Optimal Planning of Co-Located Wind Energy and Hydrogen Plants: A Techno-Economic Analysis

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Abstract. Green hydrogen produced using renewable electricity could play an important role in a clean energy future. This paper seeks to analyze the techno-economic performance of integrated wind and hydrogen systems under different conditions. A co-located wind and hydrogen hybrid system is optimized to reduce the total system cost. We have adopted and improved a state-of-the-art techno-economic tool REopt, developed by the National Renewable Energy Laboratory (NREL), for optimal planning of the integrate energy system (IES). In addition to wind and electrolyzer components, we have also considered battery energy storage, hydrogen tank, and hydrogen fuel cell in the IES. The results show that (i) adding electrolyzers to the grid-connected wind energy system could reduce the total system cost by approximately 8.9%, and (ii) adding electrolyzers, hydrogen tank, and hydrogen fuel cells could reduce the total system cost by approximately 30%.

1. Introduction

As a renewable energy source, wind energy provides a solution for environmental protection and alleviating the energy crisis, but its uncertain and non-dispatchable nature presents challenges in grid integration. The emergence of renewable gas technologies like hydrogen presents a promise of removing the bottlenecks in the storage sectors [1], which helps to tackle the uncertainty and variability inherent in renewable resources [2]. In addition, the decarbonisation drive urges for harnessing energy from non-polluting sources whereas the end energy product should also be environment friendly. Hydrogen has been widely recognized as a necessary energy carrier for achieving carbon neutrality goals [3]. The U.S. Department of Energy has launched Energy Earth shots Initiative, and the First Energy Earthshot aims to slash the cost of clean hydrogen by 80% to $1 per Kilogram in one decade [4]. Therefore, how to efficiently leverage renewable energy resources to produce hydrogen has become a focal topic in the past few years.

1.1. Literature Review

There exist three common ways to produce hydrogen, including the dissociation of water molecule (electrolysis), microbial production, and thermo-chemical processes [5]. The electrolysis of water is the most mature and economical way to produce hydrogen. *In terms of energy storage*, as an energy carrier with high energy density, hydrogen can play an important role in balancing variable renewable electricity production. Mayyas et al. [6] have analyzed the economic feasibility of hydrogen as an energy storage medium. Elberry et al. [7] have also discussed the current mainstream hydrogen storage methods. *In terms of hydrogen transport*, several offshore wind farm hydrogen transportation strategies are discussed in [8]. Miao et al. [9] compared the economic differences between high-voltage direct current (HVDC) cables and hydrogen pipelines when transmitting renewable energy over long distances.

There also exist several studies focusing on hybrid wind and hydrogen systems. For example, a linear market equilibrium model focusing on the interdependencies among electricity, hydrogen, and renewable methane gas was developed by Koirala et al. [10] to offer the required flexibility in the energy system. A wind dominated integrated electricity-hydrogen-emission framework was analyzed in [11] to evaluate the technology's cost-competitiveness compared with conventional power sources. However, most of the models used in recent studies have not considered a carbon footprint (i.e., some sort of fossil-powered generation is present) or a power-grid connected system, where the variability and uncertainty in the renewable generation are mostly managed by the robust power grid. Therefore, a techno-economic study to explore the optimal system composition and economic operation is desired for the integrated wind and hydrogen system. To this end, this work aims to explore the most feasible mix of a hybrid wind and hydrogen energy system, and study the hybrid energy system's operational behavior in response to the economic, zero carbon emission, and flexibility requirement of the system.

1.2. Research Objectives

This work performs a planning and operational study on a co-located hybrid wind and hydrogen energy system. The objective is to capture the long-term and short-term operational characteristics through detailed system modeling. Both the financial and technical constraints are considered to demonstrate the technical feasibility and financial viability of this multi-carrier system rather than relying on additional incentives or favorable policies. The resilience of the integrated energy system (IES) is also evaluated, specifically the optimal configuration of the IES under power outages. The economic feasibility of using renewable energy to produce green hydrogen is comprehensively studied by considering a number of key factors, such as hydrogen price, onsite hydrogen storage, and fuel cell generators. We seek to explore the optimal IES composition (i.e., capacity to be installed) of the wind and hydrogen generation technologies to be built on a 'greenfield'.

The remainder of the paper is organized as follows. Section 2 describes the techno-economic methodology used in this study. Section 3 presents the case studies and results with different IES components combinations. Section 4 concludes the paper and discusses potential future work.

2. Methodology

The techno-economic analysis for the sector-coupled wind-hydrogen system is performed by adopting REopt, an open-source techno-economic tool developed by NREL [12]. An overall framework of the REopt techno-economic analysis for the integrated wind and hydrogen system is shown in Fig. 1. REopt determines the IES components capacity and dispatch decisions, by considering factors such as the weather conditions at the IES location, electrical load, wholesale prices, hydrogen prices, etc., to optimize the end-user's economic savings or profits for producing energy onsite. REopt is suitable for site-specific studies rather than system level studies, where the system level constraints are enforced via the net export or import limit to the system.

