric company	- ESE Investment AG - Siemens - TSK	- Geotermika - LS Profi	- Solar Energy LLC - LS Profile Group	- AS National
Stakeholder	- Ministry of Energy of Ukraine	- Ministry of Energy of Ukraine - Ukrainian Hydrogen Council	-	- Ministry of Energy of Ukraine	-	- Ministry of Energy of Ukraine

	Project 7: Green Hydrogen Plant Lviv Region	Project 8: Green Hydrogen Industrial Cluster	Project 9: Green Hydrogen Plant Vinnytsia and Chernivtsi Regions	Project 10: H2 International Project Initiative "H2EU+Store"	Project 11: "Salt for Life"

Brief description/Goal	Green hydrogen production via SIEMENS Silyzer 300 powered by solar energy.	8.5 MW pilot project for green H2 using existing RE installations	Production of green H2 using the capacities of existing hydropower installations. Additional power supply through wind and PV installations	H2 production from RE in Ukraine, transport, storage in Austria, and market development. The key-elements are the transportation via pipeline and storage of hydrogen.	H2 production and storage in salt caverns
Location/Region	Transcarpathia Region in Western Ukraine, directly at the Slovakian border	Nikopolskyi Basin located in South-East Ukraine	Vinnytsia and Chernivtsi Regions, Dniester River	Western Ukraine	Solotvyno, Western Ukraine
Products	H2	H2	H2	H2 (Storage and Production)	H2 (Storage and Production)
Planned installed capacity (RE)	36 MW PV	The project does not plan to install additional RE capacities in the first phase. 440 MW RE already exist in the region that could be used to power 200 MW EL	40.8 MW hydropower (already installed) 37 MW PV (3 MW operating already), 10 MW wind power	Phase 1:147 MW RE (mix PV and wind power) already installed. Additional 94 MW ready-to-built Planned are 1 GW PV and 0,7 GW wind power	Established: 15 MW, currently no RE generation planned
Planned installed capacity (Elektrolyzer)	17.5 MW (Silyzer 300, SIEMENS)	Phase 1: 8.5 MW Future Perspective: 2.5 GW local market, 7.5 GW export	No data	Phase 1: 1,5 GW Phase 2: 40 TWh bis 2040 Phase 3: 80 TWh bis 2050	Unknown, Storage capacity 12 m^3
Projected timeline	No data	Phase 1: 2022	No data	Phase 1: 2020-2030. First production of H2 expected by 2025 Phase 2: 2030-2040 Phase 3: 2040-2050	
Investment volume	€70 m	Phase 1: €25 m	No data	€105 m for RAG infrastructure testing and H2-storage construction Investment volume for H2 production uncertain	€278-508 m
Usage of hydrogen	Export	Phase 1: Local Future: Local/Export	No data	Export	Local/Export
Transport	Pipeline	Pipeline (H2 or Ammonia), LOHC	No data	Pipeline	Pipeline (Transit pipeline "Brotherhood" at 50km distance)
Scalability	No data	200 MW, (2 GW electrolyzer capacity through certificates of origin scheme)	No data		
Positive Side Effects		Enable stakeholders to study practically the regulatory, commercial, technical, and logistics aspects of an establishment of a H2 economy in Ukraine	Creation of an energy cluster, possibility to work with ENTSO-E		Medical use of the particularly pure salt, especially in the treatment of lung diseases (Asthma, Covid). Rehabilitation of environmental damages caused by salt mining.
Consortium	-	- DTEK -	- PJSC "Nyzhniodnistrovska HPP"	- RAG Austria AG - Eco Optima - Bayerngas	- ENSA - SPA Speleocenter Solotvyno - IKEM - Rudolfinerhaus - AvantGarde Energy - AHK Ukraine - IAEA - PSE Engineering GmbH - EnergoAtom - Energoproekt - Girhimprom - Ukrenergo
Stakeholder	-	- Ministry of Energy of Ukraine	- Ministry of Energy of Ukraine	-	- Nobel Sustainability Trust - World Anticancer Movement