

P2X and Hydrogen Valleys enhancing Wind Power Profitability

Robert Weiss

VTT Technical Research Centre of Finland
Espoo, Finland
robert.weiss@vtt.fi

Kirsikka Kiviranta

VTT Technical Research Centre of Finland
Oulu, Finland

Jussi Ikäheimo

VTT Technical Research Centre of Finland
Espoo, Finland
<https://orcid.org/0000-0002-3920-0283>

Tiia Kanto

VTT Technical Research Centre of Finland
Oulu, Finland

Abstract— In many power markets, wind power suffers from poor capture prices due to correlated weather in the area. This paper studied the contribution of local green hydrogen production on the profitability of WP production. A local market for hydrogen was assumed. The studied hydrogen market included different levels of industrial H₂ demand and infrastructure, including investment plans for Power-to-Ammonia, Power-to-Methane, and Power-to-Methanol plants. Using the techno-economic linear optimization model SmartP2X, we showed that reaching profitability in wind power was possible when the selling price of hydrogen in the local market was 3.5–4 €/kg. At this level, the H₂ production increased the wind power revenues by 8–12 €/MWh.

Index Terms— Hydrogen, Hydrogen Market, Power Market, Power-to-X, Wind Power

I. INTRODUCTION

Many countries are relying on extensive expansion of wind and solar power to establish a sustainable and carbon neutral power system and market. However, extensive expansion of wind power (WP) capacity often results in significant price erosion during hours of high WP production. As a result, WP itself strongly reduces the market-based value of produced WP, making it challenging for new WP projects to reach bankability.

At the same time, many basic industry sectors require considerable quantities of fossil chemical feedstock, which significantly contribute to global greenhouse gas emissions. For these sectors, potential carbon-neutral and sustainable production methods are often based on power-to-X (P2X) production concepts, requiring extensive amounts of green power and hydrogen (H₂). In the European Union (EU), the green H₂ produced should preferably meet the requirements for RFNBO-H₂ stated in the EU definitions for clean Renewable Fuel of Nonbiological Origin (RFNBO) [1]. These definitions and rules stipulate that, from year 2030 onwards, green H₂ must meet a “temporal correlation” requirement of “hourly

matching”, meaning that the power used by green H₂ production in a given hour must be fully matched by renewable power, such as WP, during the same hour.

In a broader context, as the first step towards pan-European H₂ pipeline networks and H₂ market, P2X production facilities may be enlarged towards cost-efficient hydrogen valleys (HV), supplying multiple customers, and foster local H₂ markets. The profitability of WP could be enhanced through coordination with local H₂ production and the H₂ market within such HVs.

This study addresses a key research gap by providing a techno-economic assessment of how an industrial-scale HV with RFNBO-H₂ and P2X production can absorb additional WP generation in a power market area and enhance WP project profitability. The HV of this case study is located northern Finland subject, and subject to expansion from a city level investment plan to GW-scale area plans. The expansion steps represent varying levels of mobility and industrial H₂ demand and infrastructure, including P2X investment plans for Power-to-Ammonia (P2A), Power-to-Methane (P2G), and Power-to-Methanol (P2MeOH) plants. Results indicate that additional GW-scale WP can be integrated into the power bidding area by such an HV, but the viability of large-scale deployment depends on the availability of high-value RFNBO markets and favorable P2X pricing.

II. MATERIAL AND METHODS

In this section, the case HV and its probable development scenarios are presented. Also, EU targets for H₂ in industry and rules for RFNBO, used scenarios for WP and power market and the deployed optimization model are shortly discussed. More detailed descriptions and data can be found in [2] and [3].

A. Case Hydrogen Valley in Northern Ostrobothnia, Finland

The studied HV in this paper is located in the coastal city of Oulu with 215 000 inhabitants [4], located by the Bothnian Bay

in Northern Ostrobothnia, Finland. The Northern Ostrobothnia region has attracted interest from the H₂ perspective especially due to its favorable wind conditions (see Fig 7 in the Appendix) making the region an attractive location for large-scale low-cost electrolytic H₂ production. At the end of 2023, the cumulative installed capacity of WP in Finland was 6.9 GW, of which 2.7 GW (39%) was in Northern Ostrobothnia [5]. The maximum capacity of the planned new WP investments in Northern Ostrobothnia will reach up to 30 GW by 2030 [6].

Availability of point source CO₂ is also an important driver when considering the location of a potential P2X plant, and there are reliable CO₂ sources available from a pulp mill and biobased energy production, further described in [2]. The city of Oulu is also planning almost 1 200 ha of new areas for H₂-based industrial activities [7]. Excess heat from local industry is already utilized in the district heating network of the City of Oulu [8] with an annual heat demand of 1 600 GWh [9]. Therefore, the district heating network could absorb the excess heat generated by the electrolyzers.