In addition to the wind, battery, and financial models in REopt, we have built and added the electrolyzer, hydrogen tank storage, and hydrogen fuel cell models for our study. Figure 2 shows the overall architecture of the REopt modules adopted/created in this study, including the input and output parameters of each component and constraints. For modeling the wind and battery systems in this study, the user-inputs to REopt include the capital cost, operations and maintenance (O&M) cost, annual electricity consumption, battery charging and discharging

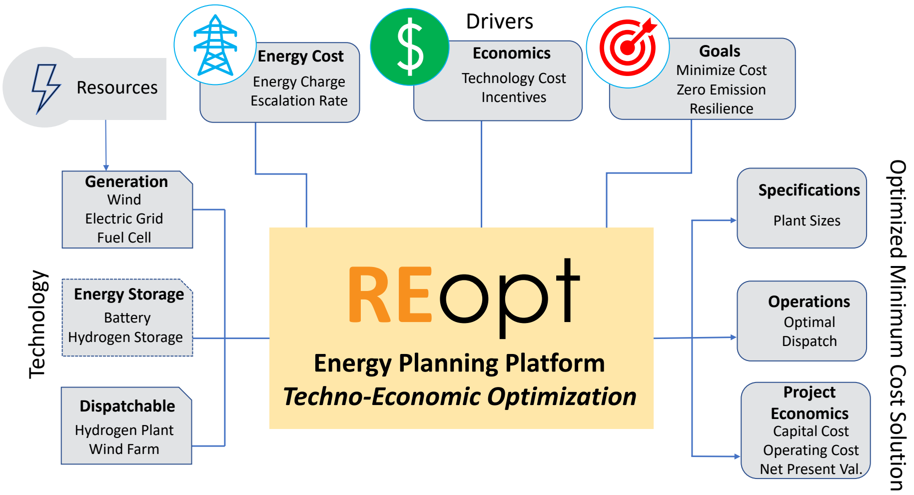


Figure 1: Techno-economic analysis framework for the integrated wind and hydrogen system (modified from [12])

efficiency, and other performance parameters of the wind energy system to estimate the power generation. For modeling the hydrogen production, the electrolyzer technology takes electricity and a feed stock (e.g., water) to produce hydrogen. The user-inputs to REopt for the electrolyzer include the capital and O&M costs, feed stock, electric energy consumed to hydrogen produced ratio, hydrogen sale price, etc. For modeling the hydrogen storage tank, the minimum and maximum capacity limits, installation and O&M cost are considered. In terms of hydrogen fuel cell modeling, in addition to the capacity limits and cost, another important parameter, hydrogen consumed to electricity produced ratio, is also considered. A number of financial parameters such as tax rates, investment based incentives, capital based incentives, production based incentives, discount rate, and modified accelerated cost recovery system (MACRS) are also taken into account in order to obtain the most realistic results.

With the integration of the electrolyzer, hydrogen tank, and fuel cell technology to the existing REopt capability, we are able to evaluate the techno-economic performance of hybrid wind and hydrogen systems under different conditions, such as grid outages, varying electricity and hydrogen prices, etc. Specifically, the following three scenarios are investigated and compared in this study.

- **Case I: Wind+Battery+Grid (Benchmark)**: A grid-connected wind energy system with a battery energy storage is considered to meet the electricity demand. Both the wind and battery storage systems can provide electricity during grid outages. The battery system could be charged from either the grid or the wind energy system, depending on the electricity price and wind energy production. A randomly selected 168 hours of grid outage is applied to evaluate the resilience of the hybrid energy system.
- **Case II: Wind+Battery+Hydrogen+Grid**: In addition to the setup in Case I, an electrolyzer is added in Case II. The electrolyzer can take electricity from both the grid and the wind system to produce hydrogen, depending on the electricity price, hydrogen price, wind power generation, and load demand.
- **Case III: Wind+Battery+Hydrogen+Fuel Cell+Grid**: In addition to the setup in Case II, a hydrogen storage tank and a hydrogen fuel cell system are added in Case III, which can supply electrical power to the grid when necessary. In addition to selling the hydrogen in real time, Case III allows the hydrogen to be stored for later use (through the fuel cell system) to provide electricity at peak load periods or during power outages.

