Influences on hydrogen production at a wind farm

Xianyong Feng, Michael Lewis, Ross Baldick, Robert Hebner[*]

University of Texas at Austin, USA

HIGHLIGHTS

- Existing electricity market structures set hydrogen price floor.
- Underground hydrogen storage makes grid support attractive.
- Markets and technology affect profitability.
- Hydrogen and wind power can be synergistic.

ARTICLE INFO

ABSTRACT

If an affordable infrastructure for low-carbon-intensity hydrogen can be developed, then hydrogen is expected to become a key factor in decarbonizing the atmosphere. This research focuses on factors an existing wind farm operator would consider when weighing participating in the electricity market, the hydrogen market, or both.

The solutions depend on the state of technology, which is changing rapidly, the local market structures, the local natural resources, and the local pre-existing infrastructure. Consequently, this investigation used an assessment approach that examined the variation of net present value. The investigation identified profitability conditions under three different scenarios: 1) Make and sell what makes economic sense at the time of production, 2) Use electrolyzer and fuel cell to consume power from the grid at times of low net demand and to produce electricity at times of high net demand, 3) Same as #2 but also market hydrogen directly when profitable.

Introduction

Hydrogen production and sale is a global industry largely supporting fertilizer manufacturing and industrial processing. Industry and governments have recognized that hydrogen can help decarbonize transportation, the grid, and industrial processes [1]. Previous research [2] noted that hydrogen is attractive for decarbonization because it can enhance energy security, is synergistic with existing industries, has viable incremental transition pathways, and is well matched to renewable energy sources.

Hydrogen supplements renewable energy because it promises heretofore unavailable long-term large-scale storage [3,4] and hydrogen can be produced with low carbon intensity using renewable sources [5]. This promise for hydrogen has prompted research into producing hydrogen from wind power, including exploiting excess wind power [6], windfarms

dedicated to hydrogen production in regions with large wind sources [7,8] and the combination of wind and hydrogen to power a building reliably and continuously [9].

Previous research confirmed the technical feasibility of combining wind power and hydrogen production. This investigation explores factors that would influence an existing wind facility that produces electricity to shift to hydrogen production or to a hybrid approach that could provide electricity or hydrogen, whichever is the greater need.

Solutions tend to be local because the best answers involve exploiting existing infrastructure and natural resources. A previous research focus has been on choosing profitable operational scenarios in wind farms with hydrogen storage. Approaches have included Markov decision process theory [10], a scenario-based stochastic method to achieve optimal performance [11], Monte-Carlo analysis combined with real options analysis to predict potential hour-by-hour profitability [12], and use of receding-horizon analysis [13]. Moreover, operational optimization approaches have been developed [14] In addition, a game-theory approach has been developed to establish appropriate profitability among the various participants in a wind-hydrogen-electricity market [15]. It has also been demonstrated that not all potential wind-hydrogen plants are economically feasible by studying a specific operation in France [16]. This investigation adds the perspective of Capex and OpEx to provide guidance as to the anticipated set of circumstances a wind farm operator my benefit by expanding into hydrogen production.

The approach taken here is generic, but the specific data are representative of the western part of Texas, a state in the United States. Consequently, the specific results are relevant for that location, but can be expected to differ for other regions with different characteristics. Western Texas is an area that has abundant commercial wind and solar electricity production, is a historic major production location for gas and oil, has appropriate geology for underground hydrogen storage, and is served by established pipelines and high voltage transmissions lines to carry the energy produced to population centers. Consequently, it is expected to be a better-than-average location for wind-produced hydrogen.

Analysis approach

The architecture of the notional system, Fig. 1, consists of four key components: wind turbines, an electrolyzer to produce hydrogen, long-term large-scale hydrogen storage, and a fuel cell to convert hydrogen to electricity. As the technology advances, consideration will also likely be given to replacing the fuel cell with a turbine generator or a bidirectional fuel cell. Utility scale systems using 30% hydrogen as fuel are marketed now and most major utility turbine manufacturers expect to support 100% [17]. As that supply chain matures, it has the potential to compete with fuel cells in this application.

