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Research article

Operational optimization of a Wind-Hydrogen Power-to-X System in Denmark: An experimental approach

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Abstract: This work optimized Power-to-X (PtX) operations in a Danish wind farm, balancing profitability and emissions through single and multi-objective optimization. The analysis was conducted through secondary data and an optimization model developed in Solver in order to evaluate operational scenarios. Among all the different evaluated solutions, Solution 3 emerged as optimal, reducing CO_2 emissions to 3146 kg while maintaining 90% of maximum profit (269,706 DKK). It allocated energy efficiently—745 MWh to the grid, 83 MWh to hydrogen (producing 1479 kg of green hydrogen), and 828 MWh to storage, with zero curtailment. Compared to profit-maximizing (Solution 1: 298,943 DKK, 12,357 kg CO_2) and emission-minimizing (Solution 5: 235,244 DKK, 2336 kg CO_2) alternatives, Solution 3 offers a sustainable compromise, supporting decarbonization goals without significant economic trade-offs. The findings highlight replicable strategies for PtX systems in renewable energy integration for future projects.

Keywords: Power-to-X; wind energy; CO_2 emissions

Nomenclature: B: battery capacity selected; BECCS: bioenergy with carbon capture and storage; °C: Celsius; CO_2: carbon dioxide; DACC: direct air carbon capture; DKK: Danish Kroner; Eg: energy supplied to grid; Ec: energy curtailed; Eh: energy supplied to hydrogen generation; Et: energy generated in total; kWh: kilowatt per hour; LP: linear programming; MOLP: multi-objective linear programming; MW: megawatt; MWh: megawatt per hour; NDA: non-disclosure agreement; PEM: proton exchange membrane; PtX: Power to X.

1. Introduction

The optimization of Power-to-X (PtX) systems is critical for progressing toward a sustainable and low-carbon economy. PtX technologies enable the conversion of renewable energy into many versatile fuels and chemicals [1]. The main challenges that PtX systems face are the variability of renewable energy sources, the need for stable operation in the downstream process, and economic feasibility for energy storage and conversion [2]. Considering such challenges, the operations of PtX systems should be optimized with a trade-off between profitability and emissions. This is important to make sure sustainability is guaranteed, meeting the needs of power generation and transmission. The present work focuses on single-objective and multi-objective optimization of PtX operations in a specific wind farm. It aims at refining the system operation regarding several technical, economic, and environmental objectives. By developing a tailored solution for a PtX system in Denmark, it is possible to maximize operational efficiency, reduce greenhouse emissions, and support the broader objective of utilizing clean energy technologies, providing a solution that can be highly replicable and adaptable to different environments. The strategic significance of this work is its demonstration that PtX systems can be operated for substantial emissions reduction without significant financial sacrifice. The identified compromise solution offers a tangible, data-backed pathway to enhance the sustainability of wind energy projects, moving beyond theoretical potential to practical operational guidance.

1.1. Zero emissions and sustainability

Zero emissions are critical to mitigate the various impacts of climate change and ensure a sustainable future for humanity. *Zero emission* means offsetting emissions by removing emissions generated either from the atmosphere or making emissions equivalent to those removed so that the net effect can be zero [3]. The approach is critical in achieving a stable global temperature and reducing the impact of global warming. The aim is to limit the annual global warming to an increase of 1.5 °C, equal to the levels before industrialization. This goal is critical to mitigate severe environmental, social, and economic consequences [4].

This net-zero emissions transition requires a holistic transformation in key sectors, including energy, industry, and transport, driven by innovation and adoption of cleaner technologies. The importance of achieving zero emissions and sustainability is that both can fix fundamental environmental problems and promote key areas such as economic development, ecological conservation, and social equity. Three related pillars form the foundation for sustainability: environmental, economic, and social. Taken together, these fundamental elements constitute the foundations for a resilient and fair community that functions within the biophysical limits of the planet [5].

Without economic and social sustainability, it is not possible to achieve zero-emission goals. Adopting renewable energy and energy-efficient technologies promotes innovation and reduces reliance on resources that are continuously depleting. Just transition and social sustainability ensure fair access to resources across every member of society [6]. This includes improvement in living standards, access to community services, and fairness in all operations within a society. Combining the three pillars of environment, society, and economy can provide a comprehensive framework [7].

1.2. Role of the power sector in zero emissions

The energy sector has a critical role in achieving net-zero energy systems. The active involvement of the energy sector is necessary in achieving the zero-emission goal. Without it, the world cannot limit global temperature increases to below the critical range of 1.5–2 °C [8]. Achieving net-zero emissions will require deep reductions in CO_2 emissions. This must be done together with offsetting, which is the removal of large residual emissions [9]. This has now become a common shared goal for many countries, states, and companies. While decarbonization of the power sector is necessary for its own emission reductions, it can also enable decarbonization of other sectors through electrification and promoting fuels driven by electricity. Decarbonized electricity systems form the backbone of net-zero energy frameworks. This sector is often successful in achieving net-zero emissions or even negative emissions before the remaining economic sectors [10,11].

A range of technologies already help decarbonize the power sector, including variable renewables such as wind and solar, dispatchable sources like hydropower, and firm low-carbon solutions such as carbon-capture technology [12]. Variable renewables are dominant in many systems because of their declining costs and minimal lifecycle emissions, but operational challenges grow at high shares [13]. Complementary measures such as energy storage, demand management, and transmission expansion will be critical in maintaining the system's reliability [14]. The technologies of carbon removal, mainly BECCS and DACC, would offset emissions in the hard-to-decarbonize sectors and prevent a sharp increase in costs as decarbonization nears completion [11].

Electrification shifts load profiles, impacting resource planning and system operations. Regional decarbonization approaches vary depending on local resources, infrastructure, and priorities. Emerging economies often lead the way in pioneering innovative approaches to address these challenges. To ensure reliability and support economy-wide decarbonization, it is essential to implement effective system management, adopt advanced technology, and make the market structure robust. Integration and coordination of the new technologies among multiple sectors will become critical enablers in the pursuit of the stretching goals of net-zero energy systems [11,15].