Moreover, Oulu is located on the Trans-European Transport Network (TEN-T) and is a notable transport hub for passenger and freight transport with an airport, harbor, and the main rail and road routes passing through [10]. Hence, the city has also been proposed in [11] as a centralized H₂ production site to fill in hydrogen refueling stations (HRS) for heavy-duty vehicles in the Northern Part of the TEN-T network in Finland.

These factors above together create a promising opportunity for a HV development in the area, requiring considerable amounts of renewable power such as wind power.

B. Development Scenarios for the Case Hydrogen Valley

For the case HV, the development scenarios in [2] describe a stepwise approach from regional towards large HV, consisting of three scenarios that represent cumulative H₂ demand of different profiles and elasticities. The approach for HV scenarios and their expansion follows the pattern of HV Archetypes defined in [12] and [13], wherein the Valley build-up typically starts from producing H₂ first for local and regional users before expanding the Valley enabling H₂ exports:

Scenario 1 (Local Hub) presents an early stage of HV development with a P2G-plant as a large local industrial H₂ off-taker, based on the current investment plans in Oulu [14] as well as the already existing Finnish market for bio-LNG. In addition, the current fossil H₂ usage in a local industrial H₂O₂ plant is replaced with electrolytic H₂. Stepwise 1-4 HRSs for H₂-based heavy-duty traffic are introduced to the HV.

Scenario 2 (City Valley) is expanded from one to two large industrial consumers. The additional industrial customer would be a future flexible P2MeOH plant, to be situated close to a pulp mill in outskirts of Oulu. The pulp mill can provide a constant supply of 1 000 kt/a biogenic CO₂ for the P2MeOH unit, corresponding to a maximum H₂ demand of 16 tH₂/h. Clean or green MeOH demand is likely to differ from fossil MeOH production as it is expected to be an intermediary product for, e.g., sustainable aviation fuels or act as a sustainable maritime fuel. In this Scenario, a local H₂ pipeline connecting the

industrial sites within the HV was assumed, with the additional assumption that it serves as lumped line pack storage.

Scenario 3 (Large Valley) expands the HV to enable exports from the Valley to another H₂ consumption center in Finland. H₂ production exceeds the local demand in Oulu and the Valley starts exporting H₂ via a transmission pipeline to a planned NH₃ plant in Kokkola. The Haber-Bosch synthesis (HBS) process for NH₃ is assumed to require a maximal H₂ input of 9 tH₂/hour and to operate flexibly. In terms of H₂ consumption, this plant represents a mid-size European NH₃ plant, and a plant of this size will offset the NH₃ imports in Finland [15].

The electrolyzer capacity is fixed at 100 MWe AEL in Scenario 1 but will be variable and optimized alongside minimizing the levelized cost of hydrogen (LCOH) in Scenarios 2 and 3. The electrolyzers can utilize both market power and dedicated WP via e.g. take-as-produced PPAs.

C. EU Targets for Hydrogen Use in Industry and Rules for Renewable Fuels of Non-Biological Origin (RFNBO)

P2X and electrolysis plant operations in the EU are directly shaped by regulatory frameworks. The European Commission's 2023 Delegated Regulation on RFNBOS mandates "hourly matching" between renewable electricity supply and green H₂ production from 2030 onward, with exemptions for hours when power prices fall below 0.36 times the EU ETS price (minimum 20 €/MWh) or in bidding zones with over 90% annual renewable electricity [1]. For power bidding areas with less than 90%, the regulation practically places emphasis on direct coupling of renewable power or the use of PPAs for direct renewable power purchase. Furthermore, the revised Directive EU/2023/2413 sets requirements the share of green H₂ amongst all H₂ used in the industry sector, including steel and ammonia production [16]. Together, these regulations are central to optimizing H₂ and P2X RFNBO production and supply chains.

D. Data Scenarios for Wind Power and Power Market

For the study in [2] as well as this follow-up study, the WP and wholesale market prices forecast scenario for 2030 considers both hourly WP production as well as wholesale power prices for the Finnish bidding zone of the Nordpool power exchange (ELSPOT-FI). The forecast, depicted in Table I in the Appendix, is a result of a power production and price optimization model concerning all Nordpool power exchange areas, including both Nordic Countries as well as Germany and France. The forecast contains four clearly differing years: two different years in wind availability (average wind and low wind) combining two different fuel price levels (high gas price and low gas price) for the thermal power plants [17]. For the years 2025–2030, a large capacity of new WP is expected to be connected to the grid within the Finnish bidding zone, decreasing the wholesale price but increasing price volatility.

