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Integrated Operating Strategies and Parameter Optimization for PEM Electrolyzers in Power-to-X Energy Systems

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ABSTRACT

"Green" hydrogen production via polymer electrolyte membrane (PEM) electrolyzers must overcome significant energy penalties and high costs to become competitive in renewables-based energy systems. Adaptive operating strategies for PEM electrolyzers—by dynamically adjusting current density, pressure, and temperature—have demonstrated efficiency improvements in simple energy systems. However, their effectiveness in the context of complex power-to-X energy systems featuring variable downstream synthesis processes remains unclear. This work shows that integrated optimization of PEM electrolyzer operating parameters in conjunction with downstream methanation processes (MP) delivers substantial system-wide efficiency and cost benefits under dynamic hydrogen demand and pressure conditions. To demonstrate this, an equation-oriented process model of a PEM electrolysis system is embedded within a higher-level energy system model to compare sequential optimization (where the electrolyzer adapts to predetermined MP operating decisions) against integrated optimization (where electrolyzer and MP operating decisions are determined simultaneously). Sequential optimization delivers 7.3% operating cost savings compared to conventional fixed-parameter operation. In comparison, integrated optimization achieves 9.9% cost reductions and 7.8% decreases in electrolysis system electricity consumption. Operating pressure emerges as the most critical parameter, with electrolyzer electricity consumption exhibiting markedly higher sensitivity than MP electricity consumption. The analysis reveals fundamental trade-offs between component-level and system-level efficiency, demonstrating that prioritizing electrolyzer efficiency optimization yields superior system-wide performance. These findings establish that system-wide coordination through integrated optimization approaches substantially enhances the economic viability of "green" hydrogen supply in complex power-to-X energy systems.

Keywords: Scheduling, Energy Efficiency, Energy Systems, Hydrogen, Optimization

INTRODUCTION

Polymer electrolyte membrane (PEM) electrolyzers enable dynamic integration of hydrogen production into renewables-based energy systems [1]. However, energy-intensive operation and high production costs continue to impede the competitiveness and large-scale deployment of "green" hydrogen technologies [2].

Intelligent operating strategies offer substantial potential to improve both energy and cost efficiency of PEM electrolyzers [3]. Two key mechanisms enable these improvements: (1) dynamic adjustment of operating parameters (i.e., current density, pressure, temperature) to select the most energy-efficient operating point for each load, and (2) information exchange between the electrolyzer and downstream hydrogen applications (e.g., end-use pressure requirements), allowing the electrolyzer to adapt its operation accordingly. While these strategies may temporarily reduce electrolyzer stack efficiency, they yield net system-level gains by reducing hydrogen compression energy demand and lowering operating cost.

These benefits have been demonstrated primarily in relatively simple energy systems comprising photovoltaic units, a PEM electrolyzer, and hydrogen storage to meet a constant hydrogen demand [3]. In contrast, in broader power-to-X applications, PEM electrolyzers are coupled with various downstream synthesis processes (e.g., methanation, Fischer-Tropsch synthesis, Haber-Bosch synthesis), which impose time-varying hydrogen demands and variable pressure requirements [4]. Whether adaptive operating strategies can deliver comparable system-wide efficiency and cost benefits under these complex, dynamic conditions remains unclear.

This work addresses this research gap by extending a previously developed electrolyzer process model to account for downstream methanation process (MP) requirements with variable hydrogen demand and adjustable operating pressures. Two optimization approaches are applied: sequential optimization (where the electrolyzer adapts to predetermined methanation process operating decisions) and integrated optimization (where electrolyzer and methanation process operating decisions are determined simultaneously). The analysis investigates how flexible management of electrolyzer current density, pressure, and storage utilization affects hydrogen production, electricity consumption, and overall system operating costs. The specific contributions are threefold: (1) characterization of optimal electrolyzer operating strategies in integrated power-to-X energy systems with dynamic synthesis requirements, (2) quantitative comparison of sequential versus integrated optimization approaches, and (3) identification of trade-offs between component-level efficiency and system-level performance, providing insights into the practical potential of adaptive operating strategies in complex renewable hydrogen-based energy systems.

METHODOLOGICAL APPROACH

The optimal operating strategy of a PEM electrolyzer is determined through integrated energy system and process optimization. An equation-oriented process model of a PEM electrolysis system forms the methodological core, quantifying the effects of operating parameter selection (i.e., current density, temperature, pressure) on electricity consumption. This process model is embedded within a higher-level energy system model to derive an operational strategy that satisfies hydrogen demand from methanation processes, which impose both pressure and quantity requirements. The electrolyzer operating strategy encompasses time-variable hydrogen production and dynamic operating pressure adjustment.