1.3. PtX systems

As the world transitions to a "greener economy", multiple engineering operations require an increasing number of redesigns to support green energy generation or to increase the sustainability of existing ones [16]. This is required to meet stringent environmental standards [17]. PtX systems are critical as they convert renewable electricity into energy (often fuel) carriers like hydrogen or synthetic fuels. PtX is an enabler for renewable energy integration, energy storage, and decarbonization of sectors difficult to electrify, such as transport and industry [18]. PtX includes multiple processes to create green hydrogen or other green fuels. This offers a great deal of scalability and provides a reliable alternative to fossil fuels at a much lower CO_2 emission rate [19].

Hydrogen production is not always green. A widespread approach to produce hydrogen is by using fossil fuels, known as "grey" hydrogen. There is a broader goal to fully replace grey hydrogen with green hydrogen through the implementation of water electrolysis powered by renewable energy [20]. However, the adaptation of green hydrogen raises certain operational challenges. The inherent variability of renewable energy sources poses a significant challenge for PtX deployment in applications requiring a stable and continuous power supply [21].

Renewable energy sources are prone to both rapid and seasonal variations. During operational activities, the consequences of such variations are passed on downstream; in a PtX setup, this directly impacts hydrogen production. This fluctuation is hard to adapt to for plants accustomed to steady-state operation and that require a reliable supply of hydrogen to run their operations or processes. To deal with the intermittency of renewable energy, buffer storage systems are of growing importance. Common solutions are either hydrogen storage tanks downstream from the electrolyzer or battery systems between renewable power plants and the electrolyzer, with some facilities using both [22].

This study is significant for its experimental validation of a replicable PtX optimization framework. This work introduces a deterministic optimization framework for wind-hydrogen PtX systems that moves beyond profit-only or emissions-only extremes. By modeling dynamic energy allocation across grid feed-in, hydrogen production, and battery storage, we identify a Pareto-optimal solution that achieves 90% of maximum profit while reducing CO_2 emissions by 75% compared to profit-maximizing baselines. The operational innovation in this work lies in decoupling battery sizing from hydrogen production—using storage solely for grid stabilization rather than as a buffer for electrolysis—enabling near-zero curtailment without over-investing in the capacity of storage. The findings offer project developers and policymakers a quantifiable model to assess the economic impact of emission reduction strategies, thereby de-risking investment and accelerating the deployment of integrated wind-hydrogen systems.

1.4. Research question

"How can a PtX system be optimized to achieve a perfect balance between profitability and emission reduction, while ensuring the sustainability of hydrogen production and addressing all the constraints in power generation, grid demand, and system configuration?"

2. Methodology

This report's methodology consisted of a systematic compilation and analysis of secondary data from various credible sources. There was a range of materials consulted, which included academic journals, company reports, government documents, and other peer-reviewed literature from an Internet search, as well as from institutional libraries and several databases. Attention was given to articles that were published from 2019 to 2024 to make the study relevant. Approximately 75% of the scientific articles utilized are not more than five years old, meaning that recently conducted studies are emphasized. The Solver tool built inside Microsoft Excel was used to run the optimization algorithm.

3. The wind farm case: Analysis

The wind farm assessed is located in one of the most important locations for renewable energy generation in Denmark. Unfortunately, the authors do not have the approval from the wind farm owner to name the wind farm (Figure 1), and it should remain confidential under the scope of this study. The farm is currently looking into increasing its operational capacity. Along with expansion, the farm aims to also investigate possibilities of hydrogen production using wind energy and thus transforming into a PtX plant. The project will integrate hydrogen production into its operation by utilizing wind power. This green energy will generate hydrogen via electrolysis. The expansion will change the character of the farm into a multi-energy generation plant, meaning that the farm will supply renewable electricity to the grid, while also supporting sustainable hydrogen production. To accomplish this, there is a need to optimize and find the most efficient energy distribution plan, the optimal turbine configuration, and the best mix of hydrogen production and battery storage capacity [23]. The goal is to achieve maximum profitability with minimal environmental impact.

Figure 1. The wind farm under study.

3.1. PtX optimization challenge

The wind-hydrogen PtX facility aims to optimize its operation with a multi-dimensional problem, which involves allocation of energy into three categories: energy supplied to the grid, energy distributed for hydrogen production, and energy curtailed as waste. The general goal is to find the optimal energy allocation, battery size, and hydrogen production in kilograms per day that maximizes profitability while keeping carbon emissions as low as possible. The optimal solution must fulfill strict daily constraints both on an operational and financial basis. According to the data received by the owner, the facility has a daily operational budget of 400,000 DKK. The grid requires at least 650 MWh daily, and the goal is to keep daily emissions at a maximum of 14,000 kg of CO_2. The plant has certain operational costs, emissions, and selling prices for each energy unit, as given in Table 1.

Table 1. Operational costs, selling prices, and emissions.

Energy allocation type	Operational cost (DKK per MWh)	Selling price (DKK per MWh)	Emissions (kg per MWh)
Energy to the grid	30	550	3
Energy to hydrogen	60	225	11
Energy curtailed	20	0	3

The optimization also includes a choice between 3 and 10 wind turbines with the V1, V2, and V3. The turbines vary in rated capacity, investment cost, and maintenance costs, which are given in Table 2.

Table 2. Wind turbine options.

