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Short Study

Green Hydrogen in Ukraine: Taking Stock and Outlining Pathways

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Content

Executive Summary

Lessons from renewable power

This study outlines the current framework for hydrogen as an energy carrier in Ukraine, its future development possibilities, as well as open technical, regulatory, and economic questions. It aims to collect existing knowledge, identify research gaps, and initiate a technical and political dialogue as well as an intensified future cooperation.

As a precondition for the production of green hydrogen, it confirms the notion that Ukraine has the geographical potential to produce green hydrogen on a large scale, for both domestic use and export. Due to its large territory and areas with high solar radiation and wind speeds, **Ukraine has favourable conditions for relatively low cost production of renewable energy.** Since the price of renewable energy is the main cost determinant for green hydrogen, this enables an economic and **large-scale hydrogen production**. Ukraine's considerable **biomass potential can complement the development of a green hydrogen sector**, as biomass and renewable power can be combined to produce hydrocarbon renewable fuels and methane.

The country is well-positioned to repeat the **rapid uptake of renewables between 2014 and 2020, which saw solar and wind capacities increase from 0.97 GW to 8.5 GW,** accompanied by an investment of € 8 billion. In 2019 alone, the energy system witnessed a tripling of PV to 6 GW and a doubling of wind power capacities to 1.2 GW. Howeverf, **the further development of the RE sector is uncertain: Due to payment arrears to RE producers, as well as a repeated postponement of the new action-based support scheme**, the **rapid increase in the RE sector has recently come to a halt.** In addition, a **further expansion of the sector is constrained by generation and transmission adequacy**: this year Ukraine lacked 2 GW of flexible generation capacity and 200 MW of electrical storage.

Defining a policy framework for hydrogen

Green hydrogen is now a priority of Ukraine's energy policy, representing a building block for the local energy system, as well as an export opportunity. **Policy efforts were kicked off in 2020. A large-scale hydrogen economy can** contribute to the uptake of the RE sector and as such **decarbonize the national energy system.** It can further contribute to scaling up the deployment of RE capacities through foreign investments and by stabilizing the national power grid.Furthermore, **Ukraine has increasingly gained international attention as a potential hydrogen supplier for the EU**. Hydrogen Europe foresees a central role for Ukraine as an energy exporter, with 8 GW of green hydrogen capacity until 2030. In addition, more than 25 Ukrainian companies have joined international hydrogen alliances, among them nuclear company Energoatom and the gas transportation system operator of Ukraine.

In 2020 a working group on hydrogen was initiated as part of the newly founded German-Ukrainian Energy Partnership. With support from the United Nations Economic Commission for Europe (UNECE), a draft for a Hydrogen Roadmap has been presented in February 2021 as a precursor to a hydrogen strategy. However, **for the development of a fully-fledged hydrogen strategy for Ukraine, technical, political and economic uncertainties that are not addressed in the draft, still have to be resolved.** This includes the existing bottlenecks and uncertainties in the renewable energy sector, where 2 GW of flexible reserve capacity are missing and the ex-post reduction of the feed-in-tarriff created additional uncertainty for investors. Beyond that, low retail electricity prices limit the investment in the power sector as a whole. Both Ukrainian and EU policymakers must act to resolve these issues.

Solving the transport question

Besides establishing the preconditions for the production of green hydrogen, **enabling hydrogen transport to Ukrainian and EU customers is crucial** for establishing a hydrogen economy in Ukraine. **Hydrogen transport via pipeline** will be the **cheapest transport option for Ukraine**, especially for export. **Maritime shipping** of hydrogen via the Danube River may be a **transport opportunity in the shorter term,** but **cannot be cost-competitive** with pipeline transport. The transport of derivatives, such as ammonia, may be a solution for riverine transport.

The **extensive existing natural gas pipeline infrastructure in Ukraine can enable cheap hydrogen transport** for both blending in the short term and pure hydrogen in the medium term. Hydrogen transport can emerge as a new business case for Ukrainian TSOs in light of declining gas transit projected in the mid-2020s. Moreover, the **possibility to retrofit existing**, idle pipelines for pure hydrogen transport gives Ukraine a major cost advantage over other potential hydrogen exporters without idle capacities. To what extent, how, and when the existing pipeline system can **transport Ukrainian green hydrogen needs further investigation**. Ukrainian DSOs and TSOs **currently undertake required technical research concerning possible blending limits** and necessary system modifications. This research should be continued, deepened, and made publicly accessible to give policymakers, project initiators and investors certainty about export possibilities.

Besides technical adaptations, the Ukrainian regulatory framework for gas transport has to be adapted for hydrogen transport. Outlining a system conversion pathway, towards pure hydrogen, will be an important strategic step. As part of this, uncertainties about local hydrogen consumption and production scale-up have to be resolved. To allow for hydrogen export via pipelines to central Europe, **transport via transit countries** such as Slovakia and the Czech Republic **has to be enabled**. The first steps of coordination between Ukraine and the transit countries have already been taken.

A green hydrogen scenario: establishing economic feasibility of hydrogen projects

Through the **installation of 8 GW until 2030**, as outlined by Hydrogen Europe in the 2x40 GW initiative, **Ukraine could produce around 21 TWh of green hydrogen annually**. This would cover 12% of the total hydrogen demand of the EU in 2030 projected in the EU Hydrogen Roadmap. Based on our scenarios this would be achievable but require immediate, significant and consistent efforts to maintain a constant growth rate of installed capacity by 64% every year until 2030. **Despite assumed technology cost reductions** (e.g. 48% decrease in electrolyzser costs until 2030), **total investments between €11.5 and €20 billion** will be required.

Uncertainties regarding government policy and hydrogen transport hamper the implementation of pilot projects. Under current macroeconomic conditions, hydrogen producers incur **high capital costs**, impeding **profitability and international competitiveness**. Therefore, policies aimed at guaranteeing offtake or improving access to capital (e.g. through guarantees) will be required, domestically but also from EU countries. Other **dominating risk factors** are the lack of **transport** (blending quotas, regulation, transit countries), and a **domestic and export market for green hydrogen**. Pilot project initiators have repeatedly pointed out the **necessity for long-term offtake guarantees and price security** in order to secure funding for projects.

Although numerous pilot projects (see annex) have been proposed, **no project has yet been implemented**. For the implementation of pilot projects, **fast development of a Ukrainian hydrogen strategy or roadmap, government-guaranteed offtake contracts and the resolving of technical and regulatory constraints of pipeline transport are crucial.** The findings of this study suggest that the rapid implementation of a **first pilot project** could significantly accelerate the development of the hydrogen sector in Ukraine, as open questions could be addressed and resolved directly, thus paving the way for the following projects. However, given the risks inherent in such a first-mover project, strong government support will be required.

Based on this analysis, recommendations for the development of green hydrogen in Ukraine include

i. the development of a national hydrogen strategy for Ukraine,

ii. securing hydrogen pipeline transport to the EU, and

iii. improving the economic feasibility of hydrogen projects in Ukraine.

Both Ukrainian and EU policymakers must take action to resolve these issues. In particular, the work on a hydrogen roadmap has to be continued and intensified in order to take the next steps towards a national hydrogen strategy.

Besides the hydrogen strategy, research in transport opportunities of hydrogen via Ukrainian pipelines should be continued, deepened, and made publicly accessible to give project initiators and investors certainty about export possibilities.

Beyond the political and technology uncertainty, economic uncertainties exist, reflected amongst others in high costs of capital. Measures such as government investment backing, loan guarantees, tax breaks, fast-track permitting or guaranteed long-term offtake contracts are tried measures for both Ukraine and its foreign partners. The findings of this study further suggest that the rapid implementation of a first pilot project could significantly accelerate the development of a hydrogen sector in Ukraine. Open questions could be addressed and resolved directly, thus paving the way for subsequent renewable hydrogen plants.

1. Ukrainian Energy and Hydrogen Policy Goals

Energy Policy Goals: past and current developments

Renewable energy (RE) generation is one of the key priorities for the Ukrainian energy sector and the national economy. As one of the first countries to ratify the Paris Agreement[1], Ukraine aims at reducing its large share of non-renewables in its energy system. These currently dominate the total primary energy supply and electricity sector but shall continuously be replaced as the development of the RE sector is promoted and energy efficiency increased. Besides Ukraine's NDC in the context of the Paris Agreement, the national energy goals are outlined in different policy papers, which are presented in the following.

Energy Strategy of Ukraine 2035 (ESU2035)

Ukraine's energy goals are officially determined in the current ESU2035 dated 18 August 2017. The strategy envisages, among other things, until 2035,

i. continuous growth of RE in the total primary energy supply to 25%,
ii. reduction of import dependence on energy resources to <33%,
iii. a two-time reduction of energy intensity to 0.13 toe/tsd USD, and
iv. the integration of Ukraine into the EU energy market.

[1] Source: https://treaties.un.org/Pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-7-d&chapter=27&clang=_en

Figure 1: Key indicators of the ESU2035[4]

Indicators	2015	2020	2025	2030	2035
Primary Energy Intensity, toe/thousand USD GDP PPP	0.29	0.20	0.18	0.15	0.13
Share of RE (incl. hydro and thermal energy) in the total primary energy supply , %	4	8	12	17	25
Share of RE (including large hydro) in electricity production, %	5	7	10	>13	>25
Share of wind and solar in electricity production, %	0.1	1.2	2.4	5.5	10.4

However, the latest OECD monitoring report points to structural weaknesses of the ESU2035: it is not aligned with the 2020 Action Plan[2], which is currently being phased out, it includes deficient monitoring mechanisms only partially aligned with EU-Ukraine Association Agreement, and it lacks information on funding[3]. Against this background, Ukraine is in the process of revising the ESU2035. The revised version is supposed to be submitted for approval to the Government in Q2 2021.

National Energy and Climate Plan (NECP)

Besides outlining its energy policy in the ESU2035, Ukraine, as a Contracting Party of the Energy Community, has committed to submit its NECP by the end of 2020. In their NECPs, member states are to provide comprehensive information on their national energy and climate policies for a period of 10 years and give an outlook to 2050[5]. Nonetheless, The NECP has not been issued on time and is expected for 2021, partly due to its interlinkage with the development of the second Ukrainian NDC and the described ESU2035 revision[6].

Concept of a Green Energy Transition (CGET)

A third policy declaration, the CGET, has been presented by the Ukrainian government in January 2020 in response to the European Green Deal, emphasizing that Ukraine is synchronizing its energy policy with that of the EU. At the time, the ambitious announcement caused a stir, but the CGET has since been on hold and is not officially adopted. The concept envisages the establishment of a climate-neutral economy by 2070, as well as the reduction of CO2 emissions by 2030 in line with the currently revised and more ambitious NDC. The main intermediate targets by 2050 are

i. 70% of electricity generation from renewable energy,
ii. 100% substitution of coal-fired power plants, and
iii. 20-25% share of nuclear energy in the energy balance[7].

