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Maximizing Value in Power-to-Hydrogen Plants within Eco-Industrial Clusters through Internal Heat Market

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***Abstract*—One of the most promising solutions for reaching carbon-neutral industrial clusters with a high penetration of renewables is using hydrogen as a versatile fuel source. However, green hydrogen production is still a controversial topic. In fact, power-to-hydrogen (P2H) plants cannot be economically operated for most hours without supportive programs because of high marginal costs. In this situation, it is crucial to provide additional value streams for these plants to justify their economic operation. This paper investigates the cost-effectiveness of P2H plants selling by-products alongside their primary output through the establishment of an internal heat market within eco-industrial clusters. To fulfill this aim, a mathematical optimization problem formulated by bi-level programming is considered for the optimal operation of P2H plants. Engaging in this internal market holds the potential to boost revenue for P2H plant owners as they sell by-products to cluster members in need. Furthermore, other industries within the cluster stand to gain from accessing energy carriers at a reduced cost. A real eco-industrial cluster named GreenLab Skive, located in Denmark is used to examine the effectiveness of the proposed method. The findings indicate that the potential sale of by-products by P2H plants could rationalize extended operational hours without the need for supportive schemes. Consequently, there is an escalation in the production of green hydrogen. Nonetheless, the primary barrier to the economically viable operation of P2H plants remains the cost of electricity, which surpasses that of hydrogen in most hours.**

***Index Terms*—Low-Carbon Hydrogen, Internal Heat Market, Power-to-Hydrogen, Economic Assessment, Eco-industrial Clusters.**

I. Introduction

The mitigation of global warming and the achievement of a carbon-neutral economy in Europe by 2050, as outlined by the Paris Agreement [1] and the European Green Deal [2], have intensified the energy transition towards sectors that are hard to abate, including industrial sectors. With the increased integration of renewable energy sources within these clusters, CO2 emissions have been significantly reduced. However, achieving a level of zero carbon emissions necessitates further effort. One of the most promising solutions to address this challenge involves converting power into a more storable and versatile energy carrier, such as green hydrogen [3]. Nevertheless, the production of green hydrogen through water electrolysis is considered costly due to its higher marginal costs [4]. Therefore, it is essential to explore methods to lower these costs by providing power to hydrogen (P2H) plants with additional value streams.

In recent years, there has been growing interest in empowering operation of P2H units in terms of economic point of view. A profit driven optimization model for the strategic participation of the operator of hydrogen and methane power plants in electricity and hydrogen markets has been developed in [5]. Similarly, authors in [6] have proposed a multi-energy trading framework for the hydrogen provider to trade electricity and hydrogen in different markets effectively considering fluctuations in power generation of renewable energy sources. A bi-level model has been formulated in [7] to address how strategically the typical virtual power plant comprising of waste gasification units and renewable energy sources can participate in both electricity and hydrogen market. Pu et al. in [8] have examined the economy of peer-to-peer electricity and hydrogen trading among different integrated energy systems. Feng et al. in [9] have suggested a strategic model for hydrogen providers to efficiently bid on the electricity market in order to minimize their overall costs. A data-driven energy management system is developed in [10] to address the profitability and flexibility of hydrogen and ammonia power plants. According to the results, power-to-gas-to-power option provides more flexibility than biomass-to-gas-to-power, however, the latter provides greater profitability. To increase the production of renewables, increase market players' profits, and reduce peak demand, a local energy market for electricity and hydrogen trading has been suggested in [11]. A cooperative game approach has been considered for wind farms and power-to-gas (P2G) facilities to enable effective participation in the day-ahead, real-time, and reserve markets, as detailed in [12]. This approach leads to an increase in the expected joint profit. Authors in [13] have proposed a new energy management model for producing green hydrogen requirement of the typical industry considering both photovoltaic and battery systems. The proposed model minimizes the overall costs along with reliable operation of technologies. Techno-economic feasibility of producing green hydrogen powered by photovoltaic systems for the strategic regions of Turkey has been conducted in [14] and it is projected that the minimum cost of producing 1kg green hydrogen ranges from 1.39 to 2.97 dollors in 2050. Authors in [15] have emphasized the crucial role of hybrid energy systems, comprising renewable energy sources and electrolyzers, in achieving a low-carbon economy. They also address the extent to which detailed modeling of electrolyzers can be beneficial for accurate calculation of the expected profit. The profitability of providing ancillary services for the typical electrolyzer has been examined in [16]. In [17], the authors have defined the conditions under which the operation of power-to-X (P2X) facilities in the energy hub is profitable. The results of this study indicate that the availability of retail hydrogen market and the existence of a sufficient supply of renewable energy are critical factors in making these units economically feasible. The economic feasibility of P2X units within a typical energy hub in Denmark has been examined in [18], taking into account the capability to sell hydrogen directly or to produce products such as ammonia and methanol. Authors in [19] have established a two-level optimization model for optimal sizing and energy management of renewable based technologies in industrial microgrids such as harbour considering electricity and hydrogen as main two energy vectors. The results demonstrated that selling price of hydrogen plays important role in making operation of electrolyzers cost competitive.