Turbine type	Rated capacity (MW)	Price of turbine (DKK)	Maintenance cost (DKK)
V1	2.00	75,000,000	53,000
V2	3.45	112,000,000	30,000
V3	4.20	149,000,000	15,000

The cost of batteries is factored at 34,000,000 DKK per MWh, and the associated maintenance cost is 60,000 DKK. A critical aspect of this problem is hydrogen production. The electrolyzer in the facility runs at an efficiency of 60% and takes 33.6 kWh to produce 1 kg of hydrogen. The electrolyzer's specific energy consumption was set at 33.6 kWh/kg of H_2. This value is below the current industry average of ~50 kWh/kg but is representative of the future high efficiencies targeted by next-generation electrolysis technologies [24]. This forward-looking assumption was adopted to assess the performance and economic viability of a future, optimized PtX system, providing a benchmark for ongoing technological advancement. The maximum capacity for the electrolyzer is 15 MW. At 33.6 kWh/kg, the hydrogen production rate at full power gives approximately 446 kg/h, which is a reasonable figure for a ~15 MW electrolyzer, if the system runs with no downtime and no ramping, which means that it runs continuously at these ideal conditions [25]. The system must use at least 5% of the total energy generated to produce hydrogen. It is assumed that curtailed energy cannot exceed 2%.

The goal of optimization should be to determine the optimal energy allocation strategy—balancing grid supply, hydrogen production, and curtailed energy for maximum efficiency. The modeling methodology adopted in this study provides a robust framework for the initial techno-economic analysis. Future research could build upon this by incorporating a more dynamic analysis of market conditions or the degradation of system components to further validate the operational strategies proposed here. The optimal solution must meet the goals of the facility in terms of minimal emissions and high profitability within the operating and financial constraints.

3.2. System configuration

The system can contain up to 10 wind turbines aiming to generate renewable electricity, which can be distributed across three paths (Figure 2). E_g is allocated to the electrical grid to meet the demand. E_h is directed to the electrolyzer for hydrogen production by splitting water into hydrogen and oxygen. E_c is curtailed energy, which is wasted if not utilized. To maximize efficiency, the system includes a battery storage unit with a capacity B. The battery stores energy for easier distribution to the grid and electrolysis. The battery also aids in ensuring a steady energy supply during periods of low wind production [26].

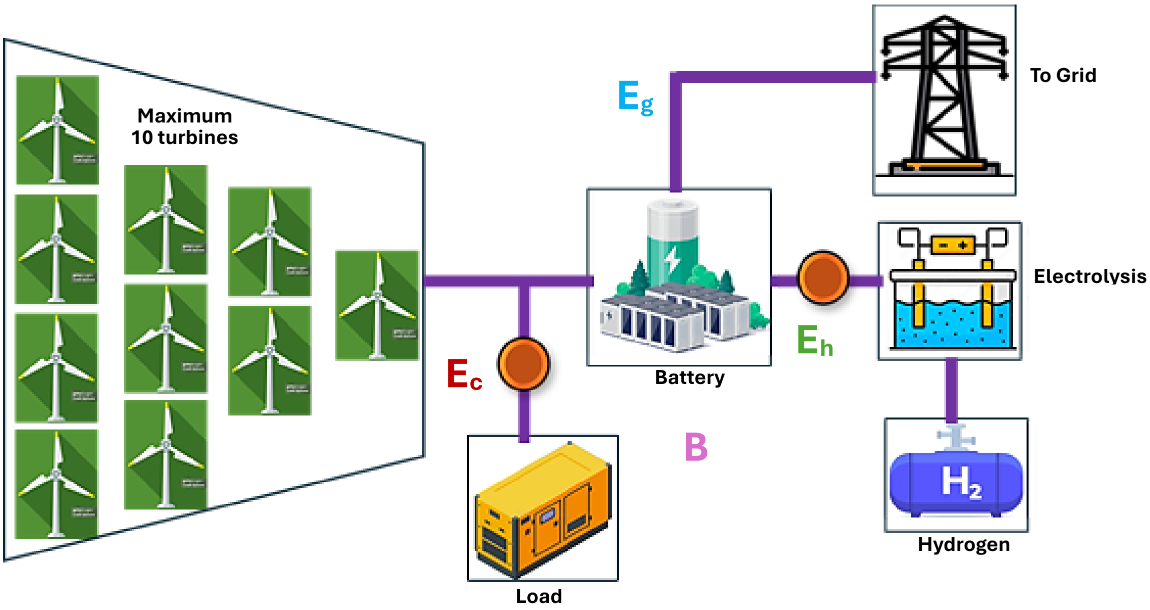

Figure 2. System configuration.

3.3. Linear programming

Linear programming is a mathematical optimization technique introduced by Leonid Kantorovich in 1939 for resource allocation and further improved in 1947 by the introduction of George Dantzig's simplex method [27]. Nowadays, it is applied extensively to solve complex problems efficiently in logistics, transportation, and manufacturing [28]. The type of LP used for the specific wind farm optimization comprises two factors: single-objective and multi-objective optimization. Single-objective LP concentrates on optimization related to a single criterion, such as cost minimization or efficiency maximization; multi-objective linear programming (MOLP) addresses multiple conflicting objectives like balancing costs and service levels at the same time. MOLP evaluates trade-offs using tools like the Pareto front, making LP an essential tool in decision-making and optimization across industries [29].

3.4. Objective function

The goal of this optimization problem is to optimize both profit and emissions at the same time. Therefore, the multi-objective function must be formalized. This can be written as:

$$Maximize\ Z = \alpha . P + \beta . \frac{1}{Em} \tag{1}$$

where

Z = Multi-objective function;
P = Objective function to maximize profit;
Em = Objective function to minimize emissions;
α = Weightage for profit;
β = Weightage for emissions.

The weights α and β represent the preference between profit and emissions. To map the trade-offs, a parametric sweep was conducted: α was varied from 0 to 1 (with β = 1 - α), generating a spectrum of optimal solutions from pure profit (α = 1) to pure emission minimization (α = 0).

The profit objective function can be defined as:

$$Maximize\ P = (C_b + M_b)B + (S_1 - O_1)\ E_g + (S_2 - O_2)E_h + (S_3 - O_3)E_c + \sum_{i=1}^{3}(C_i + M_i).X_i) \tag{2}$$

where

P = Objective function to maximize profit;
B = Selected battery capacity;
X_i = Number of wind turbines installed;
E_g = Energy allocated to the grid;
E_h = Energy allocated to hydrogen production;
E_c = Energy curtailed as excess;
C_i = Investment cost for turbines;
M_i = Maintenance cost for turbines;
C_b = Investment cost for batteries;
M_b = Maintenance cost for batteries;
$O_{1,2,3}$ = Operational cost;
$S_{1,2,3}$ = Selling price per MWh.