Even though the ESU2035 is being revised, and neither the NECP nor the CGET has been issued or approved, Ukraine positions itself as a country that seeks to make an energy transition by 2050. Relevant statements were made both by the Prime Minister of Ukraine and by the Acting Minister of Energy during the 1st German-Ukrainian Energy Day in December 2020.

To summarize, Ukraine pursues an ambitious energy transition to comply with the Paris Agreement that has been announced on various occasions. RE capacities are to be promoted and the dominance of fossil energy sources in Ukraine is to be reduced. However, the policy measures issued to date do not sufficiently reflect this ambition, as can be seen in the necessity to revise the ESU2035, which leads to uncertainties concerning the future development of the energy system. The following section will give an overview of how Ukraine's energy policy has influenced the development of the RE sector over the past years.

Recent developments in the RE sector and policy outlook

After a period of stagnation in the RE sector between 2011 and 2014, Ukraine was able to expand its renewable electricity generation capacity from 0.97 GW in 2014 to 8.5 GW (as of 1 January 2021, excluding large hydropower). The rapid uptake starting in 2014 has been driven by a total investment of € 8.1 billion in the

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[2] National Renewable Energy Action Plans should provide a clear answer on how the national renewable energy target will be reached and how it will be achieved in the main sectors of electricity generation, heating and cooling, and transport. They must also define the renewable energy support/development plans and the structure of renewable energy production, generation and consumption.
[3] Source: https://www.oecd.org/eurasia/competitiveness-programme/eastern-partners/Monitoring-the-energy-strategy-Ukraine-2035-EN-.pdf
[4] Source: Diachuk, O., Podolets, R., Yukhymets, R., Pekkoiev, V., Balyk, O., & Simonsen, M. B. (2019). Long-term Energy Modelling and Forecasting in Ukraine: Scenarios for the Action Plan of Energy Strategy of Ukraine until 2035.
[5] Source: https://www.lowcarbonukraine.com/en/lcu-submitted-draft-for-integrated-national-energy-and-climate-plan-necp/
[6] Source: https://www.energy-community.org/implementation/Ukraine/CLIM.html
[7] Source: http://mpe.kmu.gov.ua/minugol/control/publish/article?art_id=245434883

deployment of RE, incentivized by the Ukrainian "green" tariff that was first introduced in 2009 and has since been adapted several times. In 2019 alone, the investment reached € 3.7 billion followed by € 1.2 billion in 2020.[8]

Figure 2: Development of RE electricity capacity by sector 2010-2019 (GW), Based on IRENA REmap

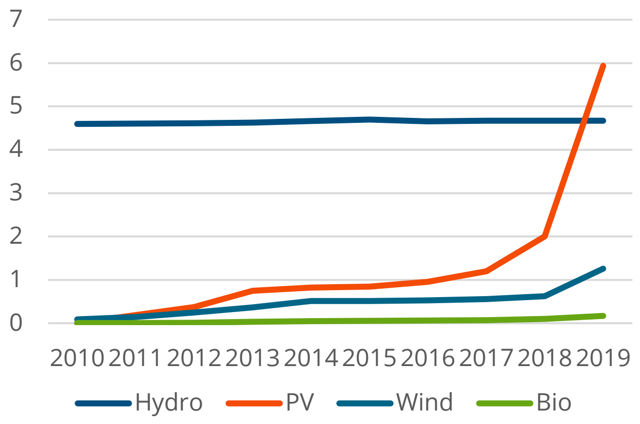
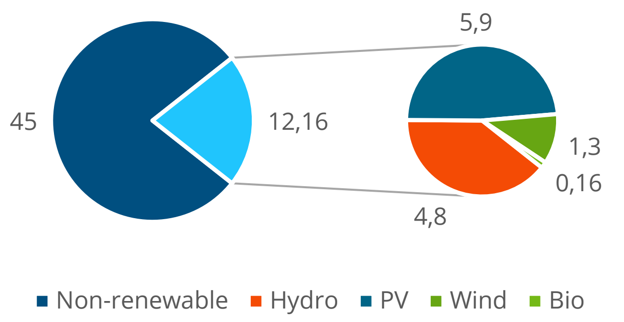


Figure 3: Installed electricity capacity 2019 (GW), Based on IRENA Remap

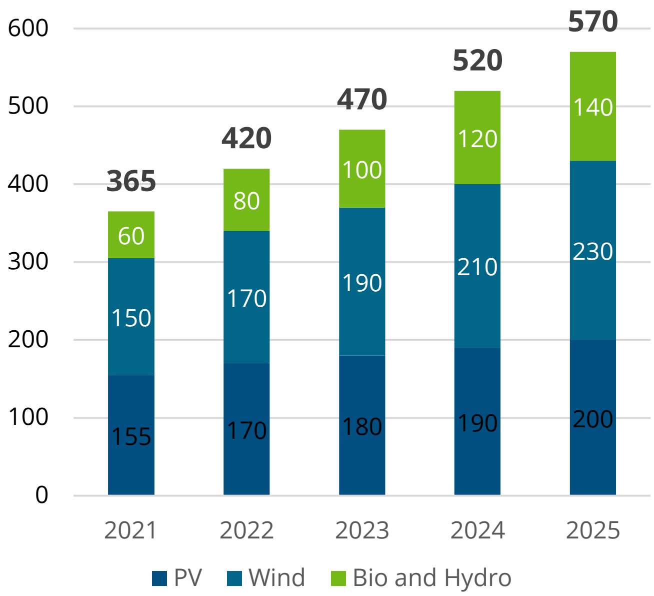


Despite the positive development in recent years, the further development of the Ukrainian RE sector is uncertain. Due to an unresolved crisis of payment arrears to producers of green electricity caused by the current support model and excessively high apportionment costs many projects were frozen resulting in a 3-fold decrease in investments from 2019 to 2020. After 9 months of talks, Ukraine signed an MoU with 2 industry associations on 10 June 2020, according to which the "green" tariff had to retroactively decrease by 7.5% (wind) and 15% (solar). On July 21, 2020, the Law on Feed-in Tariff Restructuring was passed by the Verkhovna Rada of Ukraine. The average tariff for solar power was thus reduced from €0.16/KWh to €0.1344/KWh and for wind power from €0.1017/KWh to €0.0952/KWh[9]. State losses due to lawsuits by RE producers could amount to approx. €1 billion/year.

Another factor narrowing the scope for further RE expansion is the limited grid and generation capacity. According to TSO NPC Ukrenergo, 2 GW of flexible generation capacity for peak reserve and 200 MW of electrical storage systems are missing for a stable operation and integration of additional RE in 2021[10].

As a consequence, the forecast for RE deployment over the next five years is pessimistic, compared to the past years of rapid expansion. According to the Law on the transition to the Green Auction Model passed in 2019, auctions should replace the "green" tariff and are to determine the future level of remuneration for green electricity. Although a draft for annual RE support quotas and schedule for the 2021 auctions was introduced on 3 December 2020, the implementation of the new support model is considerably delayed. Furthermore, the total capacity proposed for the auctions is only a fraction of the 1.6 GW newly installed RE capacities in 2020.

Figure 4: Forecast annual auctions for RE capacity (MW), according to Minenergo[11]



The repeated postponement of the auctions as well as low quotas may decrease the market growth. For instance, annual quotas of 300-500 MW for wind power for 2021/2022 are seen by the Ukrainian Wind Energy Association (UWEA) as necessary to stabilize the market but are currently drafted 150-170 MW[12]. However, the

[8] Source: State Agency on Energy Efficiency and Energy Saving of Ukraine, https://saee.gov.ua/uk/news/3652
[9] Source: https://greenpost.ua/news/staly-vidomi-podrobytsi-novogo-zelenogo-taryfu-i6944
[10] Source: https://ua.energy/wp-content/uploads/2020/03/Zvit-z-otsinky-vidpovidnosti-dostatnosti-generuyuchyh-potuzhnostej-2019.pdf?fbclid=IwAR2dQAbmI14EsQ1pkcvQKXPBaU-bcSgozEmp5WPwCKtgz_xyvxuqQZLJ2wM
[11] Source: http://mpe.kmu.gov.ua/minugol/control/publish/article?art_id=245495260
[12] Internal communication

here outlined annual quotas are indicative and may change depending on a variety of political decisions, such as the revision of the ESU 2035, and will ultimately be formed as a result of the auctions to be taken place.

It can be concluded that despite the small recession in the RE sector following the rapid uptake of the previous years, the short and middle-term development of RE in Ukraine remains open. In Chapter 2, where Ukraine's geographical potential for RE generation is assessed to determine the potential hydrogen production, a more detailed overview concerning possible developments of the RE sector is given. Subsequently, the recent and to be expected Ukrainian policy developments in the hydrogen sector are presented.

Hydrogen Policy development in Ukraine

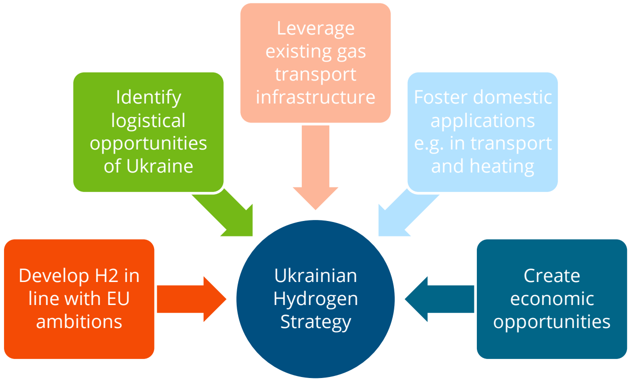
In the Short Study on International Cooperation Potential for Green Hydrogen submitted to the German Federal Ministry for Economic Affairs and Energy (BMWi) in 2019, Ukraine is among the countries with "good" suitability as a country of origin in the medium term[13]. The large geographical potential for renewable energy sources is emphasized positively. Opportunities for hydrogen are seen not only in the availability of land but also in the existing gas pipeline infrastructure that may be used for hydrogen transport. Furthermore, stagnating or declining transit volumes are expected by 2024[14] at the latest, so part of the existing infrastructure could be reallocated.