According to IRENA statistics, in 2020, land-based WP project costs were on average 1192 EUR/kW and OPEX on average 31 EUR/kW [18]. Because of technological development and larger wind turbines set to be built, in this study for new projects during 2025-2030 the average capacity factor is expected to increase to 41.5%.

With WP project costs of 1222 EUR/kW in 2030 (2.5% higher than the 2020 average), OPEX 31 EUR/kW and the capacity factor of 41.5%, using 25-year lifetime and 8% discount rate a WP cost of 40 EUR/MWh would be reached. This can be compared to reported land-based WP corporate PPA average prices of 34.5 EUR/MWh in Sweden and approximately 38 EUR/MWh in Finland in H1/2022, the lowest prices in Europe [19]. In this study, 40 EUR/MWh was used.

E. P2X Optimization Model for Hydrogen Valley Analysis

For the analysis calculations a H₂-economy and P2X optimization model “SmartP2X” is used, which is dedicated to site level P2X [3], P2X-to-power [20] and HV studies [2]. The model is a computationally efficient techno-economic linear optimization model for P2X plant operational strategy and investments, presented in detail in [2] and [3]. Some HVs might become so prominent with respect to electricity consumption that they are not anymore just price takers but act as a partial price maker in the price area of an electricity market. Thus, in [2] the optimization model has been enlarged with price elasticities for the hourly wholesales power markets, to consider the impacts from larger power market purchase and sell operations on the electricity market.

The optimization model allows for the study of how a future P2X plant or HV should be operated and dimensioned, considering volatile wholesale electricity prices as well as the dimensioning of long-term contracts with intermittent renewable power via PPAs or direct coupling, as required by EU regulations [1]. Besides cost, efficiency, and flexibility of the H₂ electrolyzers and production cost structures or production targets of downstream production units (such as NH₃ or RFNBO fuel production units), the model also considers, e.g., H₂ storage facilities, H₂ compressors, optional battery power storage facilities, as well as cold and warm start-ups of the electrolyzers, including the associated losses.

The model presents an advanced way to manage the computational burden of long-time horizons, and the related challenge of optimal dimensioning. The operation is optimized on hour-to-hour dynamical operation basis considering the intermittent availability of renewable power, volatile hour-to-hour wholesale market prices, start-up losses of electrolyzers, and physical and economical limitations of the process units. At the same time, on a daily and yearly basis, longer-term storage and pipeline line-pack operations and process unit sizes, and renewable power contract sizes are optimized simultaneously.

Optimization criteria in this study were optimal production amounts and P2X-system dimensions in the HV for a given RFNBO ex-factory sales price. Incomes from power sales operations, mainly sales of surplus WP production, were assumed to reduce the production costs of the RFNBO. At the same time, the HV is assumed to become so prominent with respect to selling surplus WP that it partially acts as a price maker in the electricity market price area, which is in this study considered via estimated price elasticities in 2030 for the ELSPOT-FI price area.

III. RESULTS

In this section, the results from the optimization of the 3 HV scenarios are presented and discussed from a WP producers’ point of view. Also, WP production as a Price Maker in the wholesales market and resulting price elasticities in the market are presented and analyzed.

A. Wind Power as Price Maker in the Power Market: Price Elasticity and Reduced Market Value

For the years 2025–30, as displayed in Table I in the Appendix, a strongly negative correlation between WP hourly capacity factors and hourly ELSPOT-FI price can be seen, this correlation was still weak during 2020–21 at low WP installation levels but increased in 2024 to a quite significant level of -0.28 due to the strong expansion of WP installations in Finland. In the power system forecast 2025–30 this correlation increases substantially to a very significant level (-0.54 to -0.67) because of a further increase of WP in the Finnish bidding zone.

This negative correlation will result for 2025-30 in a forecasted price elasticity of -5.0 to -8.1€/MWh/GW, which means 5.0 to 8.1 €/MWh lower ELSPOT-FI prices per GW WP fed into the Finnish bidding zone. This elasticity estimate can be seen as conservative, as the measured price elasticity was as strong as -12.5€/MWh/GW already in 2024.

A WP PPA price of 40€/MWh is clearly higher than the ELSPOT-FI wholesale market value of the produced WP, which was estimated to reach a yearly average of only 21-43€/MWh (average 31€/MWh) and was only 32€/MWh in 2024. This implies a substantial economic loss in WP operation for three of the four examined scenario years in 2030.

