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Bidding optimization for hydrogen production from an electrolyzer

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Abstract. This paper presents a comprehensive study on the bidding optimization for hydrogen production from an electrolyzer, focusing on a single day comprising 24 hours. With the rising demand for clean energy sources, the research aims to optimize profitability and efficiency in hydrogen production. The primary objective is to maximize profit while ensuring the fulfillment of the targeted hydrogen production by the end of the day. The optimization formulation incorporates electrolyzer maintenance, electricity, and water consumption costs. The model considered two cases with different electrolyzer efficiency values to optimize power usage, allowing for a comprehensive analysis of hydrogen production optimization. Ramping limits are imposed to maintain power system stability and reliability, preventing sudden fluctuations. By solving the formulated equations and considering factors such as energy and water prices, the research findings demonstrate the effectiveness of the bidding optimization approach in optimizing resource utilization and maximizing profit. Notably, the model successfully achieves the targeted hydrogen production by the end of the day while maximizing profit. This research contributes valuable insights into the bidding optimization process for hydrogen production, highlighting the potential for economic and sustainable hydrogen generation from electrolyzers.

Introduction

Climate change necessitates a shift to clean, sustainable energy sources to mitigate its environmental impact. Hydrogen, as a clean and efficient energy carrier, has garnered attention in the energy industry. However, traditional hydrogen production from fossil fuels without carbon capture contributes to greenhouse gas emissions. The shift towards hydrogen produced from fossil fuels with carbon capture, utilization, and storage (CCUS) offers a viable alternative, considering the high carbon production from natural gas and coal sources. This transition is crucial in combating climate change. Hydrogen can contribute to a resilient and sustainable energy future by utilizing alternative and cleaner production methods and diversifying its sources. Additionally, hydrogen can be utilized in new applications and complement electricity use, enhancing its potential. Today, more countries invest in hydrogen technologies since they recognize their importance for the future of energy. Austria announced that as part of the Austrian Climate and Energy Strategy for 2030, a hydrogen strategy based on renewable electricity would be developed. Even in Saudi Arabia, Saudi Aramco and Air Products announced their plans to construct Saudi Arabia's first hydrogen refueling station. Thus, this paper focuses on the bidding optimization for hydrogen production from an electrolyzer. [1]

To produce hydrogen as an energy carrier, an electrolyzer is required. This device utilizes electricity to split water into hydrogen and oxygen through an electrochemical process called electrolysis. The electrolyzer connects to an external circuit to provide the required electric current for electrolysis. This process makes water break down into its constituent elements of hydrogen and oxygen gases. The electrolyzer consists of an anode and a cathode. At the anode, a process

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called oxidation takes place. Water molecules near the anode lose electrons and form oxygen gas (O2) and positively charged hydrogen ions (H+). The cathode attracts hydrogen ions (H+) from the electrolyte. At the cathode, the hydrogen ions gain electrons from the external circuit and combine to form hydrogen gas (H2) in a reduction process. [2]

Bidding optimization is identifying the optimal bidding strategy in energy markets to maximize profits. Optimizing bidding for hydrogen production from an electrolyzer is crucial for a greener future and for addressing carbon emissions. Developing bidding strategies considering market prices for hydrogen, electricity, and electrolyzer costs can maximize revenue and profitability as hydrogen production gains traction. Hydrogen plants play a vital role in the clean energy sector, making bid optimization for electrolyzer-based hydrogen production a focal point. With the growing interest in hydrogen as a sustainable energy alternative, bid optimization can significantly contribute to the global transition toward a greener future [3].

Several studies have focused on hydrogen production from electrolyzer. Study [4] provides an overview of water electrolysis-based systems for hydrogen production, particularly those utilizing hybrid/solar/wind energy sources. The article emphasizes the importance of hydrogen as a clean energy carrier and discusses system configurations, electrolyzer types, catalysts, and energy sources. Study [5] delves into the role of catalysts in enhancing the efficiency and performance of electrolyzers for hydrogen production, exploring different types of catalysts and recent advancements in catalyst design. In [6], the focus is on a membrane-based seawater electrolyzer that directly splits seawater into hydrogen and oxygen using a proton-conducting membrane.

Recent studies have focused on optimization for hydrogen production from electrolyzer. In a study [7], this paper discusses optimizing a high-temperature electrolysis system for hydrogen production, considering the degradation of cell materials. It explores the factors causing degradation and investigates the influence of operating conditions on the degradation process. The paper also proposes operation strategies to balance hydrogen production efficiency and the lifespan of the stack. In the study [8], this paper's primary emphasis is modeling and enhancing an alkaline water electrolysis system employed for hydrogen generation. The study extensively covers the design and operational aspects of the electrolyzer, along with an exploration of diverse optimization methodologies. This research aims to improve hydrogen production efficiency and cost-effectiveness through electrolysis.