Consequently, the Ukrainian energy policy has taken green hydrogen into focus, as it not only represents a building block for the decarbonization of Ukraine's economy but also a potentially strong and export-oriented economic sector. In comparison to other European countries that have already released national hydrogen strategies, Ukraine is at the initial stage of forming its hydrogen policy. However, policy efforts kicked off during 2020 are aimed at forming a Ukrainian hydrogen strategy. **National Activities**

In 2020, the Ministry of Energy of Ukraine (Minenergo) held several events dedicated to the hydrogen topic, repeatedly issuing its intent to establish a hydrogen economy in Ukraine and in these occasions outlining to be addressed topics, such as the adoption of the legal system, technical development and research (e.g., production and transport) and international cooperation.

A Working Group on Hydrogen Energy Economy Issues was constituted by Minenergo during 2020 to work on hydrogen-related topics. In particular, the Working Group, consisting of Ukrainian experts from business, science and politics, aimed at drawing up the hydrogen roadmap and the hydrogen strategy, focusing on the topics displayed in Figure 5.

Figure 5: Key-topics for the development of Ukrainian Hydrogen Strategy[15]



In February 2021, the United Nations Economic Commission for Europe (UNECE) presented a draft for a Roadmap for Production and Use of Hydrogen in Ukraine, being developed as a precursor to the hydrogen strategy. The document gives a general overview of production technologies, infrastructure, potential application fields and required actions and measures on the national and municipal levels. Yet it also becomes apparent, that several questions remain towards the development of a national strategy on hydrogen. On the demand side, further prioritization and identification of realistic use cases may be needed. Bearing in mind the opportunities arising from EU regulation, a focus on industrial goods for export (such as steel) may provide more favourable economics in the short term compared to such applications in the transport sector where deployment is hindered by both high avoidance cost and the presence of suitable alternatives, such as battery-electric vehicles (BEV). On the supply side, questions need to be addressed to the extent that the momentum of renewable energy deployment can be sustained with the current challenges of grid integration.

International Activities

Within the framework of the German-Ukrainian Energy Partnership, which was founded in August 2020, hydrogen was declared one of the five central fields of action for bilateral energy cooperation. The first meeting of the hydrogen working group took place on 23 February 2021. At this meeting, cooperation priorities for 2021 as well as concrete activities were discussed. Germany has been invited to participate in the development of

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[13] Source: https://www.adelphi.de/en/system/files/mediathek/bilder/20191002%20Wasserstoff_Partnerl%C3%A4nder_Kurzgutachten%20FINAL.pdf
[14] Source: https://www.oxfordenergy.org/wpcms/wp-content/uploads/2020/03/Insight-65-Implications-of-the-Russia-Ukraine-gas-transit-deal-for-alternative-pipeline-routes-and-the-Ukrainian-and-European-markets.pdf
[15] According to Oleksandr Riepkin, Head of the Working Group.

Ukraine's hydrogen strategy within the framework of the German-Ukrainian Energy Partnership.

The EU sees great potential in Ukraine for the production and transport of hydrogen. 8 GW of electrolysis capacities in Ukraine are outlined until 2030 in the 2x40 GW green hydrogen initiative. To promote the massive increase of hydrogen across Europe, the initiative of the association Hydrogen Europe sees Ukraine as an important partner for the EU. On the business level, Ukrainian companies increasingly engage in national and international cooperation on hydrogen. Some twenty-five companies have joined the European Clean Hydrogen Alliance.[16] Among them are Energoatom and the gas transportation system Operator of Ukraine. Earlier, the Regional Gas Company announced that it had joined the European initiative EU Hydrogen Strategy.[17]

[16] Source: https://oilpoint.com.ua/bilshe-20-ukrayinskyh-kompanij-uvijshly-do-yevropejskogo-alyansu-chystogo-vodnyu/?lang=uk
[17] Source: https://www.facebook.com/RegionalGasCompany/posts/1019832471850671

2. Green Hydrogen Potential in Ukraine

Green hydrogen is produced via electrolysis, where water is separated into its components, hydrogen and oxygen. To conduct this process, electrical energy from renewable resources is required which is then converted into chemical energy contained in the hydrogen. Currently available industrial electrolyzers operate on efficiency rates between 65% and 75%[18]. To produce 1 kg of hydrogen, around 9 litres of water are required, and 8 kg of oxygen are produced as a by-product that can be released to the environment or used for further processes. In the case of freshwater scarcity and proximity to the ocean shore, saltwater can be desalinated and then used for electrolysis. The impact of desalination on total costs and energy consumption of hydrogen production is considered minor[19].

The main determining factor for the potential production of green hydrogen is the availability of renewable energy (RE), which does, and will continue to constitute the largest cost component of green hydrogen production, considering expected cost digressions of electrolyzers[20]. Depending to a large extent on the prices for renewable electricity, production costs for green hydrogen currently vary between € 2.5 and € 5 per kg under average and best conditions. In the future, these costs are expected to drop considerably with a scale-up of the renewables and green hydrogen sectors, reaching areas around € 1 per kg[21].

Installed RE capacities and development outlook

Due to its large territory including areas with high solar radiation and strong winds, Ukraine has considerable natural potential for RE generation. According to the National Academy of Sciences of Ukraine (NASU)[22], the country's natural potential allows the installation of 874 GW of RE capacities, of which 83 GW belong to photovoltaic (PV) and 688 GW to wind power. The corresponding energy would amount to an estimated

2,717 TWh annually. In its baseline scenario, the NASU predicts an annual RE production of 1,516 TWh, of which a considerable share shall be destined for the production of 337 TWh of green hydrogen. For comparison, Germany's annual hydrogen demand by 2050 is estimated at 200-450 TWh per year[23] and up to 900TWh including hydrogen derivatives (SNG, re-Fuels etc.)[24]. From these estimations, Ukraine's role as a possible producer of hydrogen becomes apparent. However, it remains to be determined to what extent this potential can be developed, i.e., these numbers do not necessarily represent an economically feasible RE development scenario.

A considerable gap exists between the calculated geographic potential and estimations concerning the economically feasible expansion of the RE sector. For instance, NASU calculates the possibility of 433 GW onshore and 250 GW offshore wind capacities, while IRENA and the Ukrainian Wind Energy Association (UWEA) rate the maximum potential for wind power at 24 GW[25].

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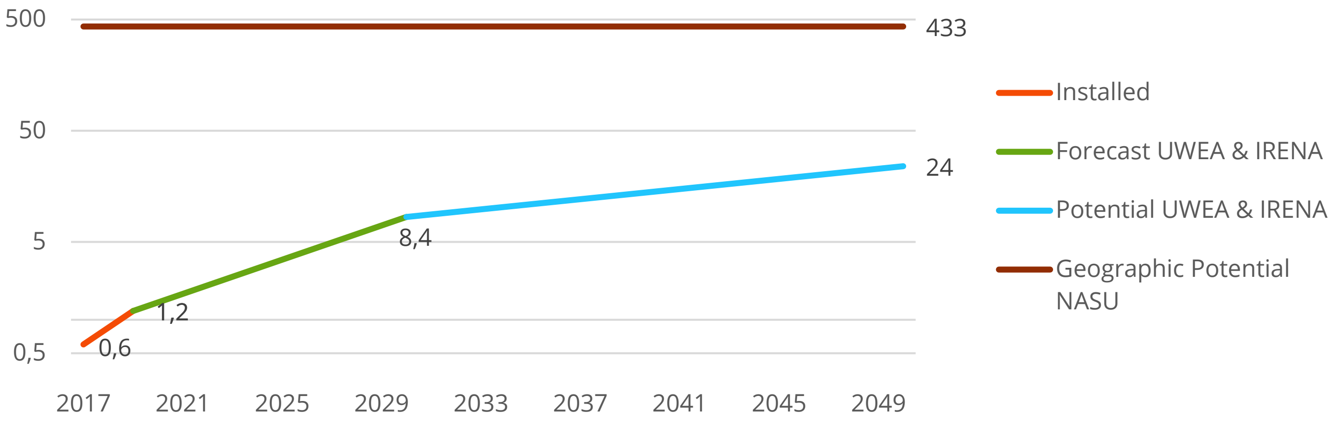
[18] Source: IRENA 2020: Green hydrogen cost; SIEMENS 2020 (Sylizer 300)
[19] Source: (EDF Energy R&D UK Centre, 10/2019), https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/866374/Phase_1_-_EDF_-_Hydrogen_to_Heysham.pdf
[20] Source: IRENA 2020: Green Hydrogen Cost
[21] Source: IRENA 2020; BloombergNef 2020: Hydrogen Economy Outlook
[22] Atlas of the Energetic Potential of Ukraine 2020. Numbers not verified. Strong focus on wind. On the contrary to NASU, SPE & LUT 2020 model 777 GW PV installations in Ukraine and Moldova in their moderate scenario for a European energy system by 2050.
[23] Source: Wuppertal Institut, DIW Econ 2020, page 103
[24] Source: dena Leitstudie
[25] Source: Atlas of Energetic Potential, IRENA 2015, UWEA 2020 internal communication

Figure 6: Outlook for wind power development in Ukraine (GW)



Past developments and prospects of the RE sector in Ukraine

In 2020, RE, including large hydropower capacities, amounted to 8% of Ukraine's total primary energy supply. Ukraine's energy policy aims to reduce the dominance of non-renewables, and recent years have brought a rapid upscaling of PV and wind power capacities. Until recently, hydropower installations represented the largest RE source in Ukraine by capacity (4.6 GW over the last decade). As further growth of hydropower in Ukraine faces geographic and social limits, Ukraine sets its focus on RE from solar, wind and biological origin. In 2019 energy from PV took the lead in Ukraine's renewables sector, after subsequent capacity increases of 48% and 196% in 2018 and 2019, respectively, now amounting to almost 6 GW installed[26]. According to the current energy policies in place, wind power and PV capacities are expected to grow at 15% (Compound annual growth rate) to reach 25 TWh/a in 2035 (1.6 TWh/a in 2015) accompanied by a more modest increase of hydropower to 13 TWh/a (7 TWh/a in 2015)[27].

Prospects for Solar, Wind and Bioenergy

PV energy production in Ukraine is a fast-growing sector. The installed capacity has almost doubled in 2018 from 1.2 GW to 2 GW and has tripled to almost 6 GW in 2019[28]. According to Solar Power Europe (SPE), installed PV capacities will reach 12 GW by 2024, based on current markets and policy frameworks in place[29]. Due to its large territory characterized by relatively high solar radiation, Ukraine is suited for large-scale PV power production. Particularly the southern regions, where annual full load hours in the range of 1,300 to 1,400 are reached, considerably higher than in Germany, where full load hours average between 800-900 with a maximum of up to 1,300 in the south[30]. In combination with the total land area of 579,290 km^2, almost double the size of Germany, the high solar radiation constitutes a potential of 99.3 TWh annually with 82 GW installed PV capacity[31]. SPE and LUT University, who, in their moderate scenario, forecast PV installations of 41 GW by 2030 and 777 GW calculate an even higher potential by 2050 in Ukraine and neighbouring Moldova[32]. On the contrary, an optimistic RE scenario recently published by IRENA expects the PV capacity at 15.6 GW by 2030, given a more progressive RE policy than currently in place[33]. The existing uncertainties concerning Ukraine's possible RE development pathways are exemplified by the heterogeneity of the different forecasts and scenarios for PV deployment.