The total energy production can be defined as:

$$E_t = E_g + E_h + E_c \tag{3}$$

The emission objective function can be defined as:

$$Minimize\ Em = Em_1.E_g + Em_2.E_h + Em_3.E_c \tag{4}$$

where
Em = Objective function to minimize emissions;
$Em_{1,2,3}$ = Emissions generated;
E_g = Energy allocated to the grid;
E_h = Energy allocated to hydrogen production;
E_c = Energy curtailed as excess.

3.5. Constraints

The constraints mentioned in the problem statement are translated into the following mathematical equations:

Maximum operating budget

$$C_b.B + M_b.B + C_1.X_1 + C_2.X_2 + C_3.X_3 + M_1.X_1 + M_2.X_2 + M_3.X_3 + O_1.E_g + O_2.E_h + O_3.E_c <= 400{,}000\ \text{DKK} \tag{5}$$

Grid energy demand

$$E_g >= 650 \text{ MWh} \tag{6}$$

Maximum peak production over demand

$$\text{\% of } E_g \text{ exceeding demand} <= 25\% \tag{7}$$

Hydrogen allocation

$$\text{\% of } E_h \text{ from } E_t >= 5\% \tag{8}$$

Curtailment limit

$$\text{\% of } E_c \text{ from } E_t <= 2\% \tag{9}$$

Maximum emissions

$$Em_1.E_g + Em_2.E_h + Em_3.E_c <= 14{,}000 \text{ kg } CO_2 \tag{10}$$

Electrolyzer capacity

$$E_h <= 900 \text{ MWh} \tag{11}$$

Minimum turbines

$$X_1 + X_2 + X_3 >= 03 \tag{12}$$

Maximum turbines

$$X_1 + X_2 + X_3 <= 10 \tag{13}$$

Battery capacity utilization

$$E_g + E_h = B \tag{14}$$

Total energy balance

$$E_g + E_h \, E_c = E_t \tag{15}$$

3.6. Single-objective optimization

Single-objective function optimization reveals two solutions: One is optimized for profit only, and the other is optimized for emissions. Figure 3 shows the solutions for the single-objective optimization method. The parametric sweep produces a set of non-dominated optimal solutions, forming the Pareto front (see Figure 3). Each point on this front represents a distinct compromise; improving one objective worsens the other. The shape of the front visualizes the trade-off, showing the increasing cost in profit for marginal emission reductions.

Solution 1 system configuration is shown in Figure 4, which consists of V2 x1 and V3 x6. The energy distribution is 813 MWh to the grid, 900 MWh to hydrogen production, and 7 MWh curtailed. This solution uses the maximum capacity of the electrolyzer. Solution 1 gives a profit of 298,943 DKK and generates 12,357 kg of CO_2 emissions. On the other hand, Solution 2 emphasizes minimizing emissions. System configuration for Solution 2, shown in Figure 5, consists of V1 x4 and V2 x1. The energy distribution is 653 MWh to the grid, 34 MWh to hydrogen production, and 0 MWh curtailed.

Solution 2 achieves a significantly lower CO_2 output of 2336 kg and generates a profit of 235,241 DKK. The trendline in Figure 3 highlights the inverse relationship between profit and emissions.

The focus of Figures 4 and 5 is to present the final, optimized outcomes (the resulting energy allocations and key metrics) of the two contrasting operational philosophies—pure profit (Figure 4) vs. pure emissions (Figure 5) minimization. Presenting the input time-series data and detailed dispatch logic was beyond the initial scope of this specific analysis, which prioritized establishing the high-level trade-offs.

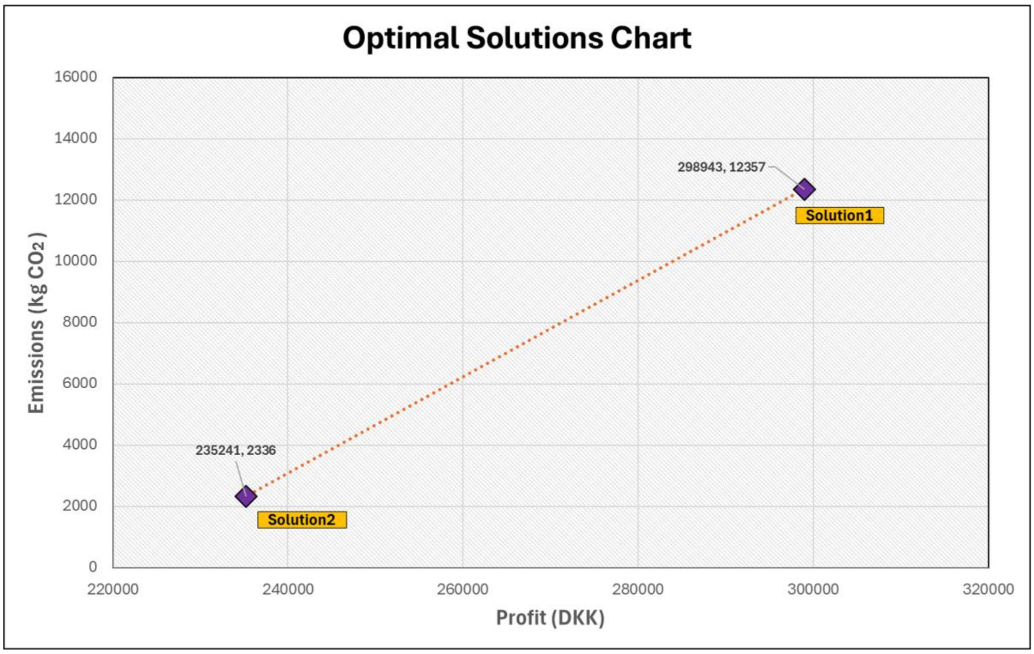

Figure 3. Solutions for single-objective optimization.