Optimizing bidding strategies is crucial for maximizing profits in electrolyzer-based hydrogen production, and it has gained significant research attention. In the study [9], an optimal bidding strategy is developed for hydrogen production from electrolyzers in renewable energy systems. The proposed mathematical model considers uncertainties in renewable energy generation and electricity prices to maximize profit. The results demonstrate the effectiveness of the strategy in maximizing profit. In [10], the potential participation of virtual power plants (VPPs) with hydrogen energy storage in multi-energy markets is discussed. The study highlights the role of hydrogen storage in VPPs and presents a two-layer optimization model considering resource complementarity and external market bidding strategies.

In addition to previous studies on hydrogen production from electrolyzers, it is essential to understand the motivation behind this research. Electrolyzers are electric loads that require electric energy to produce hydrogen (H2). However, hydrogen production plants' storage capacity allows them to schedule their operations based on electricity prices. The lack of an optimization framework integrating bidding prices presents a research gap in hydrogen production from electrolyzers. This aspect is crucial in optimizing the operational scheduling of electrolyzers. Therefore, the objective is to integrate bidding prices into the optimization process and identify the most effective strategy for achieving maximum profit while meeting the targeted hydrogen production quota. The study will utilize the GAMS software for accurate and reliable results.

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Methodology

A. Objective function

The study utilizes a bidding optimization model to maximize the profit from hydrogen production. This bidding optimization model is achieved through (1), which explains that the optimization model will maximize the profit. In this equation, F represents the profit, R represents the revenue from hydrogen production, and C represents the cost of the electrolyzer needed to produce hydrogen.

$$\max\ \mathrm{F} = \mathrm{R} - \mathrm{C} \tag{1}$$

The analysis assumes that the demand for hydrogen is already established, which allows for revenue calculation using (2). As reference [11] indicates, the selling price has been set at $11 per kilogram. The study target for hydrogen production is 1000 kilograms, resulting in a total revenue of 11000 dollars.

$$\mathrm{R} = \text{selling price} * \text{quaintity of hydrogen target} \tag{2}$$

Eq. 3 represents the cost function for the electrolyzer. In this equation, C_M represents to the maintenance cost for the electrolyzer, as derived from the reference paper [10]. According to formula 4, C_M can be calculated as 2% of the electrolyzer capital cost.

Eq. 5 to 6 illustrate the cost functions for electricity and water consumption, respectively. These equations quantify the expenses associated with utilizing an electrolyzer to produce hydrogen.

$$\mathrm{C} = \mathrm{C_E} + \mathrm{C_W} + \mathrm{C_M} \tag{3}$$

$$\mathrm{C_M} = 2\% \times \text{capital cost} \tag{4}$$

$$\mathrm{C_M} = 2\% \times 1765\ \$/\mathrm{kW} = 35.3\ \$/\mathrm{kW}$$

Eq. 5 defines the cost function for electricity consumption. In this equation, $\mathrm{P(t)}$ represents the decision variable denoting the electricity required at each time interval, covering the 24-hour duration of the study. The variable $\text{Energy price}(\mathrm{t})$ represents the corresponding energy price for each specific time interval. The data used for the energy price, expressed in $\$/\mathrm{kWh}$, was sourced from Norway on December 5, 2023 [12].

$$\mathrm{C_E} = \sum_{t=1}^{24} \mathrm{P(t)} * \text{energy price}(\mathrm{t}) \tag{5}$$

Eq. 6 defines the cost function for water consumption. In this equation, $\mathrm{W(t)}$ represents the decision variable indicating the water required at each time interval within the 24-hour study period. The variable water price(t) represents the corresponding water price for each specific time interval. The water price data, equal to 0.00669 $/kg, is sourced from Norway [13].

$$C_W = \sum_{t=1}^{24} W(t) * water\ price(t) \tag{6}$$

B. Equality constraints:

1. Constraint for Electricity Consumption:

The model considers two cases for electricity consumption related to the efficiency of the electrolyzer. The electrolyzer efficiency is set at 70% in the first case, as referenced in [9]. Eq. 7 establishes the relationship between the power input to the electrolyzer and the resulting hydrogen production. The decision variable H(t) represents the hydrogen produced at each time interval. In the second case, the efficiency is assumed to be 80%. Analyzing these two cases allows the model to explore the impact of different electrolyzer efficiencies on electricity consumption and hydrogen production.

$$\mathrm{P(t)} = \frac{50 * \mathrm{H(t)}}{\text{efficiency of electrolyzer}} \tag{7}$$

2. **Constraint for Water Consumption:**
   The model includes a constraint on water consumption, which defines the relation between the water consumption and hydrogen production decision variables, shown in Eq.8.