As seen, most existing studies have focused on increasing the operational hours of electrolyzers by exploring their potential to provide ancillary services, developing strategies for purchasing electricity, or operating in conjunction with renewable energy sources. Although all aforementioned methods contribute to higher revenues, considering additional value streams could further enhance their economic functionality especially when the electricity prices are high. The purpose of this paper is to examine to what extent selling by-products of water electrolysis, such as excess heat and oxygen, could provide supplementary benefits to these plants, even when wholesale electricity prices are rising significantly. On the other hand, eco-industrial clusters aim to maximize their decarbonization efforts while minimizing the operational costs of all industries by accelerating various symbioses which one of the most important is heat. To achieve this goal, it is essential to establish a local internal market within a cluster, offering industries the opportunity to trade their various by-products. Specifically, this paper seeks to explore how P2H units can sell their excess heat in the developed local internal market to enhance their income relative to their high electricity consumption costs. Through this framework, these plants can operate for extended periods, thereby producing more green hydrogen, zero-carbon heat, and oxygen. Moreover, it is assumed that these units can sell the oxygen they generate to the industries that need it at a fixed, agreed-upon price. This outcome not only benefits the plants themselves but also aids other industries within the cluster by offering access to energy carriers at lower costs as well as promoting further decarbonization through the production of carbon-free heat.

The organization of this paper is as follows: Section II describes the proposed method concept. The next section provides simulation results implemented into the real energy hub in Denmark, and finally, the last part concludes the paper.

II. Concept of Study

This section addresses the concept. As previously noted, industrial sectors are recognized as challenging to decarbonize, requiring substantial effort. Consequently, various strategies have been proposed to increase flexibility within these sectors. One such strategy is the exploration of potential symbioses among industries in specific clusters. However, to harness the maximum flexibility from such symbioses, market-oriented solutions need to be developed. This is vital to precisely justify the rationale for energy trading among engaged players from an economic perspective. The method proposed here aims to investigate the extent to which internal heat trading could be profitable for participating industries, while also accelerating decarbonization within the cluster. In fact, developing an internal local market offers an additional revenue stream for industries to sell by-products such as excess heat. Furthermore, this market-based platform can motivate participants to strategically engage in trading, thereby making the value of energy trading more apparent to them compared to solely promoting symbiosis through a single optimization model aimed at maximizing the cluster's overall profit. Figure 1 schematically illustrates the heat symbiosis among industries and plants within an industrial cluster.