The notional 80 MW wind farm is presumed to be in the Southwest Power Pool to provide representative electricity market data. In the analysis, one-year data for this market (i.e., Oct. 1, 2019−Sept. 30, 2020), including day-ahead and real-time electricity prices, committed day-ahead wind generation, and real-time wind generation, support the economic

benefit calculation. The data resolution for real-time electricity price and the real-time wind farm generation is 5 min. The data resolution for day-ahead electricity price and the committed day-ahead wind generation is 1 h. Net present value (NPV) is used to compare different technology solutions in each scenario. The yearly data are used repeatedly over the project lifetime.

$$NPV = \sum_{t=0}^{n} \frac{R_t}{(1+d)^t} \tag{1}$$

where, R_t is the net cash inflow-outflow during period t, d is the discount rate or interest rate, t is the time internal index, and n is the project lifetime. In this analysis, the time interval is one year.

The capital expenditure (Capex) and operation and maintenance (O&M) expenditure are considered over the project lifetime. As the study focuses on an established wind farm, the cost of the original wind farm is not considered. Only the added cost of the hydrogen systems is considered in this analysis together with the change in net revenues. The CapEx is calculated:

$$CapEx = P_{FC} \cdot C_{FC} + P_{Electrolyzer} \cdot C_{Electrolyzer} + E_{storage} \cdot C_{storage} \tag{2}$$

where, P_{FC} is the fuel cell power capacity (MW), C_{FC} is the cost of fuel cell per MW (USD/MW), $P_{Electrolyzer}$ is the electrolyzer power capacity (MW), $C_{Electrolyzer}$ is the cost of electrolyzer per MW (USD/MW), $E_{storage}$ is the size of H_2 storage (kg), and $C_{storage}$ is cost of H_2 storage per kg (USD/kg). The O&M cost is calculated in annual basis, which is expressed as follows.

$$OpEx = P_{FC} \cdot C_{FC\_OpEx} + P_{Electrolyzer} \cdot C_{Electrolyzer\_OpEx} + C_{storage\_OpEx} \tag{3}$$

where, C_{FC_OpEx} is the fuel cell annual O&M expenditure (USD/MW-year), $C_{Electrolyzer\_OpEx}$ is the electrolyzer annual O&M expenditure (USD/MW-year), and $C_{storage\_OpEx}$ is the H_2 storage annual O&M expenditure (USD/year).

The annual benefit is

$$\begin{aligned} Annual\ Benefit = {} & New\ System\ Revenue \\ & - Original\ Wind\ Farm\ Revenue \end{aligned} \tag{4}$$

The new system revenue is the overall system revenue including the additional H_2 system and the wind system. For clarity, the new system and the original wind farm system are two different standalone hardware systems. The original wind farm system is the baseline system, and the new system is the upgraded system with H_2 infrastructure.

$$\begin{aligned} New\ System\ Revenue = \sum_{i=1}^{N} & \Big(PTC_{MWh}/(1-r_{tax}) \cdot P_i^{Total} \\ & + C_i^{DAM} \cdot P_i^{Committed} + C_i^{RTM} \cdot \Big(P_i^{Total} \\ & - P_i^{Committed} \Big) + \Big(C_{H2} \cdot R_i^{H2} - C_{Water} \cdot R_i^{H2} \Big) \Big) \cdot T \end{aligned} \tag{5}$$