Additionally, the water needed in kg to produce 1 kg of hydrogen is 9 kg [15].

$$\mathrm{W(t)} = 9 * \mathrm{H(t)} \tag{8}$$

3. **Constraint for the hydrogen tank:**

Eq. 9 represents a constraint that governs the hydrogen storage in the tank at a specific time t. It ensures that the amount of hydrogen stored in the tank at time t is determined by the sum of the hydrogen storage in the tank at the previous time and the amount of hydrogen produced during time t. This constraint captures the dynamics of the hydrogen storage system, where the current storage level depends on the previous storage level and the hydrogen production during the current period.

$$\mathrm{TankStore(t)} = \mathrm{TankStore(t-1)} + \mathrm{H(t)} \tag{9}$$

C. Inequality constraints:

1. **Maximum and Minimum Consumption:**

The proposed model incorporates certain constraints to ensure electricity and water consumption remain within certain limits. Specifically, the model uses inequality constraints to set the upper and lower limits on electricity consumption as shown in Eq. 10 and water consumption as shown in Eq. 11. The model's maximum allowable electricity consumption (P_{max}) is 6000 kWh, while the minimum allowable consumption (P_{min}) is zero. Similarly, the maximum allowable water consumption (W_{max}) is assumed to be 3000 kg, while the minimum allowable consumption (W_{min}) is also zero.

$$0 \leq \mathrm{P(t)} \leq 6000 \tag{10}$$

$$0 \leq \mathrm{W(t)} \leq 3000 \tag{11}$$

2. **Constraint for the hydrogen target:**

Eq. 12 represents a target constraint that ensures the cumulative sum of H(t) over all periods is greater than or equal to the target hydrogen value. This constraint ensures that the total hydrogen produced throughout all periods meets or exceeds the desired target value.

$$\mathrm{Target} \leq \sum_{t=1}^{24} H(t) \tag{12}$$

3. **Ramping constraints:**

Ramping limits play a crucial role in maintaining power system stability and reliability. These limits constrain the rate of change of electricity, hydrogen production, and water consumption rates, preventing sudden and excessive fluctuations. Ramping limits help optimize resource utilization and mitigate the risk of disruptions or imbalances by ensuring a gradual and controlled adjustment of these variables over consecutive periods. The constraints from Eq. 13 to 15 define allowable changes in electricity consumption, hydrogen production rate, and water consumption rate between periods. They set bounds on the differences between current and previous values, preventing rapid increases or decreases. Enforcing these ramping limits supports grid stability and enhances overall system performance.

$$-355.5 \leq P(t) - P(t-1) \leq 355.5 \quad (13)$$
$$-25 \leq H(t) - H(t-1) \leq 25 \quad (14)$$
$$-100 \leq W(t) - W(t-1) \leq 100 \quad (15)$$

Results and discussion

The bidding optimization model for hydrogen production from the electrolyzer was solved using the General Algebraic Modeling System (GAMS), with the solver of choice being a linear Programming (LP) solver. This approach efficiently optimized the model, determining optimal values for decision variables and constraints. The results provided insights into maximizing profit from hydrogen production. For each period, optimal values for decision variables, including electricity consumption, water consumption, and hydrogen production, were determined. To optimize power usage, the model considered two cases with different electrolyzer efficiency values.

A. Case 1: Electrolyzer efficiency equals 70%.

In this scenario, the electricity consumption formula considers an electrolyzer efficiency of 70%. Based on Table 1, the objective function aims to maximize profit and minimize total cost. Table 2 displays the results for H(t), W(t), P(t), and Tank Storage(t), satisfying all constraints. The table confirms that the hydrogen target is achieved in the hydrogen tank at t=24. The results demonstrate the successful consideration of the dynamics of the hydrogen storage system in the bidding optimization model. Eq. 10 ensures that the amount of hydrogen stored in the tank at each time TankStore(t) is accurately calculated based on the previous storage level TankStore(t-1) and the current hydrogen production (H(t)). This enables informed decision-making for optimal hydrogen production scheduling.

Table 1. Output parameters in dollars for case 1.