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[26] Source: IRENA.org
[27] Source: KPMG 2019
[28] Source: IRENA.org
[29] Source: SolarPower Europe 2020, GMO
[30] Source: ESMAP. 2020. Global Photovoltaic Power Potential by Country. Washington, DC: World Bank.
[31] Based on calculations by the National Academy of Sciences of Ukraine. Numbers are not verified. Other calculations, e.g. SPE & LUT 2020 derive a much higher potential for PV (factor 10 more).
[32] Source: SPE & LUT 2020. The Moderate Scenario explores the most efficient way for 100% renewables in Europe by 2050.
[33] Source: IRENA 2020: Remap CES

Similar to the PV sector, the Ukrainian wind energy sector, after a phase of stagnation between 2014 and 2017, has recently gained momentum, reaching 1.25 GW installed capacity in 2019, exclusively onshore, due to a doubling capacity over one year[34]. The geographical potential for wind is estimated at 1,189 TWh annually by NASU, given an installed onshore wind turbines capacity of 433 GW[35]. These could be complemented by 250 GW offshore capacities, predominantly in the black sea, which theoretically adds 984 TWh per annum[36].

However, these numbers do not represent an economically feasible scenario but are a rough estimate of the geographical potential using data from meteorological masts. The Ukrainian Wind Energy Association (UWEA) does not confirm these numbers and instead estimates the achievable Ukrainian wind potential at a far lower 24 GW, corresponding to approximately 25% of electricity consumption in Ukraine[37]. Optimistic estimations by IRENA forecast an installed wind power capacity of 8.4 GW by 2030[38]. An economically feasible potential for the next decades is not assessed by UWEA due to the absence of political planning, such as the lack of a Ukrainian roadmap for the wind sector.

Figure 7: Outlook for PV development in Ukraine (GW)

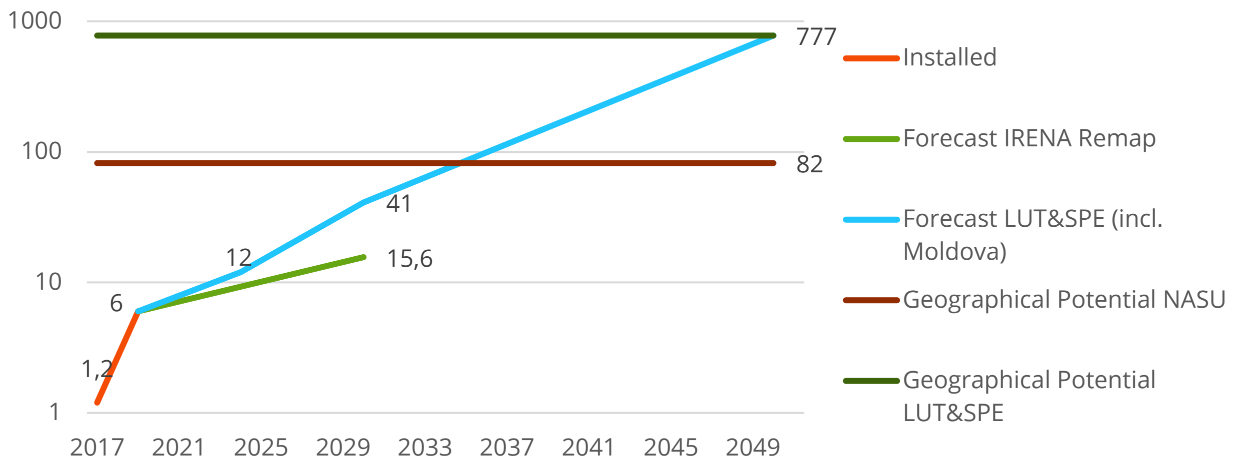


Figure 8: Solar Potential in Ukraine, Source: Global Solar Atlas

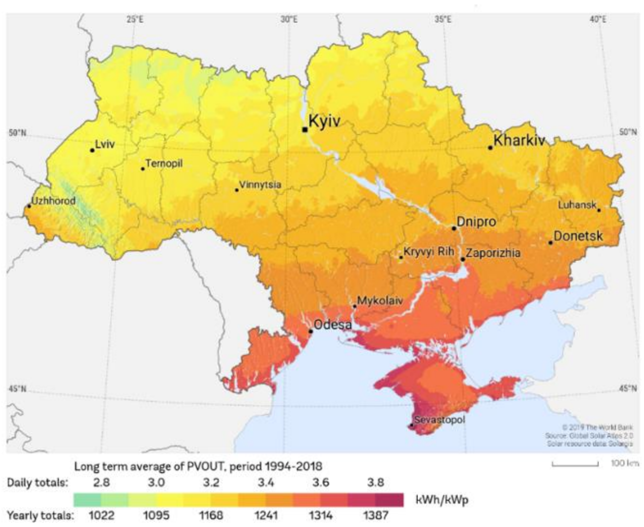
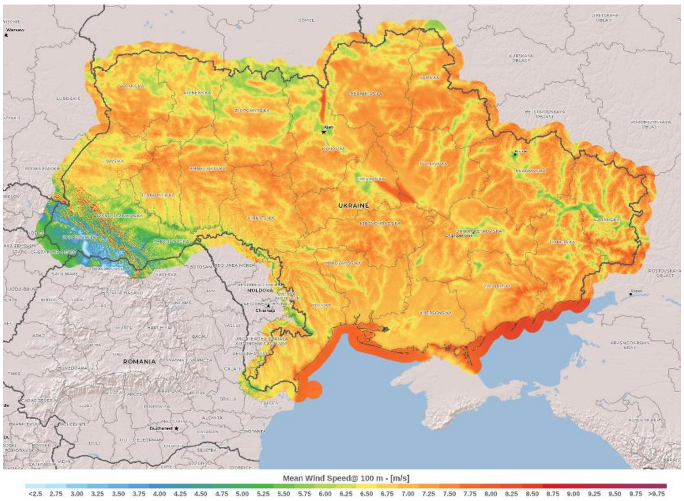
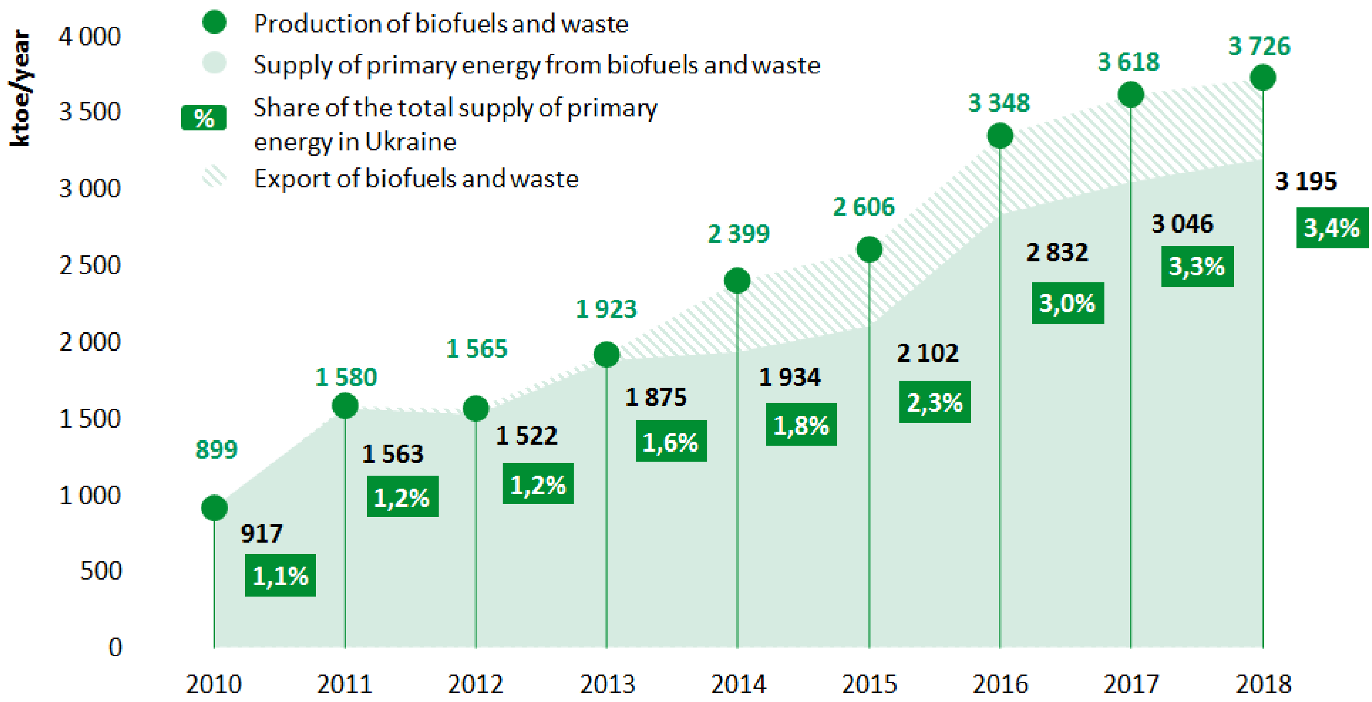


Figure 9: Wind Potential in Ukraine, Source: Gl Atlas



34 Source: IRENA.org
35Source: Atlas of the energetic potential of Ukraine.
36These numbers do not represent an economically feasible potential but relate to a theoretical scenario. A realistic scenario considering economically feasible installations of wind power to 2050 has, to the authors' knowledge, not been calculated yet.
37Source: E-Mail communication with UWEA
38 Source: IRENA 2020. Remap

Figure 10: Energy from Biofuels and waste in Ukraine, Source: UABIO



According to UWEA, the further development of the wind sector depends directly on upcoming government decisions, such as annual quotas - 300-500 MW in 2021-2022 are considered necessary to stabilize the market - and the settling of state debts for electricity delivered under the "green" Tariff. As mentioned previously, currently envisaged quotas for 2021 and 2022 contain 150 MW and 170 MW wind power , respectively.