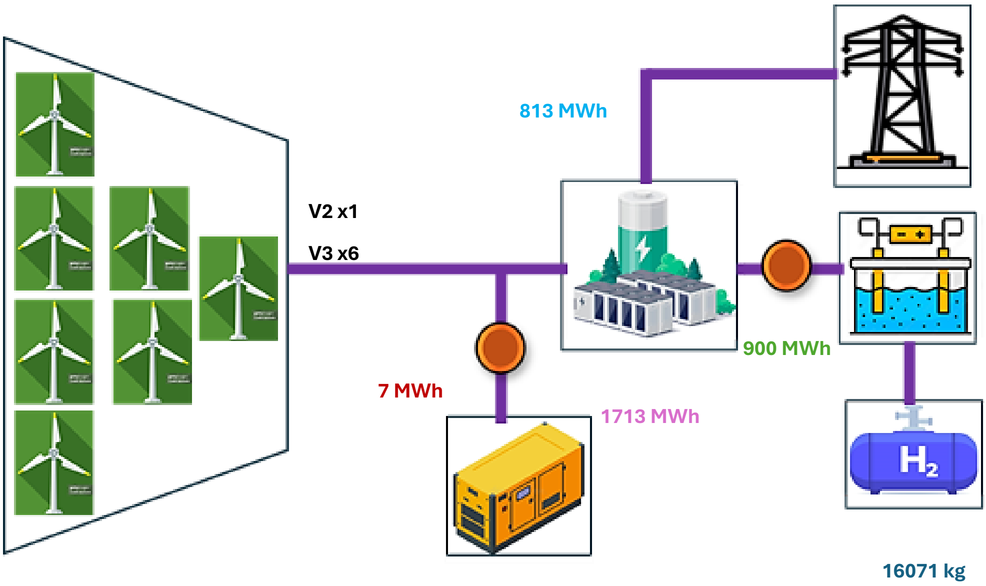

Figure 4. System configuration for optimized profit.

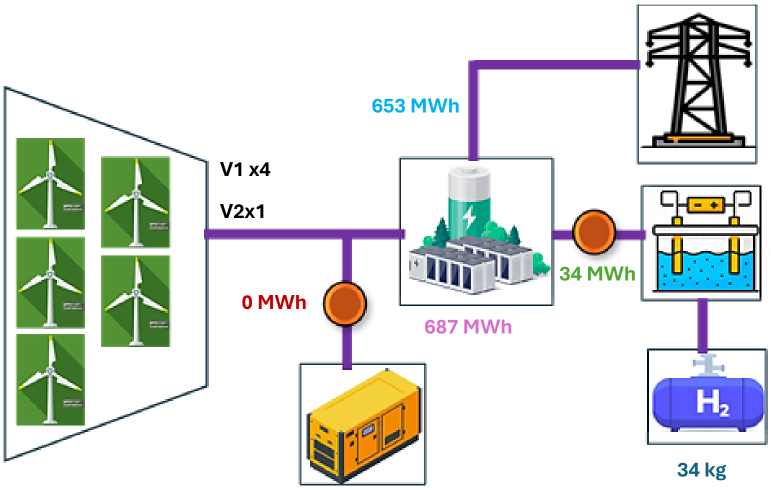

Figure 5. System configuration for optimized emissions.

3.7. Multi-objective optimization

Multi-objective optimization reveals multiple solutions. Each solution represents a balance between maximizing profit and minimizing emissions [30]. Solution 1 is the same as the single-objective optimization targeting maximizing profits. It reflects a preference for economic gain over environmental impact. Solution 5 is the most environmentally friendly solution, as indicated in the single-objective optimization. The multi-objective function optimization also yields multiple intermediate solutions when different weightages are assigned to profit and emissions [31]. Solutions 2, 3, and 4 represent various trade-offs with a gradual increase in emissions as profit rises. The trend line in Figure 6 shows a nonlinear relationship between profit and emissions. This means that an increase in profit can result in disproportionately higher emissions for this specific case.

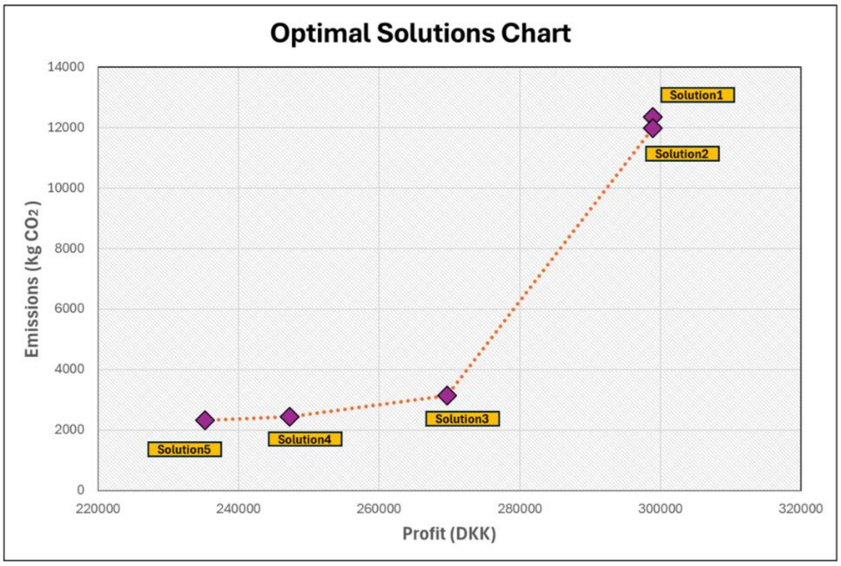

Figure 6. Solutions for multi-objective optimization.