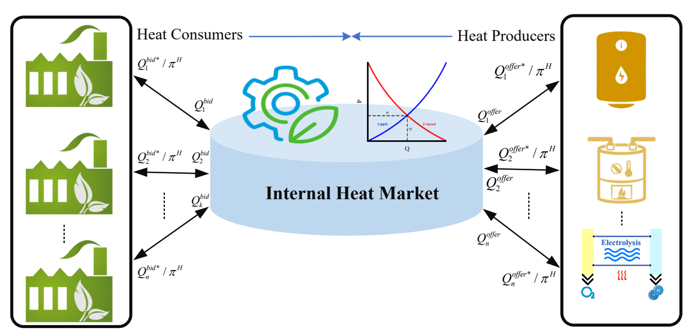

Fig. 1. Schematic of the proposed local market for the heat symbiosis

As depicted in Fig. 1, local heat symbiosis can be facilitated by developing an internal market, rather than relying solely on bilateral connections between two distinct industries. The main advantage of market-based trading is capturing precise and fair value for internal energy transactions. Additionally, developing a local market can attract more participants, especially those who cannot directly engage in the main energy markets due to various requirements. Moreover, a cluster operating as an energy hub can not only significantly reduce its carbon footprint but also harness the flexibility arising from these local markets to actively engage in external energy markets. This, in turn, can yield benefits for all industries within the cluster.

This kind of local market can be applied to each specific energy carrier, including heat, hydrogen, and electricity. However, the main focus of this work is on local heat trading. To address such issue, this study specifically aims to explore the extent to which local heat trading within a cluster can enhance the profitability of P2H plants by increasing their revenue streams. Indeed, the strategic operator of a typical P2H unit in the cluster seeks to determine how effectively participating in the local heat market can yield additional profit for this unit. Additionally, it is assumed that there is a possibility to directly sell the generated oxygen to the target industry in the cluster at an agreed and fixed price. To achieve this goal, bi-level programming has been employed for the day-ahead scheduling of the P2H unit. At the upper level, linear programming has been utilized to model the operational problem of the P2H unit, considering technical constraints of the components, while the lower level includes a market-clearing model for heat. Finally, the developed bi-level model is simplified into a single-level problem by incorporating the Karush-Kuhn-Tucker (KKT) conditions for the optimization problems at the lower level. Further details regarding the mathematical formulation are available in the Appendix. It's important to emphasize that the proposed method is universally applicable to all industries and power/energy units within the cluster, ensuring replicability and scalability.

III. Simulation and Results

This section presents a simulation aimed at evaluating the effectiveness of the internal heat market for P2H units in selling their excess heat and assessing whether the addition of extra value streams can extend their operational hours. This objective is achieved through an analysis of a 60-hectare eco-industrial cluster located in Central Jutland, Denmark, known as GreenLab Skive (GLS). This cluster includes a diverse range of industries, including pyrolysis, biogas, methanol, electrolysis, and ammonia production. Additionally, it is supported by nearby wind farms and solar parks, which supply renewable energy sources. In this simulation, A-Series A90 AEC-electrolyzer with the capacity of 12 MW is assumed as P2H unit of this cluster and its technical characteristics are summarized as Table I [18].

TABLE I
Technical Characteristics of the Electrolyzer [18]

Carrier	Unit	Production In	Production Out
Electricity	MWh	53.06	-
Water	Tons	9.55	-
Hydrogen	Tons	-	1
Heat	MWh	-	9.76
Oxygen	Tons	-	11.26

In the base scenario, it is assumed that 60% of the excess heat can be sold in the internal heat market via electrolyzer. The electricity prices are based on the day-ahead values for DK1 in 2022, which are relatively high due to the Ukraine War. The grid tariff is valued at 13.5 €/MWh, the price of hydrogen at 2.98 €/kg, and oxygen at 0.198 €/kg. Furthermore, it is assumed that the cluster's maximum heat demand is 5 MW.

This section explores four different business cases, each considering a set of technologies as a unified agent. The first case involves an agent operating solely with a 12 MW electrolyzer. The second case includes an agent with a 12 MW electrolyzer and a 30 MW wind turbine (WT). The third case combines a 12 MW electrolyzer with a 30 MW photovoltaic system (PV). Finally, the fourth case features a 12 MW electrolyzer paired with a 54 MW WT, where the WT directly powers the electrolyzer without selling its production on the market, provided it has sufficient capacity to supply the electrolyzer. Additionally, for each business case, four different scenarios are evaluated based on the electrolyzer's ability to sell its main product (hydrogen) and its byproducts (heat and oxygen). The first scenario focuses solely on selling hydrogen. The second involves selling both hydrogen and excess heat. The third encompasses selling hydrogen and oxygen. Finally, the fourth scenario concerns to selling hydrogen along with all byproducts.

A. Business Case 1

Figure 2 compares the normalized hydrogen production of the electrolyzer per different hours of year 2022 for different scenarios.