Consequently, just selling to the wholesale market is not a sustainable business model for new WP project developments in 2030. Instead, for new WP project developments, it will be crucial to focus on selling long term PPA contracts, be part of a larger power production portfolio including storage power, or be part of a higher value business, such as a P2X production.

B. Higher RFNBO Sales Price Increases Optimal Electrolyser and Wind Power capacity

In the scenarios, the higher the ex-factory sales price of the P2X products such as RFNBO-fuels, the higher price can be paid for the needed H₂ which results in higher utilization rates of the P2X production facilities and more H₂ production from the electrolyzers. This enables more investment in electrolyzer capacity, which in turn enables more investment in needed WP, as can be seen Fig 1 and Fig 2. As important is the share of used RFNBO-H₂ of all used H₂ production since it defines also if the P2X fuel is RFNBO. A higher total need for RFNBO-H₂ increases the need for WP. Consequently, in all scenarios needed WP increases with increased RFNBO sales price.

For the profitable RFNBO sales price region, the needed WP capacity would have been 220–300 MW for Scenario 1, 1500–2 000 MW for Scenario 2 and 2 100–3 000 MW for Scenario 3.

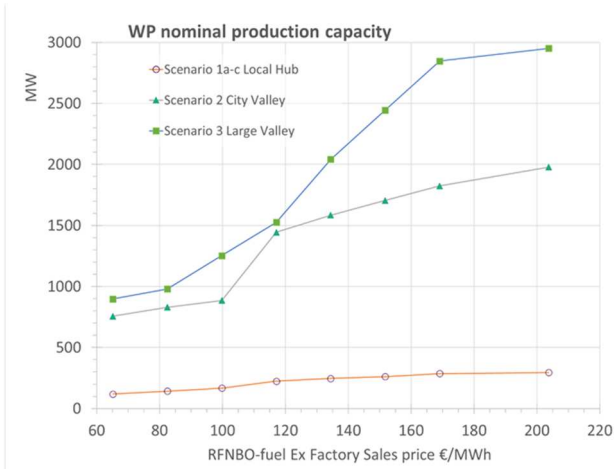


Figure 1. Optimal wind power capacity for the hydrogen valley scenarios, depending on the value of produced RFNBO-fuel.

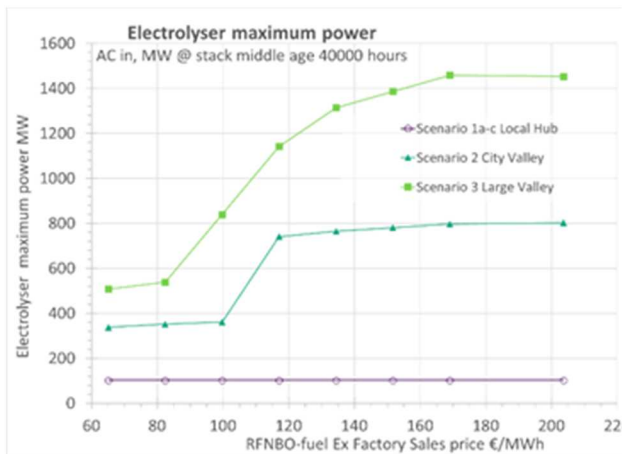


Figure 2. Optimal electrolyser power capacity for the hydrogen valley scenarios, depending on the value of produced RFNBO-fuel.

For the profitable sales price region in Scenario 2, optimal electrolyzer capacity was 15–16 tH₂/h or 750-800 MW_{ACin}, i.e. less than 50% of the nominal WP capacity, and had a utilization rate of 71–73%.

Similarly in Scenario 3, optimal electrolyzer capacity was 27–30 tH₂/h or 1150-1500 MW_{ACin}, i.e. slightly more than 50% of the nominal WP capacity and had a utilization rate of 57–64%. The lower utilization rate was a consequence of larger operation dynamics resulting from a large pipeline storage capacity and more flexibility in H₂ consumption from additional downstream production units. This allowed the electrolyzers to follow more closely the WP production.

C. Wind Power Value if All Sold to the Wholesales Market

If all the WP is sold directly to the ELSPT-FI wholesale market, instead of used for RFNBO-H₂ production, the large amounts of WP in Scenario 2 and Scenario 3 would have decreased the WP value further down to even 26€/MWh, as can be seen in Fig 3, because of the price elasticity in the wholesales market.