4. Results

Figure 7 shows the various solutions plotted against their profit levels measured in DKK. There is a trend in which profit follows a decline as the solution progresses from 1 through to 5. The greatest profit is achieved with Solution 1 at 298,943 DKK, whereas the lowest profit is achieved with Solution 5 at 235,241 DKK. Solution 2 is close to Solution 1 in terms of profitability.

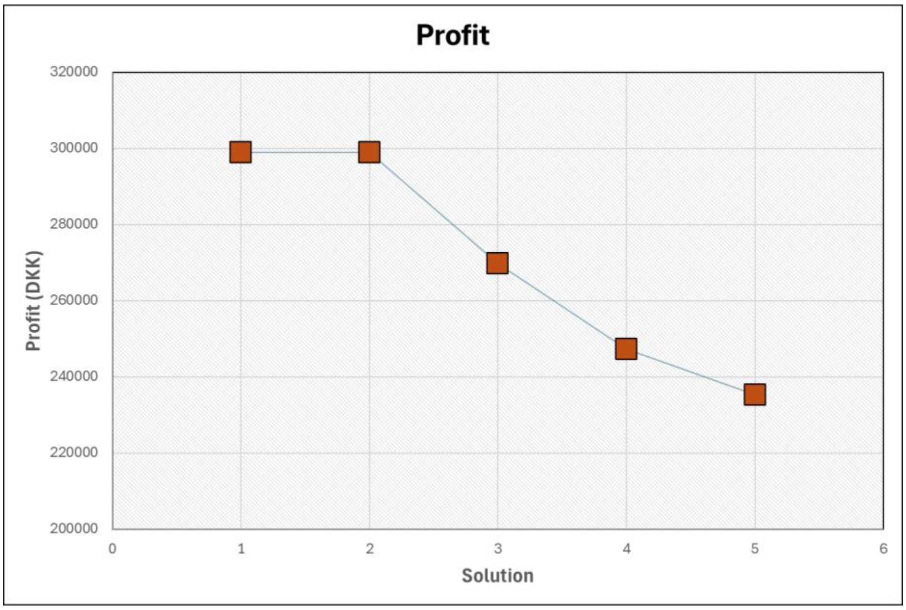

Figure 7. Profit results.

Figure 8 highlights the variation in emissions, measured in kg of CO_2, across five solutions. Emissions are closest to 12,000 kg CO_2 for both Solutions 1 and 2. This indicates a focus on maximizing economic gains with less regard for environmental impact. As the solutions progress further, the emissions drop sharply and reach 3146 kg of CO_2 with Solution 3. Solutions 4 and 5 are the most environmentally friendly solutions, reflecting a shift toward prioritizing environmental sustainability.

Figure 9 shows the amount of hydrogen produced in the five different solutions. The first two solutions reach the maximum hydrogen production of approximately 16,000 kg. This reflects a focus on maximizing hydrogen production. However, there is a sharp decline in production starting from the third solution, where hydrogen levels drop significantly to 1479 kg. The fourth and fifth solutions maintain this lower hydrogen output, which indicates a shift in priorities. This trend highlights the trade-offs involved in multi-objective optimization; achieving higher environmental sustainability may result in reduced hydrogen production.

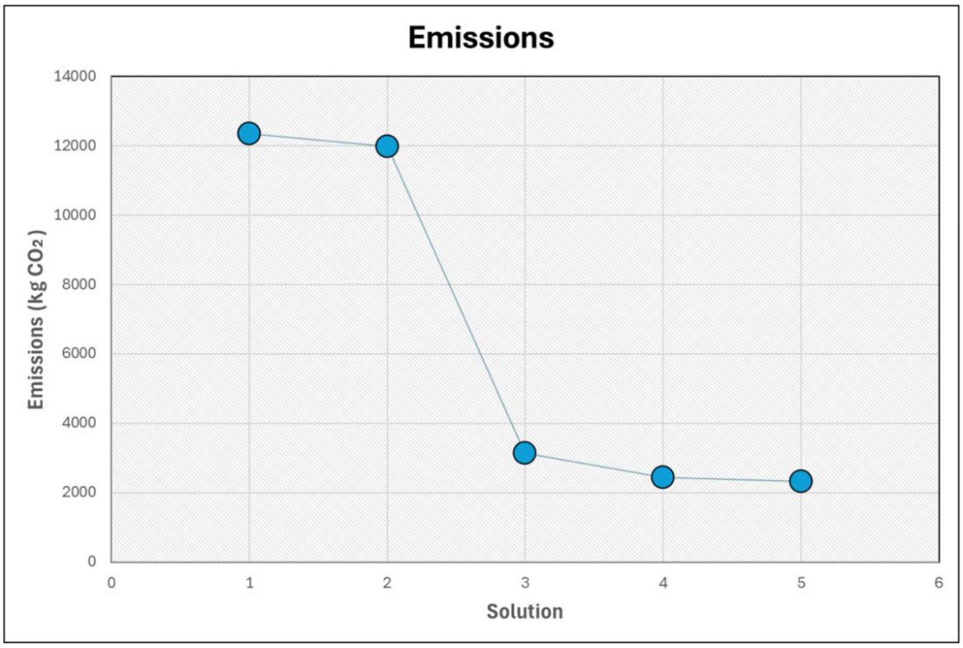

Figure 8. Emission results.