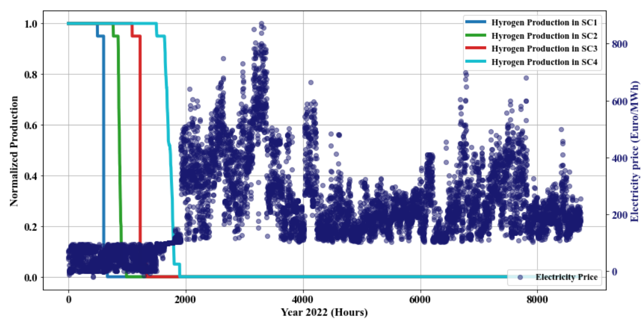

Fig. 2. Normalized hydrogen production of the electrolyzer in the first business case and electricity price

As depicted in Fig. 2, for most hours in 2022, the electricity price was relatively high, hindering the economic operation of the electrolyzer. However, during periods of low prices, the operator decided to produce hydrogen. Additionally, a clear trend towards increasing the operation hours of the electrolyzer is observed once additional value streams are introduced. The trading of excess heat within the cluster's internal local market, as seen in scenario 2, has led to increased operation hours compared to the first scenario. The ability to sell oxygen also positively impacts the electrolyzer's economically viable operating hours. In the final scenario, which allows for the sale of all byproducts in addition to hydrogen, the highest operating hours are recorded. Fig. 3 shows the proportion of income streams and electricity cost in different scenarios for this agent.

As shown in Fig. 3, the income generated from selling hydrogen is augmented by introducing additional income

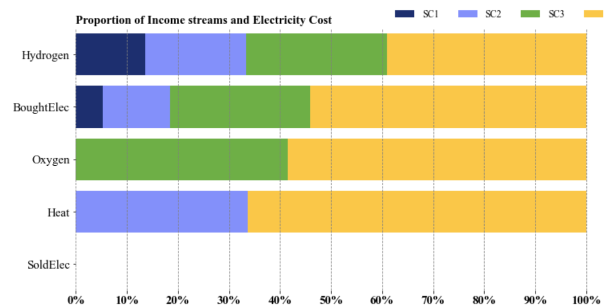

Fig. 3. Comparison of revenue sources and electricity costs across different scenarios for the first business case

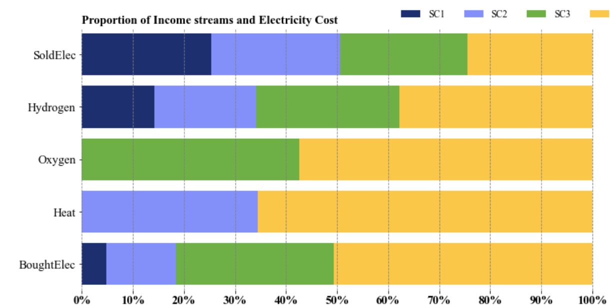

Fig. 5. Comparison of revenue sources and electricity costs across different scenarios for the second business case

streams for the electrolyzer. This rationale also applies to other income streams, such as excess heat and oxygen. However, it is expected that increased production may lead to higher electricity consumption and, consequently, higher electricity costs. Lastly, this agent does not produce electricity; hence, there is not any revenue from selling electricity for this agent across all scenarios.

B. Business Case 2

In this business case, the 30 MW WT and 12 MW electrolyzer are considered as one unified agent. The normalized hydrogen production of the electrolyzer in this case along with the WT power generation in 2022 has been shown in Fig. 4.