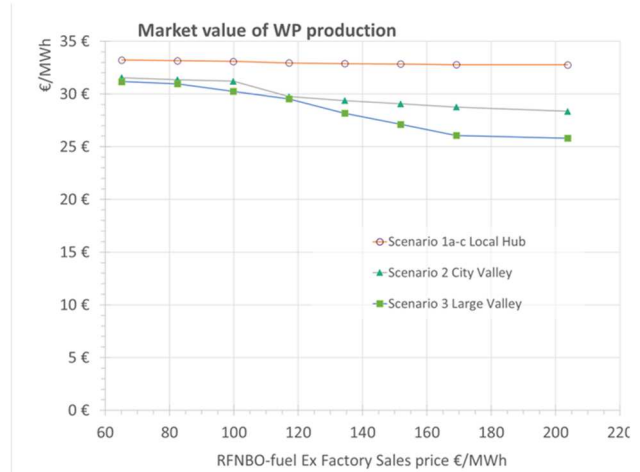


Figure 3. Market value of wind power produced in the hydrogen valley scenarios

D. Wind Power Value in P2X Production

From the produced WP, 70-85% would in the optimal strategy have been used in the RFNBO-H₂ production, the rest being surplus during WP peak production time and sold for a low price to the ELSPT-FI wholesale market, as seen in Fig 4. Clearly, the small amount of needed power maintaining the minimum RFNBO-H₂ production had to be bought for considerably higher prices, usually 3 times higher. Still this would not affect too much the total economy of production.

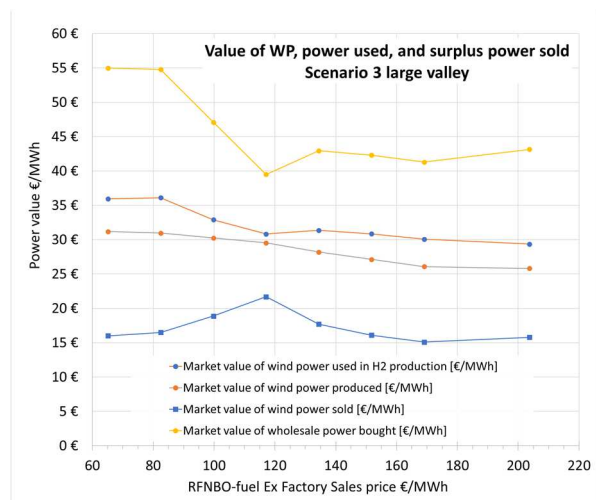


Figure 4. Market value of the wind power produced, used in the RFNBO-H₂ production and surplus wind power sold.

At a local market price of 100-118 €/MWh_{LHV} i.e. 3.2-3.5 €/kg for RFNBO-H₂, WP based electrolytic H₂ production provides already positive net added value to a WP producer in Finland, compared to just selling all WP directly to the wholesale market, as can be seen in Fig 5. At such RFNBO-H₂ price levels, the combined WP and H₂ production would reach a value of 32-35 € per MWh WP, as can be seen in Fig 6.

To reach a 40 € value per MWh WP, 118-133 €/MWh_{LHV} i.e. 3.5-4 €/kg RFNBO-H₂ local market price is needed. At this level, the H₂ production increases the WP value by 8-12 € per MWh WP.

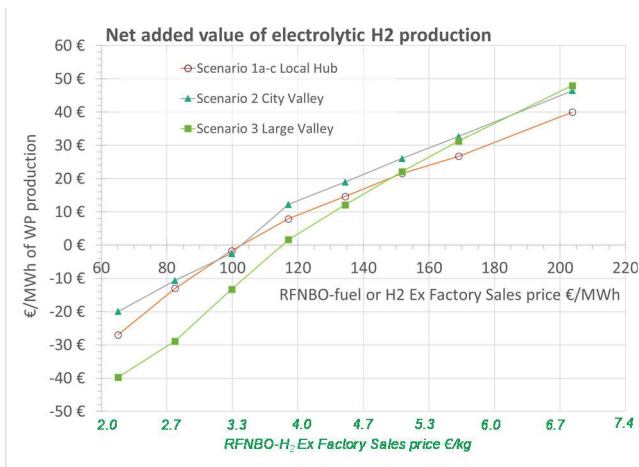


Figure 5. Net added value of RFNBO-H₂ production to a wind power producer, in terms of wind power value.