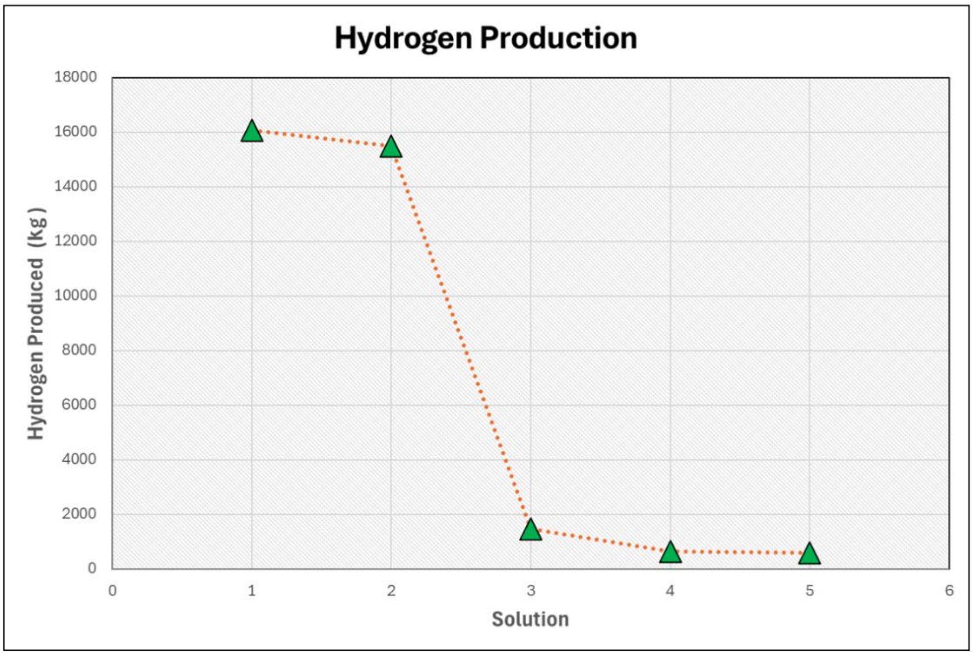

Figure 9. Hydrogen production results.

Figure 10 shows the distribution of power allocation for all five proposed solutions. At the start, battery capacity B is significantly higher at 1173 MWh than that of the first two solutions and settles at 828 MWh at Solution 3 after a huge drop. Energy allocated to the grid (E_g) remains relatively stable throughout all solutions, indicating a consistent distribution of energy to the grid. The power allocation for hydrogen production E_h starts at a peak value of 900 MWh, declining fast after the second solution and leveling off to the lowest values by the fourth and fifth solutions. The curtailed energy (E_c) is always low for all solutions. This reflects effective use of generated power. The trends show a calculated balance for energy distribution, storage, and usage. It transitions from high hydrogen production to the earlier solutions to lower energy waste in the later solutions. This graph shows the inherent trade-offs in the process of optimization for different parameters.

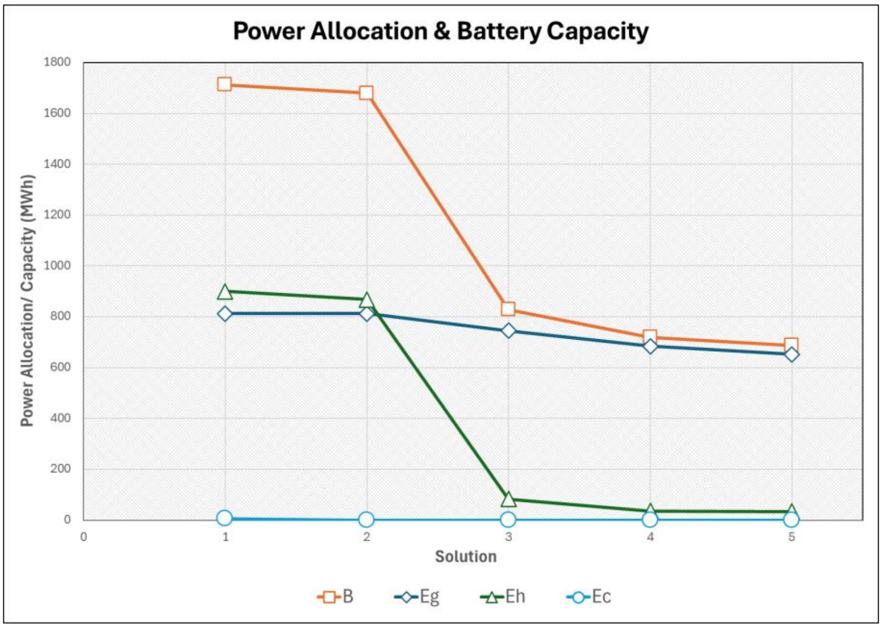

Figure 10. Energy allocation results.

5. Synthesis of findings

Based on the results available, Solution 3 represents a perfect balance between emissions and profit optimization. The solutions suggest installing four V2 3.45 MW turbines. The emissions produced using this solution are significantly lower than those of other solutions at 3146 kg of CO_2. It still maintains a profit of 269,706 DKK, which is only 10% lower than the most profit-optimized solution. Key energy allocations in this solution include energy allocated to the grid (E_g) of 745 MWh to ensure a reliable contribution to the grid. The maximum peak production is utilized to the maximum at around 25%. Energy allocated to hydrogen production (E_h) is kept at 83 MWh. This solution supports only the essential hydrogen generation required. Battery capacity B is maintained at 828 MWh. Energy curtailment (E_c) is zero for this solution.

On the other hand, Solution 1 gives the highest profit at approximately 298,943 DKK but causes the highest emissions at 12.357 kg CO_2. As such, this solution is oriented toward economic benefits but will compromise sustainability, therefore making this unsuitable for environmentally oriented strategies. Solution 5 minimizes emissions to approximately 2336 kg CO_2, but at the cost of a significant reduction in profitability at 235,244 DKK, a significant decrease of 21% from the most profit-optimized solution. Therefore, Solution 3 is the best-suited solution in terms of profitability and emissions, as it avoids both extremes. The solutions offer a strong position on profitability at much lower emissions and provide high value on both environmental and economic objectives.

Furthermore, Solution 3 also offers a strong position when it comes to hydrogen generation. It fulfills the requirement for producing essential hydrogen and limits the production to 1479 kg. Since this hydrogen is produced using renewable energy sources via electrolysis, this will be termed green hydrogen. This means that no carbon dioxide emissions are emitted during hydrogen production. This characteristic of green hydrogen makes it a highly sustainable fuel, which is well-suited for achieving the global decarbonization goals [32].