The modeling of the coupled system involves the technology, system, financial constraints that are implemented by considering a number of constraints, including energy balance constraints, battery and storage tank state constraints (where applicable), technology capacity constraints, net export to the grid and net import from the grid constraints, and the peak demand constraint. The optimization aims to minimize the total cost of the IES that consists of the electrolyzer (hydrogen) installation cost, wind energy system installation cost, battery and hydrogen storage installation costs, fuel cell installation cost (at applicable scenarios), O&M cost, electricity purchase cost, tax and incentives, and profit from selling hydrogen. Figure 2 depicts the model architecture of REopt modules created in this study, including the parameters and constraints. The detailed mathematical formulations on the objective and constraints could be found in Ref. [12]. A mixed-integer linear program (MILP) is formulated for this problem, and the FICO Xpress solver is adopted to solve the optimization problem to determine the optimal component selection, sizing, and dispatch strategy of technologies chosen from a candidate pool, such that loads are met at every time step at the minimum life cycle cost. The outputs of the optimization include the optimal sizes of the system components, the total system expenditure, the capital expenditure of each component, the optimal trade-off of wind and hydrogen production operations, the levelized cost of hydrogen (LCOH), and the levelized cost of energy (LCOE) of the IES. The results also include a range of financial parameters such as the payback period, life cycle cost, and net present vale. These results could provide a good reference for the investment, planning, and operation of the IES.

3. Numerical Experiments

In this study, it is assumed that the IES system is located at Abilene, TX. The wholesale market prices in year 2019 from the Electric Reliability Council of Texas (ERCOT) are adopted. The load profiles are simulated by the U.S. Department of Energy (DOE) Commercial Reference Building (CRB) models [13]. Figure 3 shows the electricity load and wholesale market prices used in this study. Some other key assumptions for the hybrid energy system setup are summarized in Table 1. The planning horizon of the IES is assumed to be 25 years. The 8,760 hourly data of the modeled year (i.e., 2019) is input into REopt to analyze the full planning period. A constant rate of change for future costs of grid energy, and O&M for inclusion into the discounting factors to account for projected cost escalation (or de-escalation) rates are considered. Meanwhile, we assume perfect predictions of all future events, including weather and load. All costs and benefits are discounted with the specified discount rate to present values using standard economic functions. For the capital and operating costs of the wind, battery storage, different hydrogen generation technologies, fuel cell, and others, the NREL's Annual Technology Baseline (ATB) [14] is adopted as a reference.

3.1. Results and Discussion

Table 2 summarizes the optimal sizing of IES components (i.e., wind, electrolyzer, battery, tank, and hydrogen fuel cell) and the system total costs of all three cases. It is observed that the total cost of the system in Case II and Case III is reduced by 8.9% and 30%, respectively, compared to the benchmark Case I. The battery storage is not chosen in Case III due to the addition of hydrogen storage tank and fuel cell system.

Figures 4 - 6 show the generation stack for 368 hours to balance the load in the three cases, including 168 hours of grid outages and 100 hours each before and after the outages. For Case I, during the power grid outage, the vast majority of the load demand is provided by the wind, while the battery only provides a small portion of the power. There is no difference in the source of electricity in Case II compared to Case I. But in Case II, a portion of the electricity from the wind is fed into the electrolyzer to produce hydrogen. In Case III, the battery energy