$$\begin{aligned} Original\ Wind\ Farm\ Revenue = \sum_{i=1}^{N} & \Big(PTC_{MWh}/(1-r_{tax}) \cdot P_i^{Wind} + C_i^{DAM} \\ & \cdot P_i^{Wind\_Committed} + C_i^{RTM} \cdot \Big(P_i^{Wind} - P_i^{Wind\_Committed} \Big) \Big) \cdot T \end{aligned} \tag{6}$$
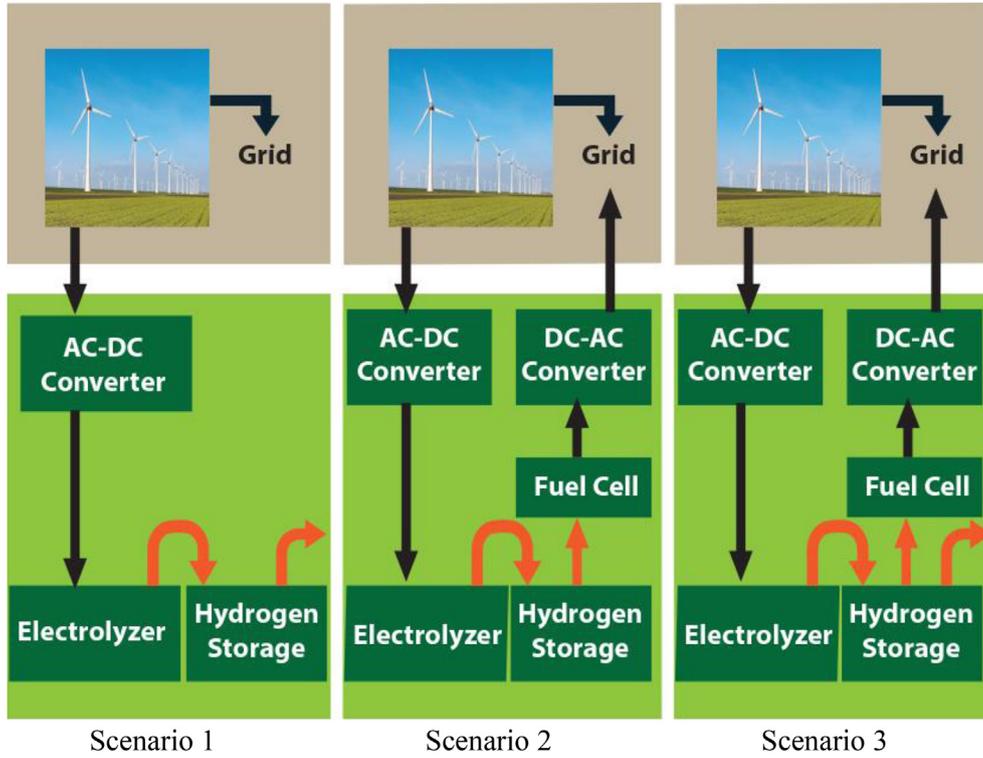
Fig. 1 — Three system architectures considered in this analysis. The green blocks highlight the key capability considered for addition to the wind farm. The black arrows show electricity flow and the orange arrows, hydrogen flow. In Scenario 1 both hydrogen and electricity are produced and marketed. In Scenario 2, the hydrogen is not sold but stored and used as needed to enhance grid performance. Scenario 3 adds hydrogen marketing to Scenario 2.

where, T is the length of the time interval, i is the time index, N is the total time intervals in a year, PTC_{MWh} is the production tax credit (USD/MWh), r_{tax} is the marginal corporate tax rate, C_i^{DAM} is the day-ahead electricity price (USD/MWh), C_i^{RTM} is the real-time electricity price (USD/MWh), C_{H2} is the H_2 price (USD/kg), C_{Water} is the water cost per kg H_2 generation (USD/kg H2), P_i^{Total} is the real-time power output to the electricity market from the new system (MW) at the meter or the point of common coupling, $P_i^{Committed}$ is the committed power of the new system (MW), R_i^{H2} is the H_2 generation rate (kg/h), P_i^{Wind} is the real-time power generation from the original wind farm (MW), and $P_i^{Wind-Committed}$ is the committed power of the original wind farm (MW).

The governing equations are shown as follows.

$$P_i^{Total} = P_i^{Wind} + P_i^{FC} - P_i^{Electrolyzer} \tag{7}$$

$$P_i^{Committed} = \max\left(P_i^{Wind_{Committed}} - P_{Electrolyzer}, 0\right) \tag{8}$$

$$SOC_{i+1}^{H2} = SOC_i^{H2} + \frac{P_i^{Electrolyzer} \cdot EFF_{Electrolyzer} - P_i^{FC}/EFF_{FC}}{LHV_{H2} \cdot W_{H2}} \tag{9}$$

where, P_i^{FC} is the power output of the fuel cell (MW), $P_i^{Electrolyzer}$ is the power input to the electrolyzer (MW), $EFF_{Electrolyzer}$ is the electrolyzer efficiency, EFF_{FC} is the fuel cell efficiency, LHV_{H2} is

the lower heating value of H_2 (MW/kg), and the W_{H2} is the H_2 storage size (kg). In this analysis, the power converter efficiency is combined with fuel cell and electrolyzer. The major constraints are

$$SOC_{min}^{H2} \leq SOC_i^{H2} \leq SOC_{max}^{H2} \quad i = 1 \ldots N + 1 \tag{10}$$

$$0 \leq P_i^{FC} \leq P_{max}^{FC} \quad i = 1 \ldots N \tag{11}$$

$$0 \leq P_i^{Electrolyzer} \leq P_{max}^{Electrolyzer} \quad i = 1 \ldots N \tag{12}$$

$$P_i^{Electrolyzer} \leq P_i^{Wind} \quad i = 1 \ldots N \tag{13}$$

where, SOC_{min}^{H2} and SOC_{max}^{H2} are the minimum and maximum allowed state-of-charge of H_2 storage, P_{max}^{FC} is the maximum allowed fuel cell power, and $P_{max}^{Electrolyzer}$ is the maximum allowed electrolyzer power. The electrolyzer power needs to be always less than the wind power generation. In other words, no power is bought from grid to charge the H_2 storage. It should be noted this is a generic formulation to estimate the NPV for the wind and hydrogen integration. A tool has been developed in Matlab to perform the study. Once the market data and infrastructure cost data are available for a certain study region, the new data can be used by this tool to generate analysis results.