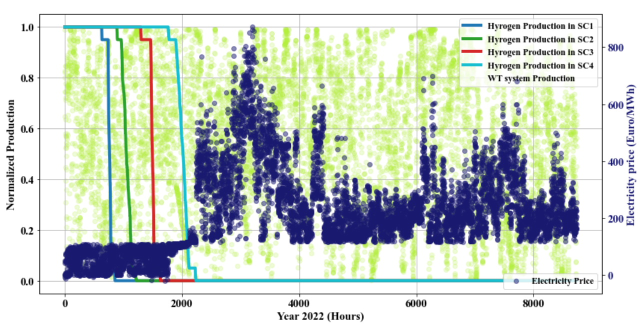

Fig. 4. Normalized hydrogen production of the electrolyzer, WT power production, and electricity price in 2022 for the second case

As shown, the coordinated operation of the WT and the electrolyzer has effectively boosted the electrolyzer's operational duration. Nonetheless, given the high electricity prices during most hours, the agent finds it more financially beneficial to sell the power generated by the WT in the day-ahead market rather than converting it into hydrogen through water electrolysis. Additionally, adding more income streams for the electrolyzer positively influences the increase in its operating hours. Fig. 5 breaks down the revenue obtained from different income streams as well as electricity consumption cost in different four scenarios for this case.

According to Fig. 5, it is observed that the quantity of power sold to the grid remains constant across all scenarios. This leads to the conclusion that, although introducing new revenue streams for the electrolyzer has enhanced its operational level, the profit derived from selling electricity to the grid is still more advantageous for the agent. Additionally, the amount of electricity purchased from the grid increases with the addition of income streams for the electrolyzer. The underlying reason is that when the electrolyzer is in operation to produce hydrogen, the WT does not supply sufficient power, necessitating the purchase of power from the grid.

C. Business Case 3

According to the third business case, the agent consists of the PV system and electrolyzer. The normalized hydrogen production for this agent in different scenarios has been compared in Fig. 6.

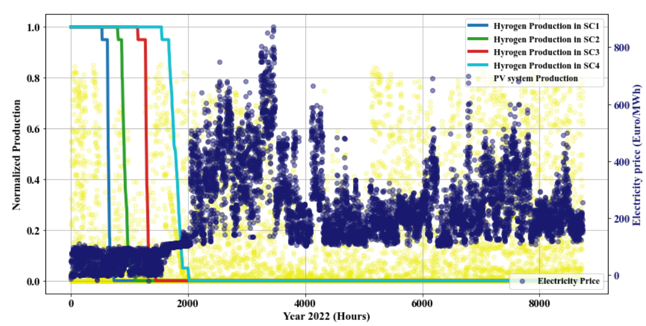

Fig. 6. Normalized hydrogen production of the electrolyzer, PV power production, and electricity price in 2022 for the third case

As expected, the joint operation of PV system and electrolyzer has led to the increase in the operating hours of the electrolyzer in comparison to the first business case that the electrolyzer provides its electricity need just from the grid. In addition, similar to the previous business cases, adding new income streams were profitable for this electrolyzer which has raised the number of operating hours. Fig. 7 analyses the income composition and electricity expenditure in the defined four scenarios for this case.

As seen in Fig. 7, the revenue generated from the sale of the primary product and the corresponding by-products is significantly higher in the fourth scenario, characterized by an increased number of income options for the electrolyzer. Moreover, a clear observation is that, despite the PV system's positive influence on prolonging the electrolyzer's operational

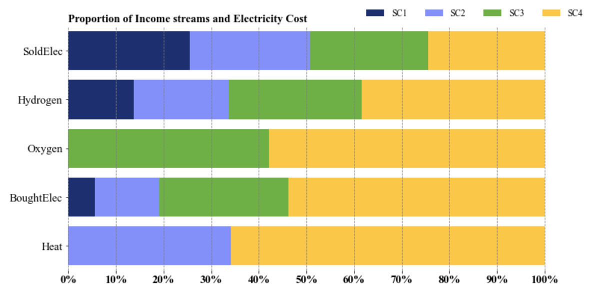

Fig. 7. Comparison of revenue sources and electricity costs across different scenarios for the third business case

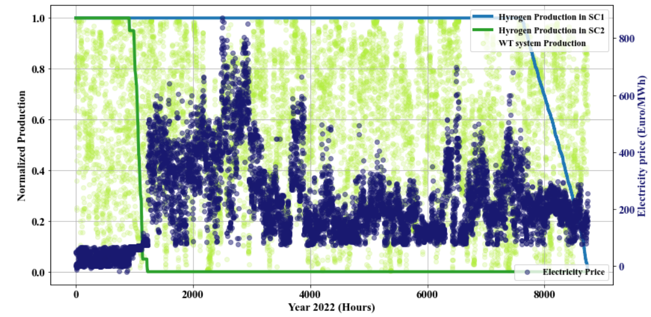

Fig. 8. Normalized Hydrogen, WT Production and Electricity Price in year 2022

duration, the surge in electricity prices in 2022 has prompted the agent to prioritize selling the majority of its generated electricity in the market rather than converting it into hydrogen. Table. II presents +90% capacity operating hours of electrolyzer in 2022 per each business case.