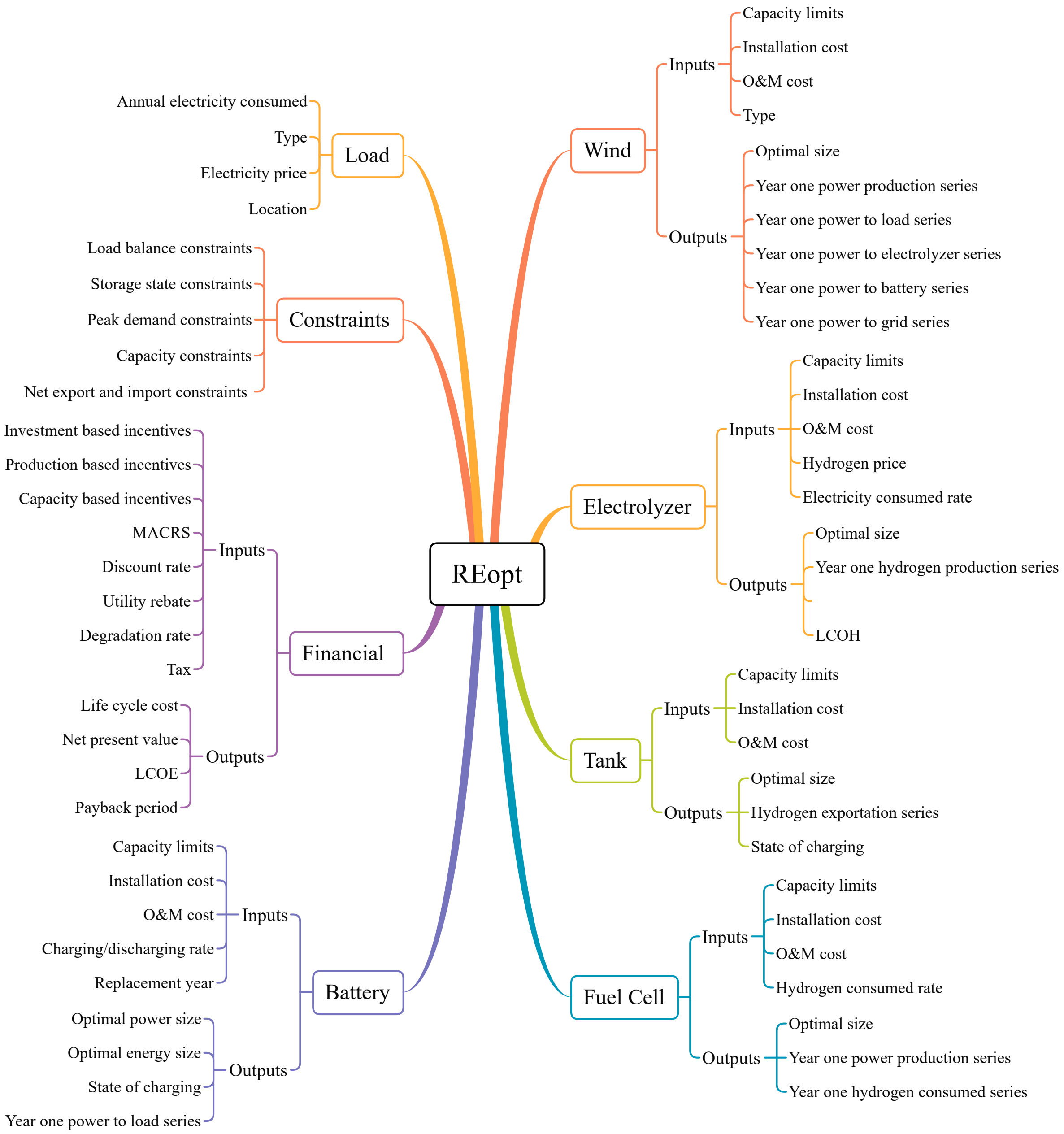


Figure 2: Model architecture of the REopt modules adopted/created in this study

storage is not chosen in the optimization, due to the selection of hydrogen fuel cell. During the grid outages, the fuel cell unit has supplied a portion of the load demand. The battery charging/discharging schedules and electricity sources in Cases I and II are shown in Figs. 4 and 5, respectively. Figure 7 depicts the electricity sources used for producing hydrogen in Case III, and the power required for the electrolyzer is provided by both the wind and grid. During the grid power outage, the wind energy can meet both the electric load and electrolyzer demand. The hydrogen tank, in addition to meeting the supply of hydrogen fuel cells, also exports the remaining hydrogen for sale, as also shown in Fig. 7.