Two optimization approaches are analyzed: sequential optimization, in which the electrolyzer adapts to predetermined methanation requirements, and integrated optimization, in which electrolyzer and methanation pressures are determined simultaneously to achieve system-level coordination.

Electrolysis system

A process model of a PEM electrolysis system [3] forms the methodological foundation. The system comprises the PEM electrolyzer itself and a multi-stage compressor. Throughout this work, 'electrolyzer' denotes the standalone electrolyzer unit, whereas 'electrolysis system' encompasses both the electrolyzer and the associated compressor.

The operational sequence begins with preheating of process water to the target stack operating temperature T_{stack}, followed by the electrolysis reaction within the cell. Hydrogen and oxygen, the reaction products, are separated through the membrane and subsequently directed to the positioned flash units. The separated hydrogen stream can be delivered through two outlets. The low-pressure (LP) outlet supplies hydrogen directly at the operating pressure p_{cat} for immediate use, while the high-pressure (HP) outlet enables compression to elevated pressure levels for storage and later use. Both outlets can operate simultaneously, allowing flexible allocation between direct supply and storage.

Electrical energy input occurs via the applied cell voltage U_{cell} and current I to the electrolyzer, as well as through compression work P_{comp} to the compressor. The electrolysis reaction generates waste heat $\dot{Q}_{waste}$, which can be recovered for preheating process water and external heat-integration applications. When the available waste heat proves insufficient for preheating requirements, supplementary heating P_{heat} must be provided by an electric heating element.

Cell voltage U_{cell} consists of three components: the open-circuit voltage U_{ocv}, activation overvoltage U_{act}, and ohmic overvoltage U_{res}. Reduced current densities j, decreased operating pressures p_{cat}, and increased temperatures T_{stack} contribute to lower cell voltage (Eq. (1) [3]).

$$U_{cell}(j, T_{stack}, p_{cat}) = U_{ocv}(T_{stack}, p_{cat}) + U_{act}(j, T_{stack}) + U_{res}(j, T_{stack}) \quad (1)$$

Aggregating all electrical input components yields the total electrical energy input to the electrolysis system (Eq. (2) [3]).

$$\dot{E}_{el}^{in} = U_{cell} I + P_{heat}(j, T_{stack}, p_{cat}) + P_{comp}(p_{cat}) \quad (2)$$

The electrolysis system efficiency η_{EL} (Eq. (3) [3]) quantifies the ratio of usable hydrogen energy to total electrical energy input. Hydrogen energy content is evaluated based on the lower heating value LHV_{H_2}. Diffusion and recombination losses $\dot{n}_{H_2}^{loss}$ reduce the total hydrogen production $\dot{n}_{H_2}^{tot}$. Beyond the previously discussed influences, the electrolysis system efficiency exhibits

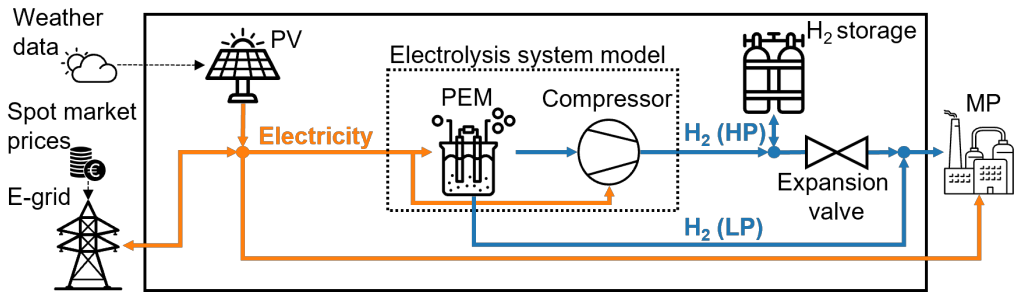

Figure 1. Energy system structure (E: Electricity, LP: Low-pressure, HP: High-pressure, MP: Methanation processes, PEM: Polymer electrolyte membrane electrolyzer, PV: Photovoltaic unit).

conflicting parameter dependencies: elevated pressures decrease compression work P_{comp}, whereas decreased pressures and elevated current densities minimize hydrogen losses $\dot{n}_{H_2}^{loss}$.

$$\eta_{EL} = \frac{LHV_{H_2}\left(\dot{n}_{H_2}^{tot}(j) - \dot{n}_{H_2}^{loss}(j, p_{cat})\right)}{\dot{E}_{el}^{in}} \tag{3}$$

Power-to-X energy system

The optimal electrolyzer operating strategy is analyzed within a higher-level energy system configuration (Figure 1). This energy system comprises a photovoltaic (PV) unit and a grid connection, enabling bidirectional electricity exchange (i.e., grid withdrawal during shortages and feed-in during PV surplus conditions), the electrolysis system and a hydrogen storage.