TABLE II
+90% CAPACITY OPERATING HOURS OF ELECTROLYZER IN 2022

Business Case	Scenario 1	2	3	4
1	603	900	1225	1785
2	782	1120	1517	2086
3	659	965	1320	1866

Table II illustrates that developing the internal local market within a cluster for providing a new opportunity for the electrolyzer to sell its byproducts to the other industries has led to an increase in the number of operating hours with the higher capacity. In addition, this higher operating of the electrolyzer provides more heat and oxygen which can be utilized by industries and the profit for the industries is that they can access to them without paying addition cost for transportation and also less than the one they can provide in the existing market or district heating system. In addition, the most number of operating hours happens when the both WT and electrolyzer are considered as one unified agent and the reason for this is that the WT's capacity factor is much better than the PV's capacity factor in the location of the cluster.

D. Business Case 4

As outlined, in this business case, the 54 MW WT directly supplies power to the electrolyzer based on its capacity to generate electricity each hour. This scenario is compared to the second business case under the assumption that the WT's installed capacity is 54 MW for that case (Modified Case 2). Furthermore, it is assumed that trading excess heat in the local internal market in GLS is only feasible. Figure 8 compares the normalized hydrogen production in these two distinct cases.

It is seen that the direct power supply from the WT to the electrolyzer has significantly increased its operational hours, underscoring the importance of supportive schemes for P2H plants. Additionally, Table III presents a comparison of the total revenue and costs associated with these two business cases, itemized by various categories.

TABLE III
TOTAL INCOME AND COST OF TWO DIFFERENT BUSINESS CASES IN GLS

Item	Case 4	Modified Case 2
Hour	7748	1125
Hydrogen Sale	5.29 M€	0.68 M€
Heat Sale	1.82 M€	0.23 M€
Water Sale	0.35 M€	0.04 M€
Electricity Cost	0.01 M€	0.01 M€
Electricity Sale	35.78 M€	56.91 M€
Net Profit	42.53 M€	57.77 M€

Table III evaluates the two business scenarios from various perspectives. The first metric discussed is the +90% capacity operating hours. As expected, direct integration with the WT results in increased operational hours in the fourth business case. Consequently, the sales of hydrogen and excess heat are higher in this scenario compared to the second. The cost of purchasing electricity from the grid remains consistent across both cases; however, revenue from selling electricity back to the grid is notably higher in the second scenario. The final row of the table compares the net profit between the two cases. It is observed that the net profit for the fourth business case is 26.38% lower than that of the second case. This indicates that if policymakers wish to encourage electrolyzers to operate for longer hours through supportive schemes, such as direct power injection from renewable sources, they should consider offering a compensation cost to the owners of renewable generators to offset the difference between these two values.

IV. CONCLUSION

The primary aim of this study was to introduce a new platform for local trading of energy carriers within an eco-industrial cluster, with a particular focus on heat symbiosis, to enhance the revenue streams for industries in the cluster and contribute to decarbonization efforts. In this regard, this paper specifically evaluated the profitability of selling byproducts from water electrolysis for P2H units situated in the cluster. The analysis was conducted across four different business cases, examining various combinations of renewable generators and P2H units, along with their supply methods.

The simulation was based on the real energy hub in Denmark (GLS), taking into account the unexpected circumstances of 2022 in terms of electricty and gas prices. The findings indicated that while generating additional income from selling excess heat and oxygen, in addition to green hydrogen, could be beneficial for these units, the high electricity prices remain a significant barrier to their economic operation throughout most of the year.