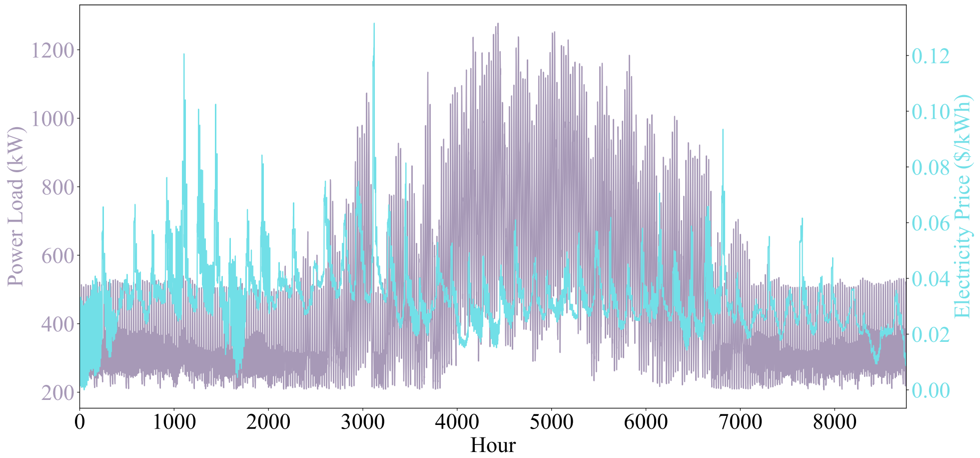


Figure 3: Annual profiles of load and electricity price

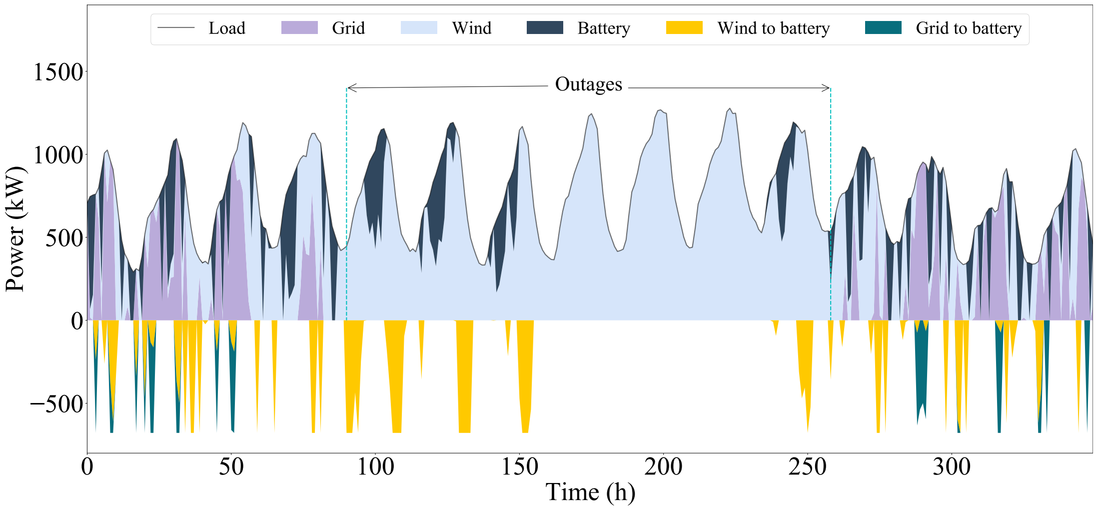


Figure 4: Case I (wind+battery+grid) load balance from different components, during both normal and grid outage periods. Negative values represent the battery charging schedules from the grid and wind.

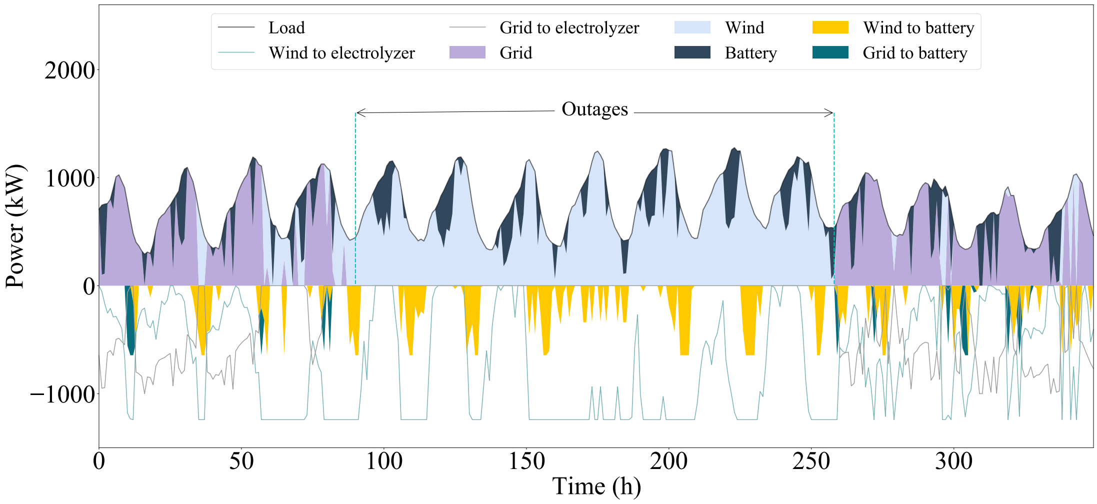


Figure 5: Case II (wind+battery+hydrogen+grid) load balance from different components, during both normal and grid outage periods. Negative values represent the battery charging and electrolyzer operation schedules.

Table 1: Key assumptions in the hybrid energy system setup

Parameter	Value
Electricity consumed per kg of hydrogen produced (low thermal energy)	48 kWh/kg
Hydrogen sale price	$2.8/kg
Hydrogen slope for fuel cell	0.076 kg/kWh
Electrolyzer installation cost	$48,000/kg/yr
Fixed electrolyzer O&M cost	$3,600/kg/yr
Variable electrolyzer O&M cost	$0.24/kg
Fuel cell installation cost	$500/kW
Fuel cell fixed O&M cost	$30/kW
Planning period	25 years

Table 2: Hybrid energy system component capacity and cost

Technology	Case I	Case II	Case III
Wind	2,666.2 kW	2,861.28 kW	2,401.37 kW
LCOE of wind	$0.0482/kWh	$0.0482/kWh	$0.0482/kWh
Fuel cell	N/A	N/A	724.82 kW
Hydrogen tank	N/A	N/A	353.163 kg
Battery energy capcity	4,025.3 kWh	3,617.28 kWh	0 kWh
Battery power capcity	678 kW	644 kW	0 kW
Electrolyzer	N/A	25.834 kg/h	26.438 kg/h
Total system cost	$5,773,458	$5,261,098	$4,055,447