Beyond identifying a specific Pareto-optimal operating point, this work contributes a replicable decision framework for PtX system design. The central insight—that battery capacity should be sized exclusively for wind fluctuation management rather than coupled to hydrogen production—offers a practical pathway to minimize both storage CAPEX and energy curtailment. This principle can be replicated directly to future wind-hydrogen projects aiming to balance grid obligations with green fuel production.

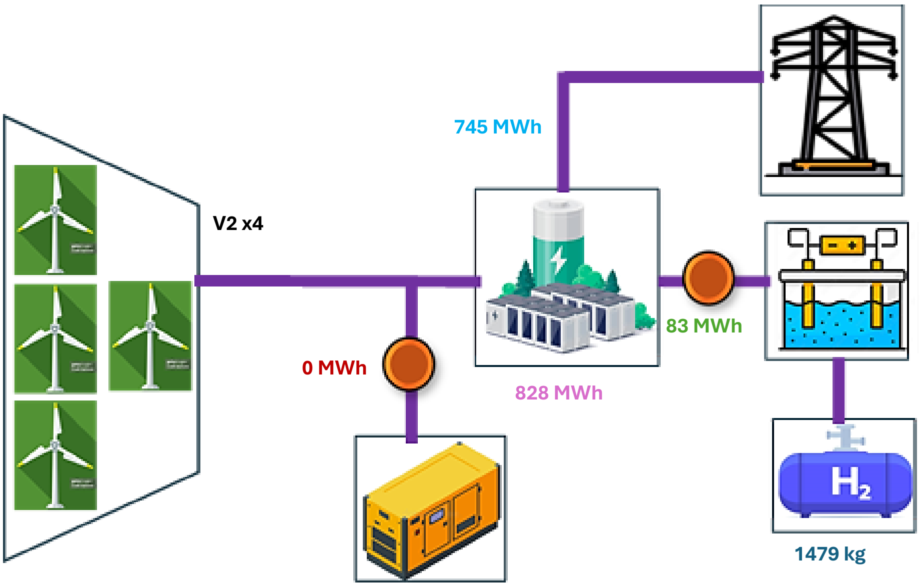

Figure 11. System configuration for ideal solution.

5.1. Limitations

There are certain limitations of this paper that should be acknowledged. This work does not provide much detail about different hydrogen production technologies. The selection of technology, such as alkaline, PEM, or solid oxide electrolysis, can have an impact on the cost and efficiency of hydrogen production [33]. The categories or types of hydrogen, such as green, blue, or gray, are also not differentiated in this report, but are potentially necessary to understand the full environmental consequences and market feasibility. Also, the plant diagram and numbers used for cost and pricing are hypothetical due to a lack of necessary NDA documentation between the company and Aarhus University, as already mentioned. The numbers and plant diagram still offer a good representation of the actual scenario; however, other case studies may not align with these cost and price figures. The optimization solutions were generated using Excel Solver; however, other options to optimize solutions were not used. These limitations indicate areas for further research and refinement in future iterations.

6. Discussion and conclusions

Although hydrogen is assumed to be produced at the specified wind farm, the source of water used in the electrolysis process largely determines the ultimate sustainability of hydrogen production [34]. Factors such as the source of energy used in the purification, pumping of the water, and the type of equipment used directly impact the carbon footprint of hydrogen production [35]. The classification of hydrogen as "green" requires that it be produced solely from renewable sources. Any use of grid electricity, which may contain non-renewable energy, necessitates a full life-cycle assessment to verify the fuel's carbon footprint and sustainability claims.

The emissions for wind turbines and batteries considered in this work are based on the complete life cycle of the products [36]. This includes emissions starting from raw materials, production, transportation, and disposal. During operations, these systems do not generate any carbon dioxide and are 100% clean [37]. A comprehensive clean energy assessment must, however, account for indirect emissions across the entire life cycle [38,39].

In this case study, the use of batteries has been shown to be equal to the energy supplied to the grid and the energy supplied to hydrogen production. This constraint is useful in fully utilizing the battery capacity and ensuring grid stability [40]. However, this setup also comes at high investment and maintenance costs of the complete system [41]. It would be more efficient to design battery capacity only to handle the fluctuations of wind turbine generation. Most energy should be directly supplied to the grid or to hydrogen production. Another solution could be to use dedicated turbines for grid and hydrogen production. In this case, batteries can only be used for grid supply to maintain stability. This can result in efficient energy output and reduced storage requirements at a lower cost.

Other aspects that could have further refined this optimization activity are the detailed analysis of sensitivity, answer, and limit reports generated by the Solver. This can provide crucial insights into how the dynamics of the problem behave. This could also provide more detailed information on how constraints and other parameters impact the objective function.

Finally, it is also relevant what each stakeholder wants or expects from the Pareto solution. Therefore, the profit-emission trade-off directly informs stakeholder decisions. Project investors would most probably select the high-profit end of the Pareto front, prioritizing financial return. Policymakers would favor the low-emission solution, accepting lower profit for decarbonization goals. ESG-focused entities (e.g., independent power producers) would choose a balanced mid-front solution, achieving significant emission reduction with a moderated profit loss. Thus, each stakeholder group can map its priorities directly onto the Pareto-optimal solutions, translating the techno-economic trade-off into practical, value-driven choices.

Future research should build upon this deterministic framework by incorporating stochastic programming to account for real-world uncertainties, such as fluctuating energy market prices and wind forecast variability. This would further validate the proposed operational strategies and enhance the model's applicability for commercial PtX deployment.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

The authors declare no conflicts of interest. George Xydis is an editorial board member for AIMS Energy and was not involved in the editorial review or the decision to publish this article.

Author contributions

Conceptualization, W.A.; Methodology, W.A.; Validation, G.X. & W.A.; Resources & data curation, W.A.; Writing—original draft preparation, G.X. & W.A.; Writing—review and editing, G.X. All authors have read and agreed to the published version of the manuscript.

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