The values for key parameters are summarized in Table I.

Table 1 – Summary of the key parameters in the analysis.

Variable definition	Value
Time interval, T	5 min
Wind system production tax credit, PTC_{MWh}	$25/MWh
Water cost per kg H_2 generation, C_{Water}	$0.05/kg H_2
Capital cost of fuel cell, C_{FC}	$0.6 M/MW [18]
Capital cost of electrolyzer, $C_{Electrolyzer}$	$1.4 M/MW [19]
Capital cost of H_2 storage, $C_{storage}$	$50/kg H_2 storage [20] (underground salt cavern)
Fuel cell annual O&M cost, C_{FC_OpEx}	$13.4 k/MW-year [21]
Electrolyzer annual O&M cost, $C_{Electrolyzer\_OpEx}$	$14.5 k/MW-year [21]
H2 storage annual O&M cost, $C_{storage\_OpEx}$	2.5% of H_2 storage CapEx [21]
Discount rate or interest rate, d	5%
Electrolyzer efficiency, $EFF_{Electrolyzer}$	67% [22]
Fuel cell efficiency, EFF_{FC}	50% [23]
Lower heating value of H_2, LHV_{H2}	33.6 kWh/kg
H2 storage size, W_{H2}	30,000 kg
Minimum allowed SOC of H_2 storage, SOC_{min}^{H2}	5%
Maximum allowed SOC of H_2 storage, SOC_{max}^{H2}	95%

Case study results

Scenario 1 – sell either hydrogen or electricity whichever provides the better return

In this scenario, electricity is sold when the day-ahead market (DAM) electricity price produces more revenue than the hydrogen market. Since storage is finite, but potentially very large compared to other grid-level storage technologies, the generated H_2 is sold to the market at the market price before the storage is fully filled. When the day-ahead electricity price is lower than a pre-selected value, the electrolyzer generates H_2. If the wind power generation is higher than the electrolyzer capacity, the electrolyzer will operate at its maximum capacity with the balance sold to the electricity market; otherwise, the electrolyzer will use all the available wind power to generate H_2. In this way, the wind farm avoids reverse power flow.

This scenario is one wind farm operators may seriously consider. Typically wind farms are remote from load centers. In many cases, the transport of the wind farm energy via hydrogen pipelines may be significantly less costly than transmission via high voltage power lines. These differences will affect the electricity and hydrogen purchase prices. The energy transmission price differential is a factor each wind farm operator will consider as the cost differential is generally affected by local infrastructure [23,24].

The electrolyzer installation capacity and DAM price for electrolyzer activation are two variables in the sensitivity analysis. The electrolyzer capacity is varied from 2 MW to 20 MW (up to 25% of the 80 MW wind farm capacity). The DAM price for electrolyzer activation is varied from $2/MWh to $40/MWh. It is assumed that the project lifetime is 15 years and the H_2 net sale price is $4/kg. Under these assumptions, the optimal size of electrolyzer is calculated to be 12 MW and the calculated optimal DAM price for electrolyzer activation is $36/MWh. Net Present Value as a function of electrolyzer size and price to start is shown a chart in Appendix A. For the best case, the NPV of the system is $16 M USD. For this case, the electrolyzer utilization percentage is around 80%. Fig. 2 shows a sample of reduced electricity for sale in the electricity market when electricity is used to produce hydrogen.

The breakeven H_2 price will vary based on the equipment costs, electricity markets, and production tax credits. . For this configuration, the H_2 price to make the solution profitable is about $3.4/kg. The price point being about $3.40 is consistent with earlier investigations [25,26]. This conclusion includes a $25/MWh electricity production tax credit (PTC) over the project lifetime. If a 25% marginal corporate tax rate is considered in the analysis, the breakeven H_2 production cost is about $3.75/kg. The H_2 breakeven cost increases with increasing value of PTC. However, the wind farm PTC decreases depending on the construction year [27]. If the PTC were zero, the breakeven H_2 production cost would be reduced to $2.1/kg.