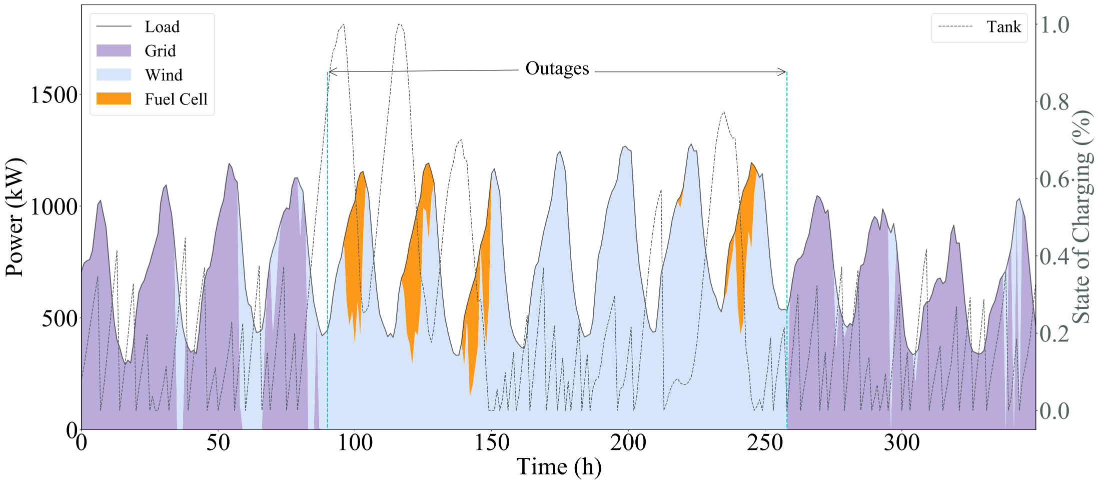


Figure 6: Case III (wind+battery+hydrogen+fuel cell+grid) load balance from different components, during both normal and grid outage periods. The right y-axis illustrates the state of charge of the hydrogen tank.

Figure 8 compares the three cases in terms of the system total cost, LCOH, battery energy capacity, and battery power capacity. For the LCOH of Cases II & III in Fig. 8b, there is only a slight difference, due to that the installation and O&M costs of electrolyzers and the price

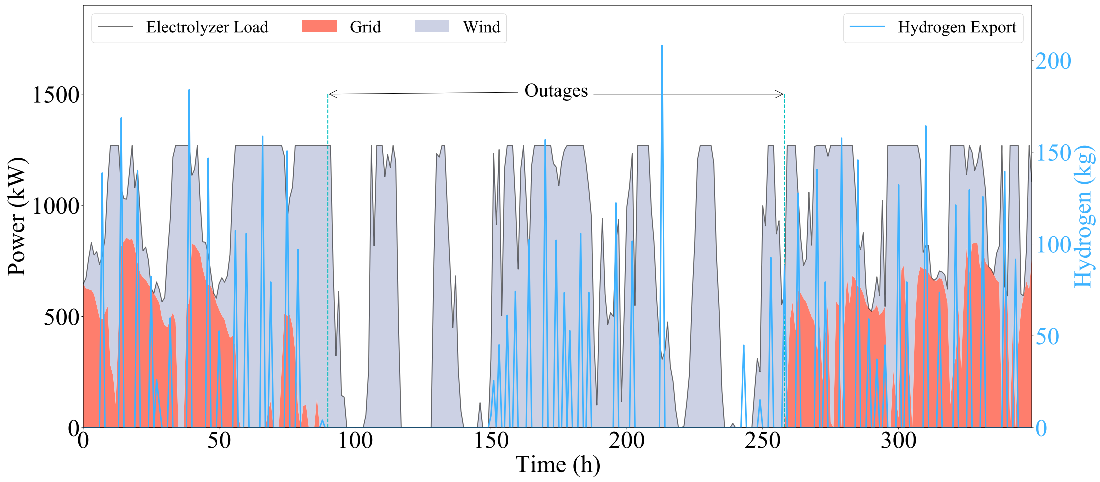
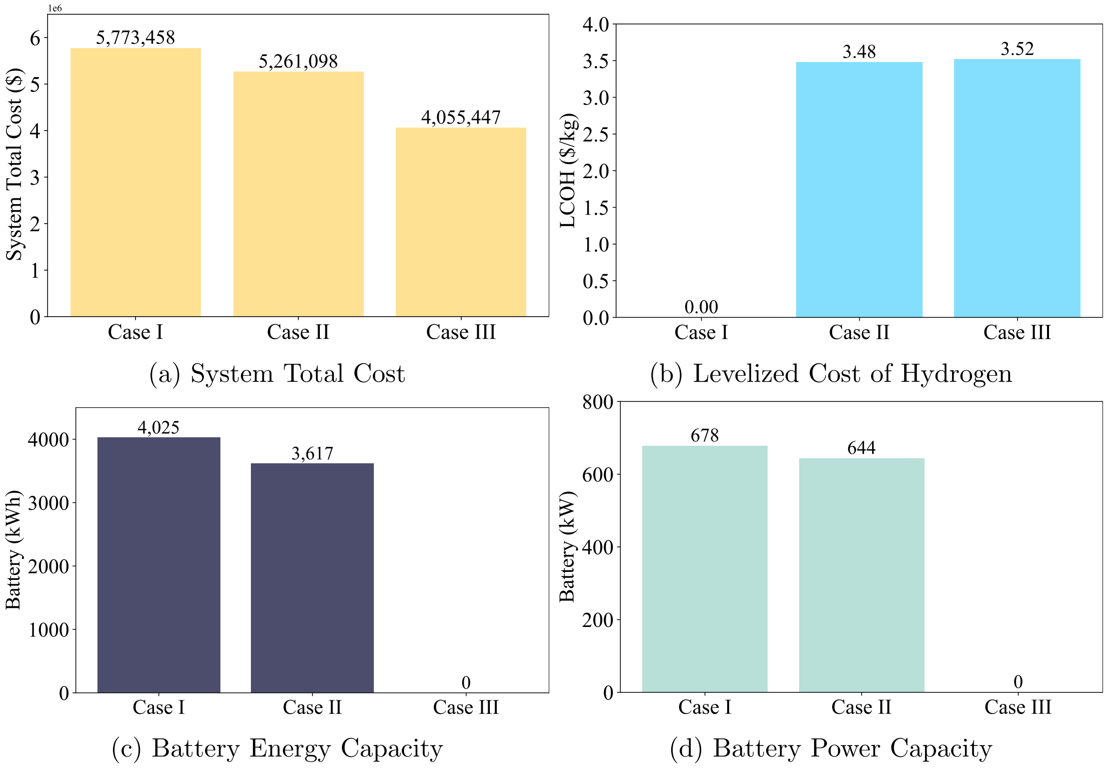