The Ukrainian bioenergy sector, having experienced a considerable uptake in recent years making increased use of the total potential of 23 Mtoe (expected total primary energy supply of Ukraine in 2035 are 96 Mtoe), may complement a developing hydrogen economy based on PV and wind power [39]. From the considerable biomass potential, with agricultural residues (44%) and energy crops (32%) representing the biggest constituents, large quantities of biomethane (CH_4) and biofuels can be produced. Biomethane can be fed into the existing gas grid and thus partially replace fossil-based natural gas. In addition to the decarbonization effect, biomethane may serve as a carrier for hydrogen blended into the gas grid, considering the declining natural gas transit through Ukraine. The CO_2 released during biomethane production can also be captured and used for the production of hydrogen-based energy carriers such as methane or other synthetic fuels[40].

Potential other uses of biomass in the hydrogen sector are the production of carbon-free hydrogen through steam reforming of biomethane and plasma gasification of municipal solid wastes[41]. The technical readiness and scalability of these options remains uncertain and is not assessed here as it would exceed the scope of this work. In the ESU2035, energy based on biomass is destined to contribute 11 Mtoe to the total expected 96 Mtoe total primary energy supply. It would thus amount to half of the contribution of all RE of which solar and wind energy generate 10 Mtoe. However, bioenergy in Ukraine is used primarily in heat production and only on small scale (169 MW in 2019) in electricity generation. Despite further growth expectations, the Ukrainian Association for Bioenergy (UABIO) forecasts the share of biomass in renewable power production to not exceed 11% in 2050 (2.5% in 2020). Consequently, biomass will not play a role in hydrogen production, but may, as mentioned, complement the hydrogen sector through biomethane production and as a CO_2 source for the production of hydrogen derivatives.

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[39] Source: https://uabio.org/en/materials/9115/
[40] Thyssen Krupp has recently announced a similar project. In Quebec, hydrogen produced via electrolysis will be converted to hydrogen-based fuels using CO_2 from waste processing. Source: https://industrie.de/mobilitaet/thyssenkrupp-uhde-chlorine-engineers-gmbh-baut-wasserelektrolyse-anlage-in-quebec/
[41] Source: https://www.bio-gas.com.ua/biovodorod/proizvodtvo-vodoroda-iz-biomassy/

Hydrogen as a catalyst for RE deployment

Besides direct benefits through export sales and local consumption of hydrogen in industry and transport, the introduction of hydrogen technologies may implicitly influence the development of Ukraine's RE sector by accelerating the deployment of further RE capacities and by stabilizing the national power grid.

Accelerating the deployment of RE. High additional capacities of PV and wind power capacities will be required to power electrolysis facilities in a large-scale hydrogen sector. These solar and wind farms can be operated off-grid to solely power the hydrogen production but may in the future also be connected to the Ukrainian power grid and feed in the surplus electricity. Thus, they would additionally decarbonize the electricity sector. Furthermore, of the investment required to establish a large-scale green hydrogen production in Ukraine, the majority will be destined to new RE capacities, inducing a strong additional growth in the PV and wind power sector over the next decades. For instance, the UWEA considers a hydrogen-driven growth of the wind sector to over 10 GW capacity possible over the next decade.

The large RE capacities required for hydrogen production may facilitate the further deployment of PV and wind power projects destined for direct decarbonization of Ukraine's energy sector. Positive economies of scale and an improved business environment can lead to cost degression and ramp up the PV and wind power deployment for power production in Ukraine.

Stabilizing the national power grid. The fast increase of RE capacities in Ukraine over the last years has repeatedly led to grid bottlenecks in times of high electricity production from renewables. Considering the required scale-up of the share of RE in power production to reach national energy targets, grid bottlenecks are increasingly likely to occur. On these occasions, RE capacities have to be temporarily shut down. Electrolyzers could bridge times of high electricity generation by producing hydrogen from surplus energy. However, due to efficiency losses in the electrolysis process (between 65% and 70% efficiency), electrolyzers connected to the power grid should only be powered by surplus renewable electricity to achieve the highest possible CO_2 abatement. Given the current costs of electrolyzers, high full load hours (3,500 – 4,500h/y) will be required to make installations cost-efficient.

As a result, the profitable usage of electrolyzers as bridging technology during grid bottlenecks is limited as long as the share of renewables in power production is not dominant (<60%-70%). For lower renewable shares, times of grid bottlenecks in which electrolyzers could be powered are too scarce to enable sufficient full-load hours. As the share of renewables in Ukraine's power production increases and the costs of electrolyzers decrease, the production of hydrogen from surplus renewable electricity, In other words, the interconnection of power and gas grids can play a role in the energy transition of Ukraine.

As this chapter focused on the potential for hydrogen production in Ukraine, the following chapter elaborates on another crucial pillar of a hydrogen economy: hydrogen transport infrastructure.

3. Hydrogen Transport Infrastructure

Transport technologies

Hydrogen can be transported in liquid form through cooling, under pressure as a gas, bound in liquid organic hydrogen carriers (LOHCs) or in form of derivatives such as ammonia, methane or liquid carbon-based fuels. Dependent on the form, different transportation options arise, such as road, rail, maritime shipping and also pipeline (pure hydrogen or blended with natural gas). For medium and long-distance transport, shipping and pipeline transport are the most relevant options in terms of costs and technical feasibility.

Pipeline transport costs have an almost linear correlation with distance and surpass the cost of maritime shipping (of liquefied hydrogen) at a certain point, estimated by the IEA at 3,500km[42]. This implies that for Ukraine, pipeline transport is the preferable option for hydrogen export to Europe given a transport distance to European customers of below 3,500 km and an already established extensive pipeline network for natural gas transport to Europe. The following section gives a brief overview of the technological feasibility of pipeline transport of hydrogen in general - pure and as a blend with natural gas - as well as retrofitting possibilities of existing pipelines. Subsequently, the Ukrainian case is explored in more detail.

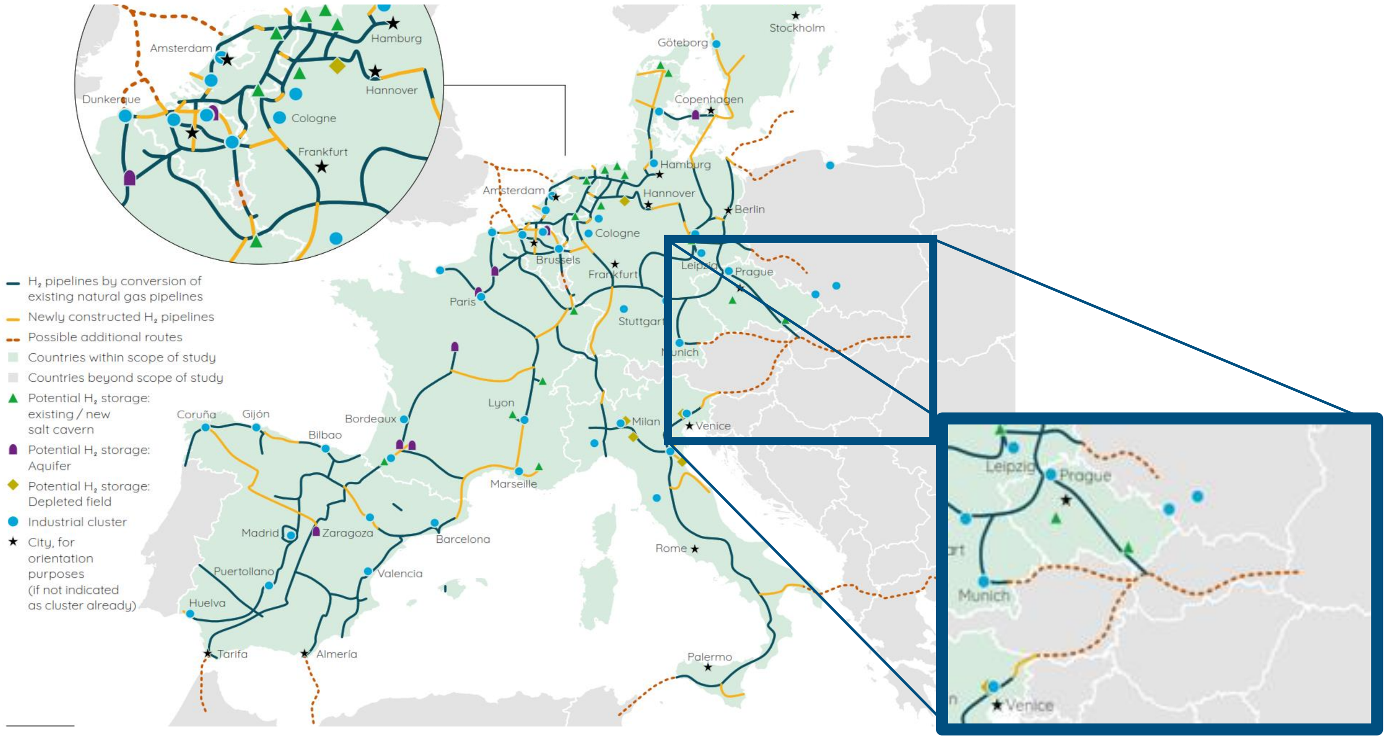
Pipeline transport of hydrogen: Blending with natural gas and dedicated H2 pipelines

Hydrogen can be transported via pipelines in its pure form using specially designed infrastructure, or as an admixture to the natural gas flow in existing pipeline systems, referred to as hydrogen blending. Hydrogen cannot be transported per se via conventional gas infrastructure, as its chemical characteristics lead to technical problems in various infrastructure components, such as transmission pipelines, compressor stations, or valves.

Dedicated H2-pipeline infrastructure

For the transportation of pure hydrogen these technical problems, e.g., hydrogen-induced cracking of steel, or pressure losses due to hydrogen's low energy density

Figure 11: Excerpt of the mature European Hydrogen Backbone, Source: European Hydrogen Backbone



[42] Source: IEA 2019: The future of hydrogen

compared to natural gas, make the construction of a specifically designed hydrogen transportation infrastructure necessary. The "European Hydrogen

Backbone" initiative led by eleven gas infrastructure companies in cooperation with the consulting company Guidehouse outlines how a dedicated hydrogen transport and distribution infrastructure can be developed across the EU with connections to non-EU hydrogen exporting countries such as Morocco or Ukraine[43]. The authors find that for a pure hydrogen infrastructure costs are reduced drastically if large parts consist of retrofitted natural gas pipelines. The CAPEX of retrofitting existing pipelines amounts to merely 10-35% of the costs of new hydrogen pipelines with a similar diameter.

However, besides ambitious plans for a European H2 infrastructure, the completion of the Hydrogen Backbone including its connection to Ukraine is not expected before 2040, leaving a transition period of two decades during which hydrogen exports from Ukraine to Europe most likely cannot be realized via dedicated H2 pipelines, independent from the hydrogen readiness of Ukrainian pipelines. An alternative may be the blending of hydrogen with natural gas transports via conventional pipelines.