The result also highlights an important market concern. The production of lower cost hydrogen with low carbon intensity is viewed as important for decarbonization of transportation and industrial processes. The wind power market, at least until it is saturated, provides a higher margin with today's market structure. Governments continue to modify electricity and/or hydrogen market structures to keep market incentives aligned with public policy objectives.

Scenario 2 - use electrolyzer to make hydrogen when electricity price is low, store the hydrogen and make and sell electricity from the hydrogen when electricity prices are high

H_2 is generated when DAM electricity price is low. The produced H_2 is assumed to be stored in a 30,000-kg (approximately 1 GWh energy equivalent) salt cavern storage system. This is a relatively small storage system compared to what is in commercial operation in recognition that not all wind farms are located near ideal geological storage. The fuel cell is used to generate electricity using the stored H_2 when needed. All the H_2 is consumed locally and no H_2 is transported.

With H_2 production cost becoming cost effective around $3.4/kg the fuel cell cannot profitably generate electricity in the DAM except under unusual conditions of very high DAM prices. Since fuel cell and electrolyzer ramp their power output in tens of seconds, however, they are qualified to participate in regulation-up and regulation-down services for bulk power system.

In this case, the wind farm generates H_2 rather than electricity when the DAM electricity price is lower than $16/MWh. The fuel cell sells electricity when the real-time electricity price is higher than $120/MWh.

Thus, this mode of operation provides ample time and opportunity for the fuel cell to participate in regulation-up service when the regulation price is high and electrolyzer to participate in regulation-down service when the regulation-down price is high. Based on the SPP regulation market data in 2019—2020 [28,29] the service times for regulation-up and
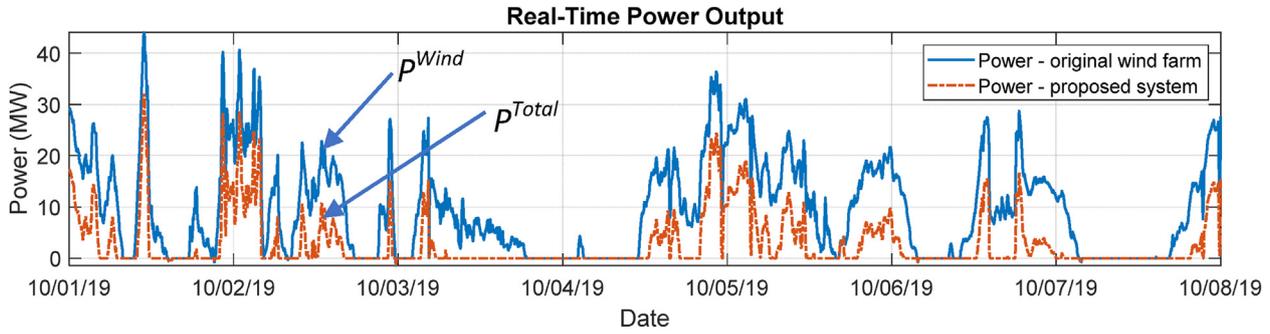
Fig. 2 — One-week data for electric power output from baseline system and baseline plus H₂ system.

regulation-down are selected as 1955 h and 1300 h with averaged prices of $34.3/MW-h and $22.6/MW-h. In this analysis, the fuel cell will provide regulation-up service only when the regulation price is high enough to offset the relatively high H$_2$ generation cost. It is also assumed that the energy consumption for regulation-up service is 8% of the total committed power in the analysis. This would make the regulation service profitable even with a relatively high H$_2$ price.

The electrolyzer installation capacity and the fuel cell installation capacity are two variables in the sensitivity analysis. The capacities are varied from 2 MW to 30 MW. It is assumed that the project lifetime is 30 years (mainly due to lower utilization factor of H$_2$ facility) and the H$_2$ price is $4/kg. The project NPV is compared to determine the best operational case based. For these conditions, the optimal size of electrolyzer is 6 MW and the optimal fuel cell capacity is 30 MW with a NPV of 5 MUSD. A chart giving the variation of the net present value for various fuel cell capacities and electrolyzer capacities is in Appendix A.

Under the optimal conditions, the electrolyzer utilization percentage is around 43% and the fuel cell utilization percentage is less than 10%. Fig. 3 shows the detailed analytical

data over one year. Again, this analysis is based on $25/MWh PTC for wind farm. If PTC is 0, balancing market profit could double for the best case (30-MW FC and 6-MW electrolyzer). One year data is important as it shows that the storage chamber is filled in spring when the electricity demand in this area is relatively low, and the storage is drawn down over the summer when the demand is relatively high. This is the equivalent of storage of wind power for several months.