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APPENDIX

The mathematical formulation of the optimal operation of the x^{th} P2H unit in the cluster for participating strategically in the developed internal heat market in the cluster can be outlined as follows:

$$\begin{aligned}\text{Min}: \sum_t \pi_t^{El} Q_{t,x}^{El} + \sum_t \pi_t^{H_2O} m_{t,x}^{H_2O} - \sum_t \pi^{H_2} m_{t,x}^{H_2} \\ - \sum_t \beta^{O_2} \pi^{O_2} m_{t,x}^{O_2} - \sum_t \beta^{Heat} \pi_t^{H} Q_{t,x}^{Heat}\end{aligned} \quad \text{(A.1)}$$

$$Q_{t,x}^{El} = Q_{t,x}^{El-H_2} + Q_{t,x}^{comp.} \quad \text{(A.2)}$$

$$m_{t,x}^{H_2} = Q_{t,x}^{El-H_2} \eta^{Elz-H_2} \quad \text{(A.3)}$$

$$m_{t,x}^{O_2} = Q_{t,x}^{El-H_2} \eta^{Elz-O_2} \quad \text{(A.4)}$$

$$m_{t,x}^{H_2O} = Q_{t,x}^{El-H_2} \eta^{Elz-H_2O} \quad \text{(A.5)}$$

$$Q_{t,x}^{Heat} = Q_{t,x}^{El-H_2} \eta^{Elz-Heat} \quad \text{(A.6)}$$

$$Q_{t,x}^{El-H_2} - Q_{t-1,x}^{El-H_2} \leq R_{Elz}^{Up} \quad \text{(A.7)}$$

$$Q_{t-1,x}^{El-H_2} - Q_{t,x}^{El-H_2} \leq R_{Elz}^{Down} \quad \text{(A.8)}$$

$$Q_{t,x}^{comp.} = \frac{RT_{in}}{2(\gamma-1)\eta^{comp.}} \left(\left(\frac{P_{out}}{P_{in}}\right)^{\frac{\gamma-1}{\gamma}} - 1 \right) m_{t,x}^{H_2} \quad \text{(A.9)}$$

$$\begin{aligned}[\pi_t^H] \in \text{argmin} \Bigg\{ \sum\nolimits_n \pi_{n,t}^{offer} Q_{n,t}^{offer} - \sum_k \pi_{k,t}^{bid,H} Q_{k,t}^{bid} \\ \text{Subject to:} \\ \sum_n Q_{n,t}^{offer} - \sum_k Q_{k,t}^{bid} = 0, : \pi_t^H \\ 0 \leq Q_{n,t}^{offer} \leq \overline{Q}_{n,t}^{offer}, : \forall t, \forall n \\ 0 \leq Q_{k,t}^{bid} \leq \overline{Q}_{k,t}^{bid}, : \forall t, \forall k \Bigg\}\end{aligned} \quad \text{(A.10)}$$

Equation (A.1) describes the objective function of the P2H unit, which comprises five terms. The first one is about the total electricity consumption of the electrolyzer. The next one stands for the water consumption cost. The next one shows the revenue from selling hydrogen in the hydrogen market. Finally, the last two terms refer to the revenue obtained from selling byproducts of hydrogen and excess heat. In addition, β^{O_2} and β^{Heat} are parameters to show whether this unit wants to participate in the internal local market of those energy carriers or not. The total electricity consumption is the sum of the electricity converted to hydrogen and the amount used in the compressor as outlined in (A.2). Equations (A.3) - (A.6) illustrate the amount of produced hydrogen, oxygen, water, and heat according to the electrolyzer's typical efficiency. Ramp-up and down constraints for this unit have been considered in Eqs. (A.7) and (A.8). Equation (A.9) demonstrates the power consumed for compressing the hydrogen. In this equation, R stands for gas constant, T_{in} shows the inlet temperature of hydrogen, P_{in} and P_{out} refer to the inlet and outlet pressure. Finally, the last constraint is related to the optimization problem of the lower level where the price for trading heat is derived through clearing the internal market for that specific carrier. In this simulation, we assumed that the internal market is just cleared for the heat, and the fixed oxygen price is assumed for trading oxygen. Moreover, in order to solve this optimization problem with the existing commercial solvers, the KKT conditions for the last constraint of the problem are written and replaced with it.