Hydrogen blending with natural gas

If hydrogen is blended with natural gas, the technical constraints associated with hydrogen transport via pipeline become less relevant for lower hydrogen concentrations. Blending ratios between 5% and 15% are expected to be compatible with the main elements of gas transmission, storage and distribution without significant infrastructure modifications[44]. According to the European Network of Transmission System Operators for Gas (ENTSO-G), admixtures of 10% hydrogen have successfully been tested in several European countries, other sources state 6% as the maximum possible blending quota in the short term (e.g. French TSO GRT Gaz). ENTSO-G recommends an EU-wide target of 10% blending quota for 2030, as higher concentrations of hydrogen would require network modifications[45], and are limited to 20% due to the requirements of the appliance industry[46]. To determine the maximum possible blending quotas for a specific pipeline or gas infrastructure section, a case-by-case investigation is required, as gas infrastructure systems differ in significant characteristics such as age, transportation capacity, material quality and maintenance.

Ukraine's natural gas infrastructure: Available assets for the transport of hydrogen

The Ukrainian gas transmission system is one of the most extensive and powerful networks of trunk gas pipelines worldwide with an entry capacity of 281 bcm, an exit capacity of 146 bcm per year, representing

Figure 13: Ukrainian Gas Transmission System 2019, Source: ENTSOG

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[43] Source: Hydrogen Backbone 2020
[44] Source: Marcogaz 2019, Overview of available test results and regulatory limits for hydrogen admission into existing natural gas infrastructure and end-use; Malaina et al. 2013, Blending hydrogen into natural gas pipeline networks: a review of key issues
[45] Source: Marcogaz 2019
[46] Source: Entsog workshop 2020

approximately 165% of the annual natural gas consumption of Germany (88,7 bcm in 2019)[47] It consists of two main corridors that run in western and southern direction[48]. The Western transit corridor consists of the pipelines Soyuz, Kyiv-Western Ukraine, and Progress and connects to the gas transportation system of the EU.

As a consequence of Russia's diversification of gas transport corridors – Nord Stream 1 & 2 and TurkStream – the gas transit business in Ukraine is in decline. This has officially been acknowledged in December 2019, when Gazprom and the Ukrainian oil and gas company Naftogaz signed a 5-year gas transit agreement over 65 bcm in 2020 and 40 bcm annually between 2021-2024[49]. These numbers will result in an unused pipeline exit capacity of 106 bcm annually over the following 4 years alone, and an increase in gas transit is not in sight.

Usage of Ukrainian natural gas pipelines for H2 transportation

The declining gas transport business gives an incentive for Ukrainian pipeline operators to develop new business models, such as the transportation of hydrogen. To that end, the existing pipeline infrastructure with its upcoming surplus transport capacities may play a significant role. Existing pipelines could constitute a major advantage for Ukraine in comparison with other potential hydrogen exporting countries, as hydrogen transport – a significant cost factor for exported hydrogen – may be facilitated considerably. The majority of the initiators of the green hydrogen projects in Ukraine presented in the Annex plan to make use of the existing pipeline infrastructure. For the short- and middle-term, hydrogen transport as a blend to natural gas is envisaged for hydrogen produced in Ukraine, in the long term, gas transit pipelines could gradually be retrofitted to hydrogen pipelines, with major cost savings – 65% to 90% - relative to the construction of entirely new hydrogen pipelines.

However, it remains uncertain to what extent the existing pipeline system can be used for hydrogen transport to Europe, especially for the blending of hydrogen with natural gas. Research results confirming blending quotas similar to the European case (around 10%[50]) for the Ukrainian gas infrastructure have not been published so far.

In January 2021, Gas transportation system Operator of Ukraine, the operator of the gas transmission grid, announced a large-scale project to study the effects of hydrogen blending on pipelines and gas transportation system infrastructure[51]. Together with external experts from national research institutes, the readiness of the Ukrainian gas transportation infrastructure to transport hydrogen to the EU will be studied in 2021-2022.

In contrast to the gas-transmission network, research on the effects of hydrogen blending on local gas distribution infrastructure was already initiated in 2020 by a Ukrainian DSO Regional Gas Company, the operator of a 250,000 km pipeline network. Hydrogen blending in proportions from 5% to 100% on gas distribution infrastructure is currently being tested in 5 different regions of Ukraine. The research project will cover over 150 experiments and tests. The first unofficial results of the tests were presented in October 2020 at the 6th Ukrainian Gas Forum[52]. Researchers pointed out problems with pressure drops, leaks, and pipeline degradation. Although pipelines built past 1995 appear to be apt for hydrogen, technical nuances such as diameter and thickness as well as quality determine the hydrogen readiness of each pipeline. It was agreed that further experiments and analysis, as well as a Ukrainian regulatory framework for hydrogen use in the gas transmission system, are required. The project is expected to give recommendations concerning acceptable blending quotas, required reconstruction of gas distribution networks, and the development of a regulatory framework for hydrogen transport and usage.

The role of transit countries for pipeline transport

In addition to the Ukrainian infrastructure, transit pipeline systems and regulatory frameworks in neighbouring Eastern European countries such as Slovakia, the Czech Republic, Hungary and Romania must also be made ready for the transport of hydrogen to consumer countries in Central Europe.

A potential hydrogen transport corridor in Central Europe is the Slovakian gas transportation system which has an

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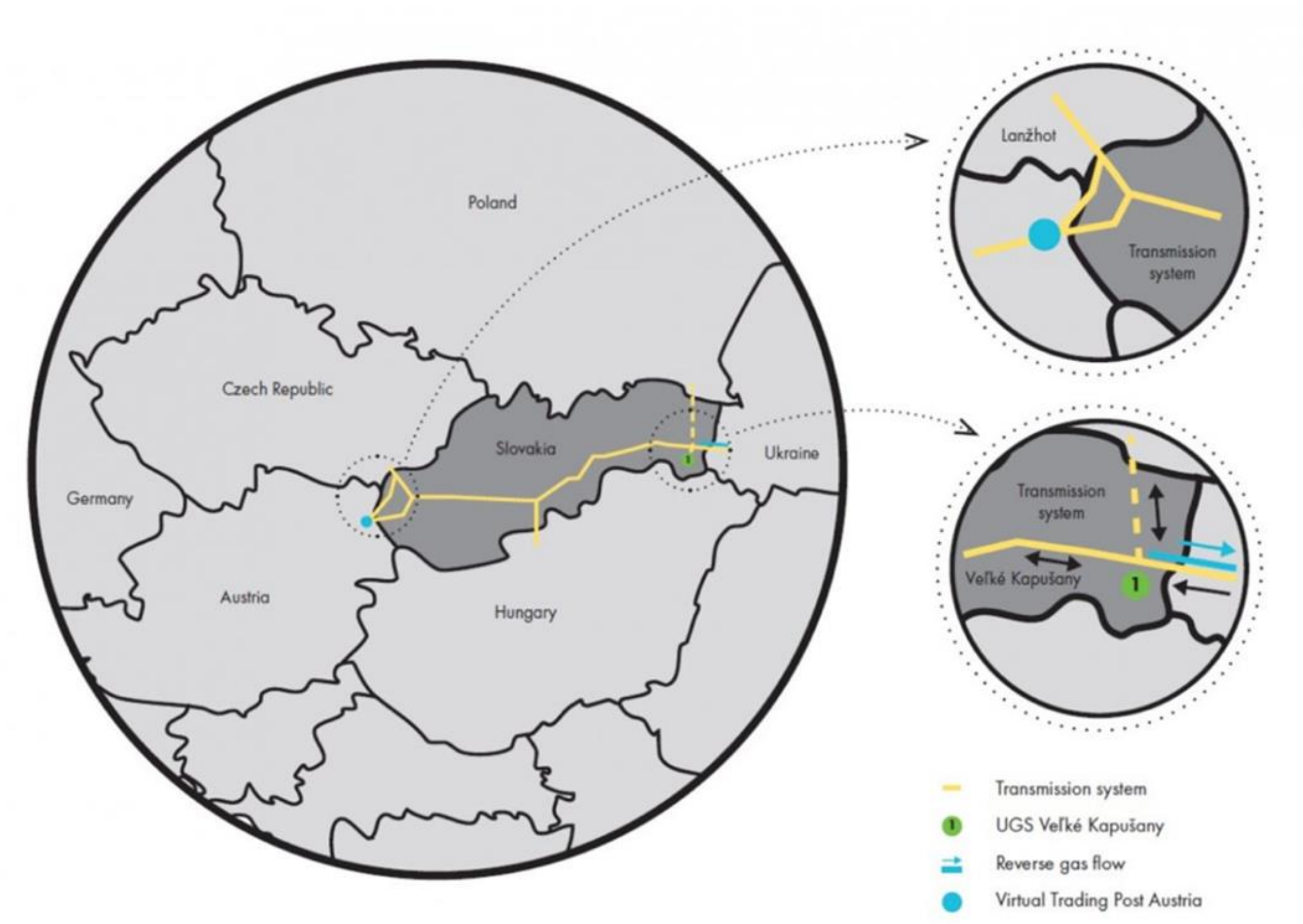
[47] Source: https://tsoua.com/en/, BP 2020, Statistical Review of World Energy
[48] Source: Energy community, https://www.energy-community.org/implementation/Ukraine.html
[49] Source: Oxfordenergy 2020, Implications of the Russia-Ukraine gas transit deal for alternative pipeline routes and the Ukrainian and European markets
[50] Source: Marcogaz 2019
[51] Source: https://tsoua.com/en/news/the-gas-tso-of-ukraine-engages-research-institutes-in-a-large-scale-project-to-study-aspects-of-hydrogen-transportation/
[52] Sources: https://kosatka.media/en/category/blog/news/vodorod-vmesto-gaza-rezultaty-pervyh-ukrainskih-issledovaniy?fbclid=IwAR39dhtLPmm1vmoi9kBMg4eTWkGfw4dpt2KcMYAaVdkcqH3lzxVuL-O2u9g
https://www.epravda.com.ua/projects/greendeal/2020/11/12/666675/; https://www.epravda.com.ua/projects/greendeal/2020/11/5/666903/

annual capacity of 90 bcm of natural gas[53]. However, the feed-in of hydrogen into Slovakia's gas transportation system is not regulated yet and technical research concerning possible blending quotas between 20% and 30% is currently being carried out, with results yet to be published[54]. Similar uncertainties regarding hydrogen transport via existing transit pipelines also arise in Hungary and Romania. Both countries have agreed to collaborate with Ukraine by establishing international working groups and an engagement in specific hydrogen transport projects but these collaborations are at an initial stage. Given these uncertainties, concrete statements regarding the technical and regulatory feasibility of hydrogen transport via transit countries cannot be made at this point. Further progress on legislative uncertainties and technical research will have to be expected.