Scenario 3: use the stored hydrogen to provide ancillary electrical services and market hydrogen

H$_2$ is generated using wind farm electricity and stored. Storage is assumed to be a 30,000-kg storage system (underground salt cavern). A fuel cell generates electricity using the stored H$_2$. It is assumed that H$_2$ is sold from storage when the H$_2$ price is $4/kg if there is sufficient hydrogen in storage. The electrolyzer generates H$_2$ when the DAM price is lower than $36/MWh. The fuel cell generates electricity when the real-time electricity price is above $200/MWh. For this analysis it is assumed, as in Scenario 2, that smaller amounts of hydrogen will be used to participate in the regulation-up service when
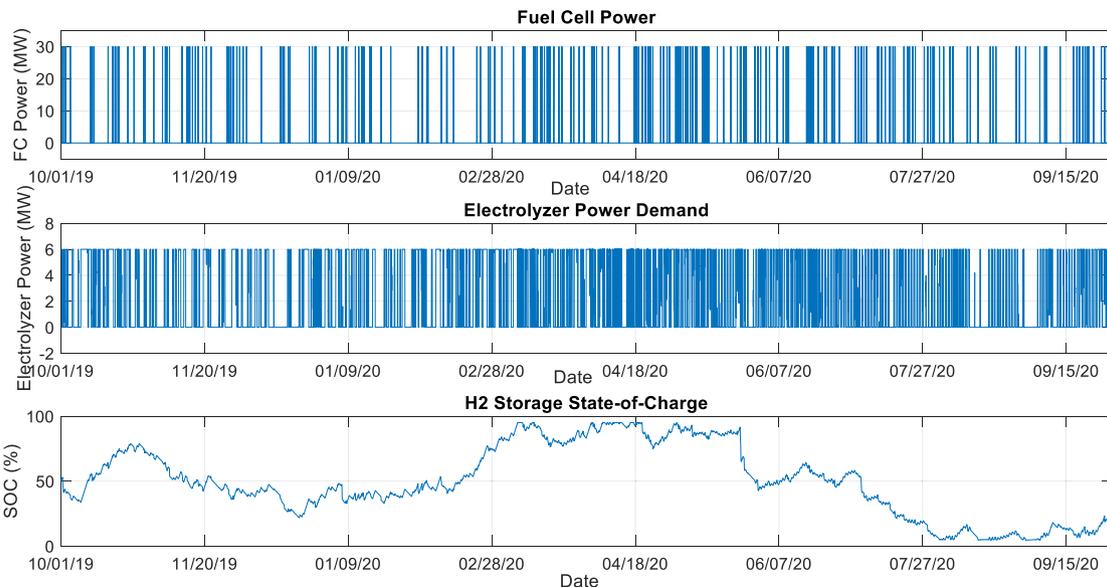

Fig. 3 — One-year data for fuel cell power, electrolyzer power, and H₂ storage state of charge.

the regulation price is higher than $34.3/MW-h and hydrogen is produced as part of participation in the regulation down market the regulation price is higher than $22.6/MW-h.

The electrolyzer installation capacity and the fuel cell installation capacity are two variables in the sensitivity analysis. The capacities are varied from 2 MW to 30 MW. It is assumed that the project lifetime is 40 years and the H_2 price is $4/kg. To achieve the 40-year operation, it assumed that the electrolyzer system is replaced at year 14 and year 28.

Under these conditions, the highest net present value of $36 M USD is found to occur with a 26 MW electrolyzer and a fuel cell capacity of 30 MW, which is the maximum considered. So, a local optimum was not determined. The optimal fuel cell size depends on both the H_2 consumed to provide regulation-up service and the H_2 price. The fuel consumption for regulation-up service varies year-by-year and by power market regions.

If the H_2 price is lower than $2.8/kg and the wind farm has PTC at $25/MWh, this solution may not be profitable for most cases except for a larger size fuel cell and a smaller size electrolyzer. If the PTC drops to 0 and maintaining the H_2 price at $4/kg, the profit can be significantly increased. Charts highlighting the range of net present value are in Appendix A. If PTC is 0, the breakeven H_2 production cost for this scenario would be $1.0−1.5/kg for cases with larger size fuel cell and smaller size electrolyzer.

While further analyses would be needed to determine an optimal size for the components, the results will depend not only on the variations in the electricity market, but also in the hydrogen market and those variations will be local not generic. So, this approach can support individual assessments.