Figure 7: Case III (wind+battery+hydrogen+fuel cell+grid) electrolyzer load balance from different components, during both normal and grid outage periods. The right y-axis shows the hydrogen export volume.

of energy for hydrogen production are same between the two cases. It is observed from Figs. 8c and 8d that, hydrogen has completely replaced batteries as the new energy storage medium in Case III; the size of the battery is smaller in Case II compared that in Case I, due to the capacity increase of the wind energy system.



(a) System Total Cost

(b) Levelized Cost of Hydrogen

(c) Battery Energy Capacity

(d) Battery Power Capacity

Figure 8: Comparing the three cases in terms of total system cost, LCOH, and battery capacity.

3.2. Sensitivity Analysis

A sensitivity analysis is performed to study the impact of hydrogen sale price on the system LCOE. In this sensitivity analysis, we only consider the LCOE of on-site energy generation, including the cost of wind power, electrolyzer, fuel cell and hydrogen tank, and the profit from selling hydrogen. Since hydrogen does not present in Case I, this sensitive analysis is performed only in Cases II & III. In the benchmark Case I, the hydrogen sale price is \$2.8/kg.For the sensitivity analysis, we have varied the hydrogen sale price from \$1/kg to \$4.5/kg. A total of 8 new cases are simulated, and Fig. 9 shows the relationship between the LCOE of the IES and the hydrogen price. It is shown that the system LCOE is highly impacted by the hydrogen price. For example, when the price of hydrogen increases from the benchmark \$2.8/kg (used in previous case studies) to \$4.5/kg, the system LCOE of Case II and Case III is decreased to \$0, meaning that the system could be operated independently with the grid.

To evaluate the robustness of adding electrolyzers and fuel cells in reducing total system costs, another sensitivity analysis is performed on wind farms located at four different independent system operator (ISO) territories across the United States with diverse weather conditions and wholesale electricity prices. The four wind farms are: the Shiloh Wind Farm in the California ISO, the Bent Tree Wind Farm in the Mid-continent ISO, the Blue Creek Wind Farm in the PJM Interconnection, and the Maple Ridge Wind Farms I & II in the New York ISO. Figure 10 illustrates the changes in the total cost of the four wind farms in the three cases. As seen from the figure, although the total cost for maintaining the same benchmark case varies for each wind farm, it invariably shows a gradual decrease in the total cost after adding electrolyzers and fuel cells. Overall it is found that having co-located wind and hydrogen plants could potentially reduce the total cost of the system under different weather conditions and electricity markets.