Profit	Revenue	Total cost	C_E	C_W	C_M
$1497.799	$11000	$9502.201	$9406.691	$60.210	$35.500

The model successfully satisfied the inequality constraints (Eq. 11-12) on electricity and water consumption, ensuring they remained within the specified limits. Additionally, the optimized hydrogen production (H(t)) adhered to the ramping constraint (Eq. 15), maintaining a controlled rate of change between consecutive periods. Figures 1 and 2, corresponding to Table 2, illustrate the 24-hour trends in electricity usage and hydrogen tank storage. Figure 1 shows that P(t) steadily increases as time progresses and then slightly decreases due to the increase in energy prices. Subsequently, hydrogen production increases, leading to simultaneous increases in P(t) and W(t). The initial hydrogen production is recorded as 4.977 kg, reaching a maximum value of 77.117 kg after 24 hours.

Table 2. Hourly output parameters for case 1.

Time [hr]	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
H(t)	4.98	9.95	14.93	19.91	24.89	29.86	34.84	39.82	44.79	49.77	52.23	47.26
Tank storage (t)	4.98	14.93	29.86	49.77	74.66	104.5	139.36	179.17	223.97	273.74	325.97	373.22
P(t)	355.50	711.00	1066.50	1422.00	1777.50	2133.00	2488.50	2844.00	3199.50	3555.00	3730.83	3375.33
W(t)	44.79	89.59	134.38	179.17	223.97	268.76	313.55	358.34	403.14	447.93	470.08	425.29
Time [hr]	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
H(t)	42.28	37.30	32.32	37.30	42.28	47.26	52.23	57.21	62.19	67.16	72.14	77.12
Tank storage (t)	415.50	452.80	485.12	522.42	564.70	611.96	664.19	721.40	783.58	850.74	922.88	1000.000
P(t)	3019.83	2664.33	2308.83	2664.33	3019.83	3375.33	3730.83	4086.33	4441.83	4797.33	5152.83	5508.33
W(t)	380.49	335.71	290.91	335.71	380.50	425.29	470.08	514.88	559.67	604.46	649.26	694.05

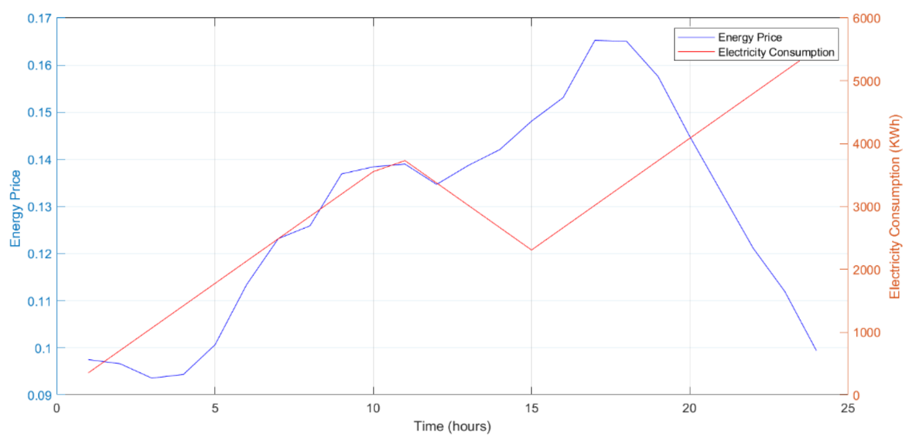

Figure 1. Electricity consumption and energy price for case 1.

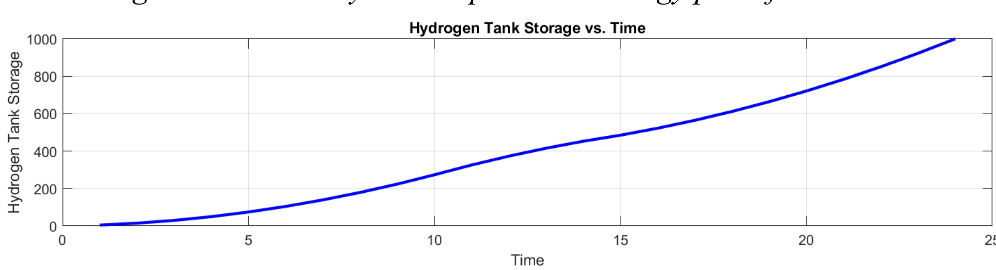

Figure 2. Hydrogen Tank Storage for case 1.