In summary, hydrogen pipeline transport making use of existing infrastructure, as a blend or through retrofitting may represent a crucial factor for the ramp-up of a Ukrainian hydrogen economy. With natural gas transit in further decline and hydrogen production on the rise, the Ukrainian pipeline system can be of use through hydrogen blending in the short- and middle-term and gradually be retrofitted for pure hydrogen transport in the long term. In the latter case, the existing infrastructure represents a major cost reduction compared to a hydrogen transmission system based on newly constructed infrastructure. To assess the realistic prospects of Ukraine's gas infrastructure to enable hydrogen exports to Europe as an admixture to natural gas, reliable and qualified results of current tests on hydrogen blending, especially in Ukrainian transmission pipelines, but also in neighbouring transit countries, are required. A better knowledge base would facilitate investment in Ukrainian green hydrogen projects, as the export of hydrogen produced in Ukraine to the EU has to be secured to guarantee a large market for green hydrogen.

Figure 14: Slovakian Gas Transit Corridor, Source: cepconsult.com



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[53] Source: https://cepconsult.com/publications/eustream-creates-its-way-into-the-future/
[54] Source: https://cms.law/en/int/expert-guides/cms-expert-guide-to-hydrogen/slovakia

Maritime shipping via the Danube

Besides pipeline transport, maritime shipping could represent an option for hydrogen export to Europe, in particular, along the Danube River. Hydrogen produced in the south-western part of Ukraine around Odesa, where wind and solar conditions are favourable for large-scale RE production, could be liquefied or converted to LOHCs and shipped.

The IPCEI[55] project Blue Danube initiated by the Austrian energy provider VERBUND promotes this transport possibility for hydrogen from South-East Europe and plans the set-up of necessary infrastructure along the Danube. The Ukrainian project Danube Hydrogen Valley which is presented in more detail below also proposes maritime shipping as a transport option.

However, due to efficiency losses through conversion processes, operating costs for vessels and necessary conversion terminals, shipping may be considerably more costly than pipeline transportation. Also, costs for river transport may be even higher per kg of hydrogen than ocean shipping, as smaller vessels and thus smaller tanks are required, leading to higher efficiency losses. As mentioned earlier, maritime transport can only compete economically with pipeline transport for distances of more than 3,500 km[56]. Therefore, hydrogen transport along the Danube can only be a relevant option as long as pipeline transport is not possible. This may be the case, depending on the future development of the natural gas infrastructure.

Figure 15: Outline of the Danube Hydrogen Region, Source: VERBUND

[55] Important Project of Common European Interest
[56] Source: IEA (2019), The Future of Hydrogen

4. Economic Potential

Possible hydrogen development pathways for Ukraine

With its natural potential for renewable energy production and promising possibilities for low-cost transport of hydrogen to the EU using existing pipeline infrastructure, Ukraine possesses the prerequisites for large-scale and export-oriented green hydrogen production. As a result, national and international stakeholders from business, industry and politics take interest in the development of a Ukrainian hydrogen economy.

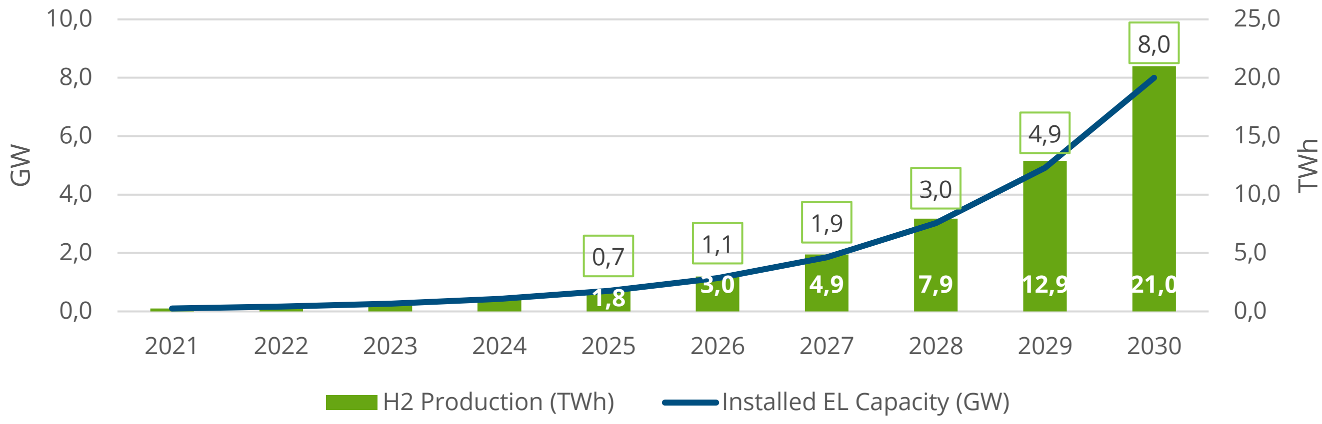
In the 2x40 GW Initiative, Hydrogen Europe proposes a strategy for a fast scale-up of the hydrogen economy in the EU. The strategy proposes the installation of 40 GW electrolyzer capacity in the EU, and 40 GW in Ukraine and North Africa until 2030. For Ukraine, the initiative proposes the installation of 8 GW electrolysis capacity by 2030 to produce pure hydrogen destined for export to the EU, as well as 1.8 GW for the production of green ammonia for the domestic market. From the 8 GW electrolyzer capacity destined for export, 21 TWh of green hydrogen, which is 12% of the EU demand in 2030 outlined in the European Hydrogen Roadmap, could be produced annually, assuming 3,500 full load hours operating at an efficiency rate of 75%.[57]

Whereas Hydrogen Europe's 2x40 GW Initiative outlines hydrogen production in Ukraine only after 2025, current developments, especially the number of pilot projects that are already being developed across the country, give reason to expect the first installations of electrolyzers on a multi-megawatt scale already before 2025. Taking this into account, a developing scenario is outlined here characterized by starting with 100MW installed in 2021[58] and a constant compound annual growth rate[59] of 67% over the next 10 years, reaching 8 GW installed electrolysis capacity by 2030 (Figure 16). The majority of capacities in the proposed scenario are planned for the end of the decade.

However, given the number of envisaged hydrogen pilot projects in Ukraine that are already in planning, small magnitudes of capacities are likely to be installed and operating over the next 5 years, possibly already in 2021.

The construction and operation of electrolyzer capacities on this scale, as well as the additional RE capacities needed for operation, will require and attract large investments and contribute to economic growth by creating jobs and a sustainable energy system. However, many questions concerning the economic competitiveness of hydrogen production in Ukraine are still open. These include, amongst others, future

Figure 16: Installed electrolyzer capacity and green hydrogen production by year, Source: own elaboration



[57] This calculation based on 3.500 full load hours is rather conservative. Under optimal conditions, electrolyzers could run on more full load hours, (e.g. 4.200 as in IRENA 2020), increasing hydrogen production to 25 TWh annually. Production capacities of over 30 TWh given 8 GW of electrolyzer capacity, as assumed by Hydrogen Europe, could only be reached with more than 5.000 full load hours.

[58] Given the number of pilot projects in the development pipeline, it is possible that the first installations of electrolyzers could be realized towards the end of this year. Even if the projects are further delayed, over the next years installations on a multi-megawatt scale can be expected in case some of the pilot projects are implemented.

[59] Compound Annual Growth Rate

hydrogen production and transport costs, market prices for hydrogen, government funding and regulation as well as domestic use of hydrogen. These uncertainties may disincentivize the disposition of stakeholders to invest in hydrogen projects in Ukraine, which is crucial given the required capital-intensive deployments of electrolyzers and RE capacities. To illustrate potential difficulties regarding the economic feasibility of a large-scale hydrogen economy in Ukraine, the following section gives a brief overview of the investment required to realize the 8 GW scenario and outlines the main economic barriers for a fast market scale-up.

Hydrogen Production: Investment Costs

The costs of green hydrogen production consist primarily of the costs for renewable electricity, which in the case of Ukraine will be predominantly supplied by PV and wind power followed by electrolyzer costs[60]. Similar to recent cost digressions experienced especially in the PV but also in the wind power sector, costs for electrolysis capacities are also expected to decrease over the next decades due to innovation and large-scale production[61]. For instance, a cost decrease in the CAPEX of electrolyzers of 48% in the next decade is assumed by LUT University, from € 685 per KW in 2020 down to €363 per KW in 2030. Until 2050, costs are expected at below €248 per KW. Other sources assume even more drastic cost reductions, for instance, IRENA, which expects €108 (USD 130) per KW electrolyzer capacity in the future.

An optimistic, baseline and a conservative scenario were modelled to estimate the potential investment costs for Ukraine's green hydrogen scale-up until 2030. Considering expected cost digressions for new RE installations and electrolyzers (see Annex), the investment needed to enable the proposed 8 GW development pathway will amount to between €11.5 and €20 billion, excluding interest rates. The considerable range in investment costs of €8.5 billion illustrates the difference between the modelled scenarios and originates from different assumptions for additional RE capacities and the respective share of PV and wind power required to operate electrolyzers on 3,500 full load hours annually.