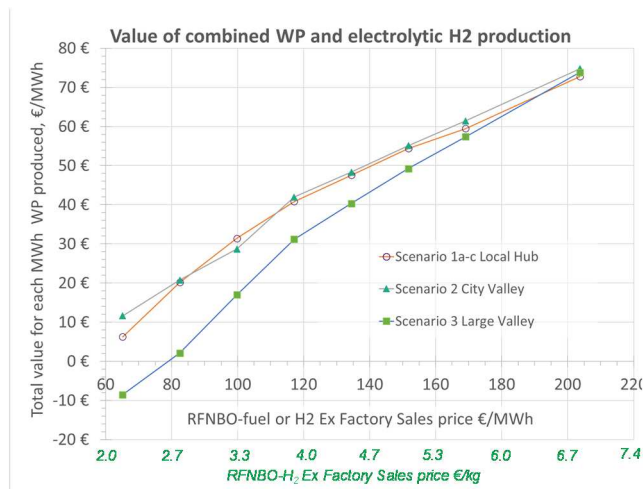


Figure 6. Combined value of RFNBO-H₂ and wind power production to a wind power producer, in terms of wind power value

IV. SUMMARY AND CONCLUSIONS

This study examined the impact of local RFNBO-H₂ production on the profitability of wind power (WP) production, as the scale and complexity of a hydrogen valley (HV) located in northern Finland increases. The studied HV considers different levels of industrial H₂ demand and infrastructure, including P2X investment plans for Power-to-Ammonia, Power-to-Methane, and Power-to-Methanol plants, reflecting potential development in the region.

The findings indicate that at a local market price of 3.2-3.5 €/kg (or 100-118 €/MWh_{LHV}) for RFNBO-H₂, electrolytic H₂ production from WP provides already generates a positive net added value to a WP producer in Finland, compared to selling all the WP directly to the wholesale market. At these RFNBO-H₂ price levels, combined WP and H₂ production reaches a value of 32-35 € per MWh WP, slightly lower than the WP power purchase agreement level in Finland in 2021 (38-40€/MWh). To achieve an estimated WP production cost of 40 €/MWh, a local market price of 3.5-4 €/kg (or 118-133 €/MWh_{LHV}) for RFNBO-H₂ is required. At this price, the H₂ production increases the WP market value by 8-12 € per MWh of WP.

In optimal installations, the estimated ratio of WP to electrolyzer capacity was approximately 2:1, and sales of surplus WP to the wholesales market at very low prices have a minimal impact on the overall economic viability of the production.

The study also demonstrates that higher sales prices for P2X products lead to increased utilization rates of the P2X plants, thereby improving takeoff and price for RFNBO-H₂. This, in turn, enhances the value of combined WP and H₂ production, promoting greater investments in new WP projects. Consequently, to support large-scale WP investments in power markets with high WP penetration, it is crucial to establish new, high value “green” markets for RFNBO-H₂ and the green P2X products.

ACKNOWLEDGMENT

This research was carried out in the FFS2 – Towards Fossil Free Steel Phase 2 public research project (Dnro 5667/31/2023), with funding from Business Finland, VTT and company partners.