B. Case two : electrolyzer efficiency equals 80%.

In this scenario, the electricity consumption equation considers an electrolyzer efficiency of 80%. According to the results presented in Table 3, the objective function achieved in this case, considering both maximum profit and minimum total cost, shows improvement compared to case 1. The profit is higher, while the total cost of the electrolyzer is reduced.

Table 3. Output parameters in dollars for case 2.

Profit	**Revenue**	**Total cost**	**C_E**	**C_W**	**C_M**
$ 2743.899	$11000	$ 8256.101	$ 8160.591	$ 60.210	$35.500

The results for $H(t), W(t), P(t)$, and $\text{Tank Storage}(t)$ are shown in Table 4. All the constraints were satisfied for all the variables. Fig. 3 visualizes the trends in electricity consumption with energy prices over time. As depicted in the figure, P(t) steadily increases as time progresses until reaching a stable point. Subsequently, it decreases due to the rise in energy prices. However, when the energy prices start decreasing, P(t) steadily increases again. In this scenario, hydrogen production ranges between 5.688 kg and 78.043 kg. Notably, the hydrogen production range is more significant than in case 1, highlighting the improved flexibility and variability in hydrogen production achieved through the optimization framework.

Table 4. Hourly output parameters for case 2.

Time [hr]	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
H(t)	5.69	11.38	17.06	22.75	28.44	34.13	39.82	45.50	51.19	55.29	49.60	43.92
Tank storage (t)	5.69	17.06	34.13	56.88	85.32	119.45	159.26	204.77	255.96	311.25	360.85	404.77
P(t)	355.50	711.00	1066.50	1422.00	1777.50	2133.00	2488.50	2844.00	3199.50	3455.67	3100.17	2744.67
W(t)	51.19	102.38	153.58	204.77	255.96	307.15	358.34	409.54	460.73	497.62	446.42	395.23
Time [hr]	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
H(t)	38.23	32.54	26.85	32.54	38.23	43.92	49.60	55.29	60.98	66.67	72.36	78.04
Tank storage (t)	442.99	475.53	502.38	534.92	573.15	617.06	666.67	721.96	782.94	849.60	921.96	1000.00
P(t)	2389.17	2033.67	1678.17	2033.67	2389.17	2744.67	3100.17	3455.67	3811.17	4166.67	4522.17	4877.67
W(t)	344.04	292.85	241.66	292.85	344.04	395.23	446.42	497.62	548.81	600.00	651.19	702.38

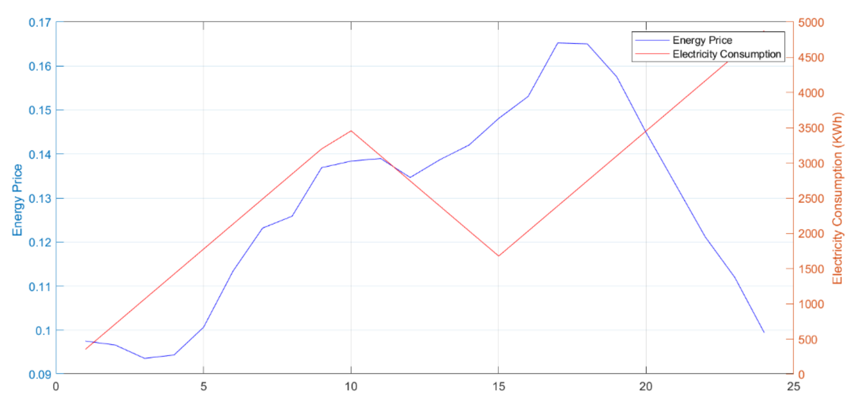

Figure 3: Electricity Consumption and Energy price for case 2.

Conclusion

In conclusion, this research paper has presented a comprehensive study on optimizing the bidding process for hydrogen production through an electrolyzer. The primary objective was to develop an optimization framework that maximizes profitability while meeting the targeted hydrogen production quota. Two cases were considered: Case 1, which incorporated an electrolyzer efficiency of 70% in the electricity consumption equation, and Case 2, where electrolyzer efficiency was 80%. For Case 1, hydrogen production started at 4.977 kg and reached 77.117kg after 24 hours. However, Case 2, which considered 80% electrolyzer efficiency, yielded improved outcomes regarding maximum profit and minimum total cost. Hydrogen production ranged from 5.688 kg to 78.043 kg., with higher profitability achieved. These results emphasize the importance of considering various factors, such as electrolyzer efficiency, in the bidding optimization process. Overall, this research emphasizes the importance of bidding optimization in hydrogen production, offering valuable insights for the energy industry's transition towards sustainable and economically viable hydrogen generation.

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