[60] In further explanations, alternative RE sources such as hydropower or biomass were excluded due to their limited expansion potential in Ukraine.
[61] Source: IRENA 2020: Green hydrogen cost; GAP & LUT 2020: Powerfuels in a renewable energy world

Figure 17: Newly installed capacities per year (GW), own elaboration[62]

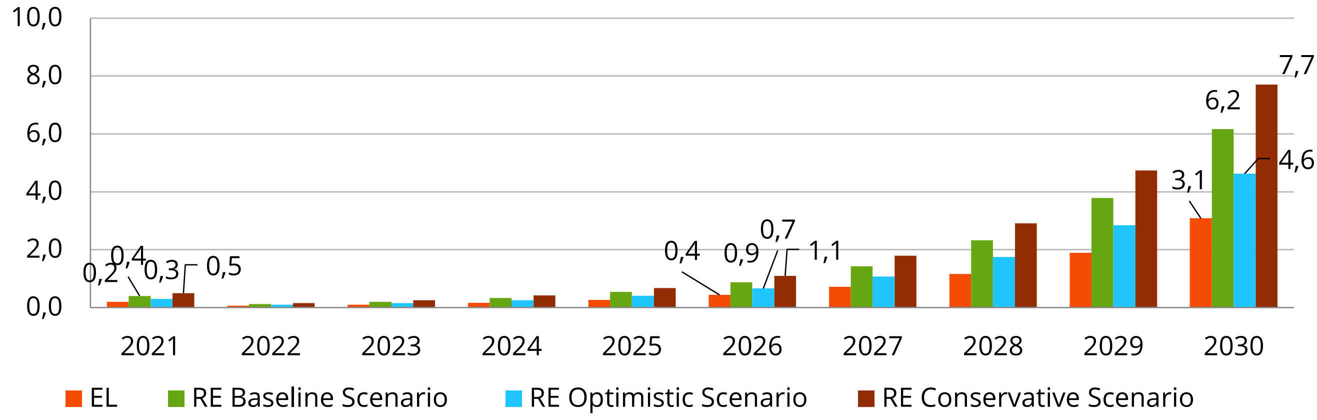
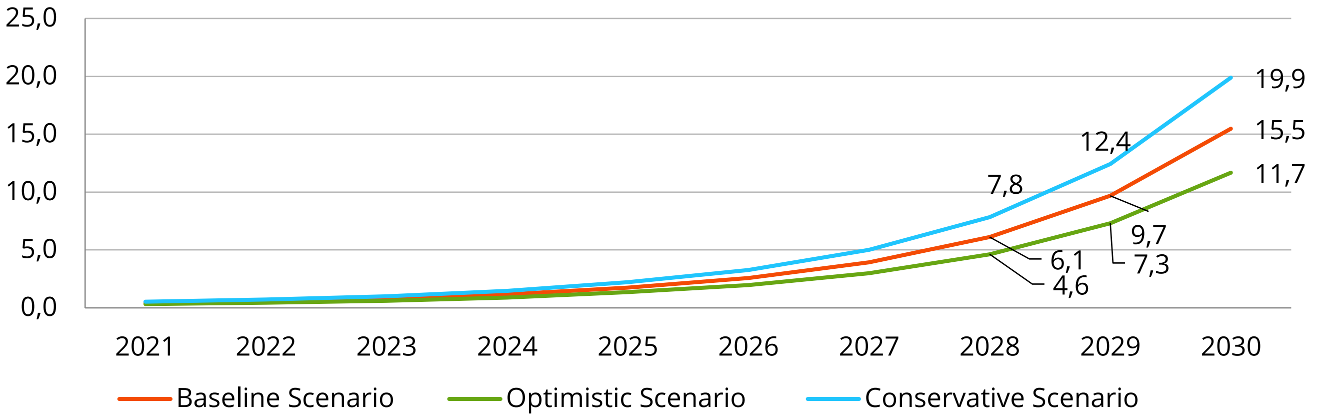


Figure 18: Accumulated investment without interest (€ billion), own elaboration



Economic uncertainties: Financing and cost of capital

It remains to be determined if the installation of hydrogen production facilities of this magnitude will be economically feasible in Ukraine. Whether or not the required investment volumes are illustrated in **Fehler! Verweisquelle konnte nicht gefunden werden.**, amounting to €11.7 billion even in the optimistic scenario, can be generated over the next decade, will depend on the competitiveness of hydrogen production in Ukraine compared to other places, which is strongly driven by the cost of financing those investments. The weighted average cost of capital in Ukraine is around 15% for the oil and gas sector, mainly driven by the cost of debt and the country's risk premium. This compares to around 7% in Germany and other EU countries and may be considerably higher for hydrogen projects due to a variety of additional risks[63]. Previous research has shown that the effect of this reduction in the cost of capital amounts to a decrease in the levelled cost of hydrogen of around one-third[64].

Three insecurity factors were identified in a survey of project stakeholders and are backed up by research results stated in the previous chapters. They strongly contribute to high capital costs and as such is crucial to the economic viability of hydrogen production. These are

i. uncertainties in Ukraine's energy and hydrogen policy,

ii. uncertainties in the business environment for hydrogen, and

iii. uncertainties concerning hydrogen transport and demand.

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[62] Scenario Assumptions: Baseline Scenario – 50% PV, 50% wind power onshore, RE to EL ratio = 2:1; Optimistic Scenario – 60% PV 40% wind power onshore, RE to EL ratio = 1.5:1; Conservative Scenario – 40% PV, 60% wind power onshore, RE to EL ratio = 2.5:1

[63] Source: waccexpert.com

[64] Source: dena/GIZ/Navigant/adelphi 2019: Grüner Wasserstoff: Internationale Kooperationspotenziale für Deutschland. Kurzanalyse zu ausgewählten Aspekten potenzieller Nicht-EU-Partnerländer.

Policy Uncertainties

Besides the general country risk, which in Ukraine is higher than, for example, in countries of the EU, the first factor includes specific political developments in the Ukrainian energy sector. As described in Chapter 1, no hydrogen strategy has yet been drafted for Ukraine, and the first attempt for a hydrogen roadmap does outline neither concrete policy actions nor (domestic) use cases for hydrogen. Although government representatives have repeatedly issued an interest in hydrogen, the lack of an official strategy, and thus the development of the hydrogen sector in the long-term, increases the uncertainties for potential investors. The recent halt in the deployment of RE energy, caused by payment arrears and uncertainties concerning future funding, exemplifies the importance of a hydrogen strategy to ensure predictability and trust in the future development of the hydrogen sector.

Business/Project Uncertainties

Next to the uncertainties in the political sphere, uncertainties for pilot projects, and as such capital interest rates, are high, because the business environment is not yet established. Despite numerous proposed pilot projects, green hydrogen projects have never been implemented before in Ukraine. The initiators are partially unknown in the energy sector and the proposed projects differ significantly in scale, planning stage, accessibility of information, and professionalism of the project presentation. Although some projects have already passed the idea phase and currently elaborate feasibility studies, and engage in financing and construction partnerships with German businesses, no industrial-scale electrolyzer has yet been installed in Ukraine. Predictable and unpredictable difficulties, of regulatory and technical origin, in production, transport, and end-use of hydrogen may occur, hampering the economic success of the respective project.

Demand Uncertainties

In particular, uncertainties are apparent in the demand for hydrogen and its fulfilment. This third factor comprises unresolved questions concerning hydrogen transport as well as a national and international sales market for hydrogen, including potential sales prices for green hydrogen.

As discussed in detail in Chapter 3, pipeline transport of hydrogen will most likely be the preferred transport option for Ukraine, especially for long-distance transport to the EU. However, uncertainties concerning possible blending quotas, the regulatory framework for gas transport and potentially required system modifications have not yet been resolved. Answers to these questions are urgently required to give investors the security that hydrogen can not only be produced but also be transported safely and at a low cost to be delivered to national and international customers.

Under the light of possible constraints in hydrogen transport, especially over long distances and through transit countries, the uptake of a local sales market for Ukrainian hydrogen becomes more important. According to a still to be published study from the Energy Community on hydrogen potential of its Contracting Parties[65], prospects for domestic hydrogen applications in Ukraine are "most conducive to promoting H2"[66]. Ukraine has a well-developed industrial base, in particular in ammonia and steel production, two sectors where green hydrogen could be applied. Yet, the topic of local consumption of green hydrogen has not been in the focus of either the majority of pilot projects or government communications. Instead, hydrogen production in Ukraine has been predominantly promoted as an export opportunity. This may strongly be influenced by the expectation of higher market prices for green hydrogen in the EU. Currently, Ukrainian appliance sectors are less likely to pay for the expensive green hydrogen than their counterparts in the EU, as they underlie a less restrictive legislative framework for carbon-intensive products. Nonetheless, the Carbon Border Adjustment (CBA) mechanism of the EU may incentivize a local market for hydrogen, as export products with low-carbon intensity, such as green steel, become economically more attractive.

Similar to uncertainties regarding green hydrogen purchases on the local market, the future price structure for hydrogen on the EU market is still unclear. The project initiators in Ukraine are in contact with potential investors, but cannot guarantee the economic viability of their projects, as they have neither certainty about who will buy their green hydrogen, nor about future purchase prices.

Because of all the described uncertainties in policy, business environment as well as in transport and offtake of hydrogen, green hydrogen projects that are in an advanced planning stage and could soon start implementation are on hold. They do not have financing options, as capital interest rates under the large number of uncertainties would be too high to successfully implement a project in terms of economic profitability. However, some now dominating problems may be resolved in the near future, especially through effective policy. The following closing chapter will give a brief outlook on possible measures that can be taken to improve the economics of the Ukrainian hydrogen sector, all of them aimed at reducing the identified uncertainties in policy, the business environment, hydrogen transport, and hydrogen offtake.

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[65] Albania, Bosnia and Herzegovina, Kosovo, North Macedonia, Georgia, Moldova, Montenegro, Serbia and Ukraine
[66] Source: Energy Community (2021), not published

Annexes

Hydrogen Project Proposals

Although the hydrogen sector in Ukraine is only in its initial phase, a variety of pilot projects are currently being initiated by both, Ukrainian as well as international stakeholders. The projects include the production of green hydrogen for domestic use and export, and partly also hydrogen storage. All projects are still in development/idea stages, 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 partially established already. The next steps would be securing investments (national and international) and the implementation of the already more advanced projects. However, according to the project initiators, investments could not yet be secured. The reasons, which were stated, are the uncertainties in the offtake market, a lack of transport options for hydrogen, and the missing Ukrainian hydrogen policy, which are described in detail above.

The table below gives a brief overview of current green hydrogen pilot projects in Ukraine. They are sorted by scale, with largest projects listed first. The two projects focusing primarily on hydrogen storage instead of production are listed as projects 10 and 11.

	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	Pipeline, also railway transport possible	Pipeline, road, and rail	Either by das carriers of by pipeline. Solution	Rail and road. Pipeline transport at a

		direct pipeline transport to Germany via existing gas transport system (additional research required)			expected in the next 2-3 years.	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

Cost development of selected technologies

Figure 19: Cost development of selected technologies, Source: LUT University

Technologies	Unit	2020	2025	2030	2035
Electrolysis	Capex €/kW_{H2}	685	500	363	325
	Opex €/kW_{H2} a	27	20	12.7	11.4
PV optimally tilted	Capex €/kW_{el}	432	336	278	237
	Opex €/kW_{el} a	7.8	6.5	5.7	5
Wind onshore	Capex €/kW_{el}	1,150	1,060	1,000	965
	Opex €/kW_{el} a	23	21	20	19

List of abbreviations

Abbreviation	Term
ESU2035	Energy Strategy of Ukraine 2035
NECP	National Energy and Climate Plan
CEGT	Concept of a Green Energy Transition
UNECE	United Nations Economic Commission for Europe
PV	Photovoltaic
bcm	Billion cubic meters
NASU	National Academy of Sciences of Ukraine
ENTSO-G	European Network of Transmission System Operators for Gas
SPE	Solar Power Europe
UWEA	Ukrainian Wind Energy Association
UABIO	Ukrainian Association for Bioenergy

List of figures

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