REFERENCES

- [1] The European Commission, “Detailed Rules for the Production of Renewable Liquid and Gaseous Transport Fuels of Non-Biological Origin,” 2023. [Online]. Available: https://energy.ec.europa.eu/system/files/2023-02/C_2023_1087_1_EN_ACT_part1_v8.pdf.
- [2] R. Weiss, T. Kanto, K. Kiviranta, J. Ikäheimo, and J. Kärki, “Large scale power-to-X production enabling hydrogen valleys: A case study of future industrial hydrogen valley opportunity in Finland,” *Appl. Energy*, vol. 388, no. March, 2025, doi: 10.1016/j.apenergy.2025.125596.
- [3] R. Weiss and J. Ikäheimo, “Flexible Industrial Power-to-X Production as Virtual Hydrogen Storage enabling Large Scale Wind Power Integration : A Case Study of future Hydrogen Direct Reduction Iron Production in Finland,” *Appl. Energy*, vol. ACCEPTED, pp. 1–37, 2024.
- [4] City of Oulu, “Statistics of Oulu,” 2024. .
- [5] Finnish Wind Power Association, “Wind power in 2023 in Finland.,” 2024. <https://tuulivoimayhdistys.fi/media/wind-power-statistics-finland-2023.pdf>.
- [6] K. Kiviranta, J. Hopsu, T. Kanto, A. Saarikoski, J. Kärki, and J. Lehtonen, “Pre-study on transition to hydrogen economy, specifically in Northern Ostrobothnia,” 2023.
- [7] J. Ala-Mursula, “Oulu region is the northern home for clean solutions.,” 2024. https://oulu.com/wp-content/uploads/2024/02/17_businessoulu-cleantech_juha_ala_mursula.pdf.
- [8] Oulun Energia, “District heating protects against fluctuations in electricity prices.,” 2024. <https://www.ouluenergia.fi/en/whats-new/blog/kaukolampo-suojaa-sahkon-hinnan-heilahteluilta/>.
- [9] Finnish Energy, “District heating statistics.,” 2024. <https://energia.fi/en/statistics/district-heating-statistics/>.
- [10] Traficom, “Euroopan laajuinen liikenneverkko TEN-T.,” 2024. <https://www.traficom.fi/fi/liikenne/liikennejarjestelma/euroopan-laajuinen-liikenneverkko-ten-t>.
- [11] J. Ihonen, S. Viiko, and M. Hurskainen, “Next Nordic Green Transport Wave - Large Vehicles: Detailed analysis for large-scale hydrogen transport in Finland,” 2021. [Online]. Available: <https://norden.diva-portal.org/smash/get/diva2:1681694/FULLTEXT02>.
- [12] U. Weichenhain, M. Kaufmann, A. Benz, and G. Gomez, “Hydrogen Valleys: Insights into the emerging hydrogen economies around the world,” 2021. [Online]. Available: https://www.clean-hydrogen.europa.eu/system/files/2021-06/20210527_Hydrogen_Valleys_final_ONLINE.pdf.
- [13] U. Weichenhain, M. Knauffmann, M. Holscher, and M. Scheiner, “Going Global: An update on Hydrogen Valleys and their role in the new hydrogen economy,” 2022. [Online]. Available: https://www.clean-hydrogen.europa.eu/system/files/2022-09/Hydrogen_Valleys_online_2022.pdf.
- [14] Oulun Energia, “Ouluun suunnitteilla suuri teollisen mittakaavan vetäilylaitos.,” 2024. <https://www.ouluenergia.fi/uutiset/2--2024/ouluun-suunnitteilla-suuri-teollisen-mittakaavan-vetylaitos/>.
- [15] Flexens Oy Ab, “Ammoniakin tuotantolaitos, Kokkola Ympäristövaikutusten arviointiohjelma,” 2023. [Online]. Available: https://www.ymparisto.fi/sites/default/files/documents/YVA-ohjelma_Flexens_final_päivitetty_16082023_%281%29.pdf.
- [16] European Commission, “Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council ,” *Off. J. Eur. Union*, vol. 2413, no. 401, pp. 1–77, 2023.
- [17] M. Koivisto, L. Murcia, and J. Pablo, “Pan-European wind and solar generation time series (PECD 2021 update),” 2022. doi: 10.11583/DTU.c.5939581.
- [18] IRENA, *Renewable Power Generation Costs in 2020*. 2020.
- [19] BloombergNEF, “Wind and Solar Corporate PPA Prices Rise Up To 16.7% Across Europe,” *European Corporate PPA Price Survey*, 2022. <https://about.bnef.com/blog/wind-and-solar-corporate-ppa-prices-rise-up-to-16-7-across-europe/>.
- [20] R. Weiss, M. Rautanen, V. Saarinen, J. Kiviaho, J. Pennanen, and O. Himane, “Integration of Reversible Solid Oxide Electrolysis (rSOC) to Wastewater Treatment Plants for Sustainable Green Gas Production and Balancing of Green Power,” *ECS Trans.*, vol. 111, pp. 1639–1655, 2023, doi: 10.1149/111106.1639ecst.
- [21] NordPool, “Market Data 2021-2022,” 2022. <https://www.nordpoolgroup.com/>.
- [22] Fingrid, “Finland’s transmission system operator,” 2022. <https://www.fingrid.fi/en/>.
- [23] Renewables Finland, “Wind power map,” 2025. <https://suomenuusiutuivat.fi/tuulivoima/hankkeet-ja-voimalat-suomessa/kartta/>.

V. APPENDIX

TABLE I. POWER MARKET AND WIND POWER DATA FOR FINLAND IN THE FORECAST SCENARIO

		Forecast Scenario 2030				Measured Data ^a		
		year with						
		Low gas price		High gas price				
		Average wind	Low wind	Average wind	Low wind	2020	2021	2024
Wholesale power, ELSPOT FI								
average	€/MWh	30	46	36	60	28	72	46
max	€/MWh	183	380	217	368	254	1000	1896
min	€/MWh	2	2	2	2	-2	-1	-20
std dev	€/MWh	20	24	30	34	21	66	74
Wind power capacity factor								
average	%	43	40	43	40	38	36	31 ^d
std dev	%	27	27	27	27	25	26	22
Wind power, cost, and value								
WP installed ^b	MW	9640	9640	9640	9640	2250	3200	8224
PPA cost ^c	€/MWh	39	42	39	42		38	
ELSPOT value	€/MWh	21	33	25	43	24	64	32
correlation coefficient		-0.63	-0.67	-0.54	-0.62	-0.26	-0.17	-0.28
Price elasticity €/MWh/GW _{feedin}		-5.0	-6.0	-6.4	-8.1	-10.2	-18.0	-12.5

^a Historical data from the years 2020-21 and 2024 are displayed here for comparison. Wholesale power price data is for the Finnish bidding zone of the Nordpool power exchange [21]. WP hourly capacity factors were calculated based on actual production and available capacity for the Finnish bidding zone provided by the Finnish Transmission System Operator [22].