Assessment of scenario results

For a simple comparison of selling electricity or hydrogen from a wind farm, selling electricity is more profitable until the cost of hydrogen exceeds about $3.40/kg. The legacy electricity market provided an electricity production credit of $25/MWh. Without that production tax credit, the transition point is $2.1/MWh. A production tax credit for hydrogen is an approach government are using to make the use of wind power to produce electricity or hydrogen a more nuanced decision.

Exploiting storage, the wind farm has another option, electricity-only option to increase profitability. It can produce and store hydrogen when the price of electricity is low and use the stored hydrogen to produce needed electricity when the electricity supply is low, and the demand is high.

The final situation analyzed, and the most profitable, augments the use of stored hydrogen by not only using it to improve grid operations but also to provide hydrogen to hydrogen markets. This focuses on producing as much electricity as possible whenever the wind is blowing and storing the excess energy as hydrogen when the electricity demand is sufficiently low. The stored hydrogen can be sold either as hydrogen or as electricity in the future depending on the relative market values.

Conclusions

Adding hydrogen to the energy mix provides an additional coupling among the electricity, natural gas, and water markets that is expected to be influenced by demand both for electricity and for transportation applications. Hydrogen-augmented electric vehicles offer benefits that will likely lead to growth in hydrogen demand. Emerging hydrogen technology makes it likely that the structure and oversight of these markets will become increasingly interdependent.

Underground long-term hydrogen storage is shown to be profitable under some circumstances to provide additional reliability to the electrical grid. The fact that storage can enhance grid reliability is not surprising as utility-scale batteries have been used successfully for this application.

Hydrogen storage in salt domes has been done commercially for decades when the local demand was sufficient. Research shows that this storage is long term and individual locations can store several terawatt hours of energy equivalent [30]. This large storage potential, with smaller scales in commercial use, provides promise for larger-scale dispatchable renewable energy. It also foreshadows future competition with utility scale batteries.

Decarbonizing and enhancing the reliability of the electricity grid is one potential hydrogen application. It is also targeted for transportation and expanded industrial uses. Large scale storage permits wind energy to be accumulated in real time and used in the future in coupled markets, potentially far exceeding the minimal desire that wind power be dispatchable.

Both technology and market structure affect profitability. This study shows the relative magnitude of some of those influences on plausible initial steps to meet the anticipated growth in hydrogen demand.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2022.12.243.

REFERENCES

[1] Chapman A, Itaoka K, Hirose K, Davidson FT, Nagasawa K, Lloyd AC, Webber ME, Kurban Z, Managi S, Tamaki T, Lewis MC. A review of four case studies assessing the potential for hydrogen penetration of the future energy system. Int J Hydrogen Energy 2019 Mar 8;44(13):6371–82.

[2] Griffiths S, Sovacool BK, Kim J, Bazilian M, Uratani JM. Industrial decarbonization via hydrogen: a critical and systematic review of developments, socio-technical systems and policy options. Energy Res Social Sci 2021 Oct 1;80:102208.

[3] Tarkowski R, Uliasz-Misiak B. Towards underground hydrogen storage: a review of barriers. Renew Sustain Energy Rev 2022 Jul 1;162:112451.

[4] Bünger U, Michalski J, Crotogino F, Kruck O. Large-scale underground storage of hydrogen for the grid integration of renewable energy and other applications. In: InCompendium of hydrogen energy. Woodhead Publishing; 2016 Jan 1. p. 133–63.

[5] Hosseini SE, Wahid MA. Hydrogen production from renewable and sustainable energy resources: promising green energy carrier for clean development. Renew Sustain Energy Rev 2016 May 1;57:850–66.

[6] Apostolou D, Enevoldsen P. The past, present and potential of hydrogen as a multifunctional storage application for wind power. Renew Sustain Energy Rev 2019 Sep 1;112:917–29.

[7] Almutairi K, Dehshiri SS, Dehshiri SJ, Mostafaeipour A, Issakhov A, Techato K. A thorough investigation for development of hydrogen projects from wind energy: a case study. Int J Hydrogen Energy 2021 May 25;46(36):18795–815.

[8] Greiner CJ, KorpÀs M, Holen AT. A Norwegian case study on the production of hydrogen from wind power. Int J Hydrogen Energy 2007 Jul 1;32(10–11):1500–7.

[9] Valverde-Isorna L, Ali D, Hogg D, Abdel-Wahab M. Modelling the performance of wind–hydrogen energy systems: case study the Hydrogen Office in Scotland/UK. Renew Sustain Energy Rev 2016 Jan 1;53:1313–32.