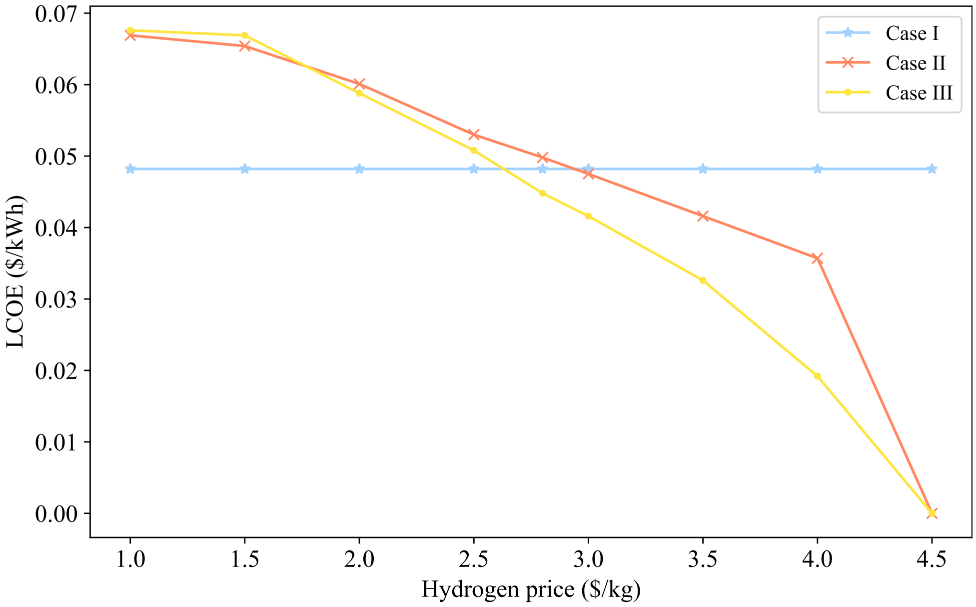


Figure 9: System LCOE versus the hydrogen price.

4. Conclusion

This study evaluated the techno-economic performance of integrated wind and hydrogen systems. A techno-economic tool REopt was adopted and improved to perform the optimal planning of the hybrid energy system. The results showed that (i) adding electrolyzers to the grid-connected

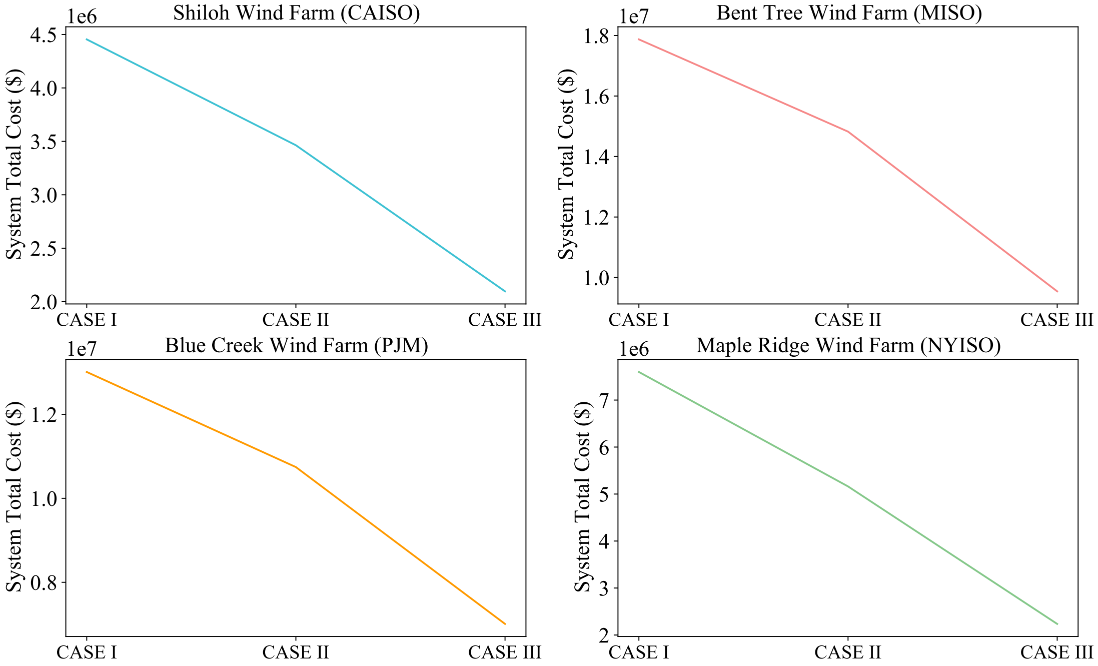


Figure 10: System total cost changes of four different wind farms in the three cases.

wind energy system could reduce the total system cost by approximately 8.9%, and (ii) adding electrolyzers, hydrogen tank, and hydrogen fuel cells could reduce the total system cost by approximately 30%. It was also found that using hydrogen tank and fuel cell to replace batteries as an energy storage medium could reduce the system total cost. The levelized cost of hydrogen is mainly affected by the price of adopted energy sources for hydrogen production and the price of hydrogen.

As for potential future work, this research could be further extended into several directions. An offshore wind and hydrogen planning and operation model could be developed, with a focus of optimizing the hydrogen storage and transport strategies. Other energy conversion methods that are safer and easier to store and transport could be explored, such as converting wind energy to ammonia and methanol.

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