^b Capacity at end of the year

^c Data for 2021 based on [19]. For 2030 based on 40€/MWh adjusted with the yearly wind power produced.

^d Reason for the reduced capacity factor in 2024 was large number of hours with 0 or negative wholesale power prices, forcing some wind power producers to curtail production.

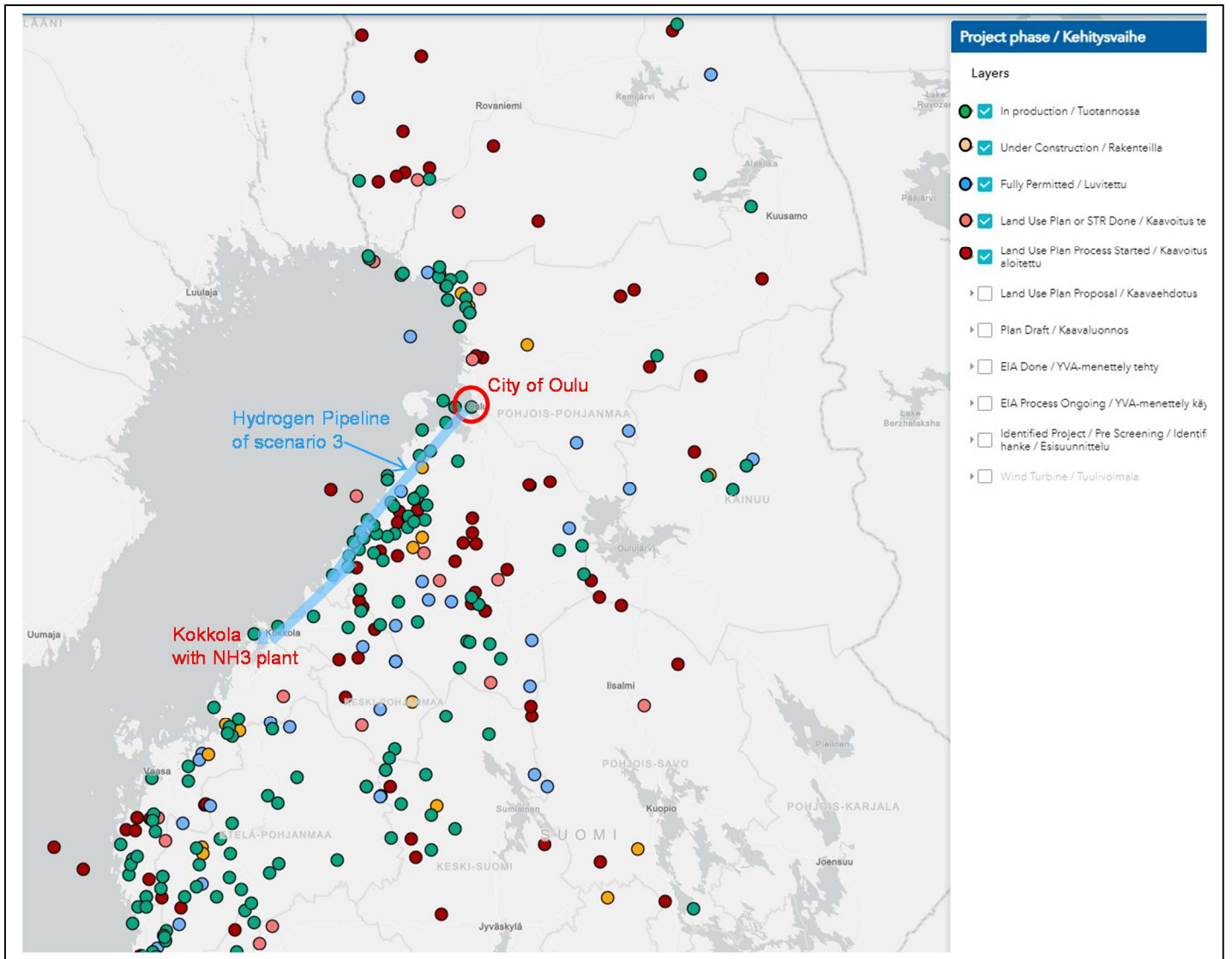


Figure 7. Wind power in Northern Finland, in production and planned[23], the location of City of Oulu, and the H₂ pipeline section to Kokkola Industry park with planned NH₃-plant in Scenario 3