[10] Schrotenboer AH, Veenstra AA, uit het Broek MA, Ursavas E. A Green Hydrogen Energy System: optimal control strategies for integrated hydrogen storage and power generation with wind energy. Renew Sustain Energy Rev 2022 Oct 1;168:112744.

[11] Xiao P, Hu W, Xu X, Liu W, Huang Q, Chen Z. Optimal operation of a wind-electrolytic hydrogen storage system in the electricity/hydrogen markets. Int J Hydrogen Energy 2020 Sep 21;45(46):24412–23.

[12] Kroniger D, Madlener R. Hydrogen storage for wind parks: a real options evaluation for an optimal investment in more flexibility. Appl Energy 2014 Dec 31;136:931–46.

[13] Korpas M, Holen AT. Operation planning of hydrogen storage connected to wind power operating in a power market. IEEE Trans Energy Convers 2006 Aug 21;21(3):742–9.

[14] Hou P, Enevoldsen P, Eichman J, Hu W, Jacobson MZ, Chen Z. Optimizing investments in coupled offshore wind-electrolytic hydrogen storage systems in Denmark. J Power Sources 2017 Aug 15;359:186–97.

[15] Wang X, Li B, Wang Y, Lu H, Zhao H, Xue W. A bargaining game-based profit allocation method for the wind-hydrogen-storage combined system. Appl Energy 2022 Mar 15;310:118472.

[16] Loisel R, Baranger L, Chemouri N, Spinu S, Pardo S. Economic evaluation of hybrid off-shore wind power and hydrogen storage system. Int J Hydrogen Energy 2015 Jun 8;40(21):6727–39.

[17] Nose M, Kawakami T, Araki H, Senba N, Tanimura S. Hydrogen-fired gas turbine targeting realization of CO_2 -free society. Mitsubishi Heavy Industries Technical Review 2018;55(No. 4). De.

[18] Kharel Subodh, Shabani Bahman. Hydrogen as a long-term large-scale energy storage solution to support renewables. Energies 2018;11(10).

[19] Cost of electrolytic hydrogen production with existing technology. DOE Hydrogen and Fuel Cells Program Record; 2020. https://www.hydrogen.energy.gov/pdfs/20004-cost-electrolytic-hydrogen-production.pdf.

[20] Ahluwalia RK, Papadias DD, Peng J-K, Roh HS. System level analysis of hydrogen storage options. https://www.hydrogen.energy.gov/pdfs/review19/st001_ahluwalia_2019_o.pdf.

[21] Bockris JO. The hydrogen economy: its history. Int J Hydrogen Energy 2013 Feb 27;38(6):2579–88 [Pipelines cheaper than power lines].

[22] Technology brief: analysis of current-day commercial electrolyzers. National Renewable Energy Laboratory; 2004. https://www.nrel.gov/docs/fy04osti/36705.pdf.

[23] Hydrogen fuel cells. US Department of Energy Hydrogen Program; 2006. https://www.californiahydrogen.org/wp-content/uploads/files/doe_fuelcell_factsheet.pdf.

[24] Rhodes J, Deetjen T, Hebner R, Lewis M, Bouwkamp N, Weeks B, Davidson F, Lloyd A. Renewable electrolysis in Texas: pipelines versus power lines. https://sites.utexas.edu/h2/featured-publications/.

[25] Morton Ella M, Deetjen Thomas, Goodarzi Shadi. Optimizing hydrogen production capacity and day ahead market bidding for a wind farm in Texas. Available at: SSRN: https://doi.org/10.2139/ssrn.4135752, ssrn.com; June 13, 2022. abstract=4135752.

[26] Jovan DJ, Dolanc G. Can green hydrogen production be economically viable under current market conditions. Energies 2020 Dec 14;13(24):6599.

[27] Advancing the growth of the U.S. Wind industry: federal incentives, funding, and partnership opportunities. https://www.energy.gov/sites/default/files/2021-07/us-wind-industry-federal-incentives-funding-partnership-opportunities-fact-sheet-v2.pdf.

[28] SPP Real-time balancing market data. https://marketplace.spp.org/groups/real-time-balancing-market.

[29] Southwest Power Pool real-time balancing market data. https://marketplace.spp.org/groups/real-time-balancing-market.

[30] Lankof l, Urbańczyk K, Tarkowski r. Assessment of the potential for underground hydrogen storage in salt domes. Renew Sustain Energy Rev 2022;160.