The primary objective of this energy system is to satisfy the electricity and hydrogen demands of two methanation processes. Hydrogen must be delivered at pressure levels between 1 and 20 bar (cf. Scenario definition). Direct supply via the low-pressure (LP) outlet without additional compression can be achieved by maintaining an electrolyzer operating pressure sufficiently elevated. Alternatively, hydrogen can be pressurized to 200 bar via the high-pressure (HP) outlet for temporary storage and subsequent withdrawal. This storage pathway provides operational flexibility to respond to time-variable electricity prices and fluctuating PV generation patterns. Depending on the optimization mode (cf. Scenario definition), direct hydrogen supply via the HP outlet is also possible.

Optimization problem

Determination of the electrolyzer operating strategy requires solving an energy system optimization problem (Eqs. (4) [3]). The objective function minimizes total operating costs C, representing the balance between electricity procurement expenditures and feed-in revenues (Eq. (4a)). Cost calculation incorporates electricity purchase prices $c_{el,t}^{buy}$, feed-in tariffs $c_{el,t}^{sell}$, and corresponding energy quantities $\dot{E}_{el,t}^{buy/sell}$, scaled by the time step duration Δt and the number of aggregated period occurrences n_t^p (i.e., scaling aggregated time series costs to annual values).

$$\min_{\mathbf{d},\dot{\mathbf{E}}} C = \Delta t \sum_{t\in\mathcal{T}} n_t^p \left(c_{el,t}^{buy}\dot{E}_{el,t}^{buy} - c_{el,t}^{sell}\dot{E}_{el,t}^{sell}\right) \tag{4a}$$

s.t.

$$\sum_{k\in\mathcal{K}}\left(\dot{E}_{k,e,t}^{out} - \dot{E}_{k,e,t}^{in}\right) + \dot{E}_{e,t}^{buy} - \dot{E}_{e,t}^{sell} = \dot{E}_{e,t}^{D}, \quad \forall e \in \mathcal{E}, \forall t \in \mathcal{T} \tag{4b}$$

$$\dot{E}_{PEM,\mathrm{H}_2,t}^{out} = \dot{n}_{\mathrm{H}_2,t} LHV_{\mathrm{H}_2}, \quad \forall t \in \mathcal{T} \tag{4c}$$

$$\dot{E}_{PEM,el,t}^{in} = U_{cell,t} I_t + P_{heat,t} + P_{comp,t}, \forall t \in \mathcal{T} \tag{4d}$$

$$\dot{E}_{MP,el,t}^{in} = \dot{E}_{MP,el,t}^{in,ref} + \frac{\Delta \dot{E}_{MP,el}^{in}\left(\dot{E}_{MP,\mathrm{H}_2,t}^{in}\right)}{\Delta p_{MP}}\left(p_{MP,t} - p_{MP,t}^{ref}\right), \quad \forall t \in \mathcal{T} \tag{4e}$$

$$p_{cat,t} \geq p_{MP,t}, \quad \forall t \in \mathcal{T} \tag{4f}$$

$$\mathbf{g}(\mathbf{d}, \dot{\mathbf{E}}) \leq \mathbf{0}, \tag{4g}$$

$$\mathbf{d} \in \mathcal{D} = \{T_{stack,t}, p_{cat,t}, j_t, p_{MP,t}\}, \ \forall t \in \mathcal{T} \tag{4h}$$

$$\dot{\mathbf{E}} \in \left\{\dot{E}_{k,e,t}^{out}, \dot{E}_{k,e,t}^{in}, \dot{E}_{el}^{buy}, \dot{E}_{el}^{sell}\right\}. \quad \forall k \in \mathcal{K}, \forall e \in \mathcal{E}, \forall t \in \mathcal{T} \tag{4g}$$

Energy balance constraints must be satisfied for all energy system components ($\forall k \in K$), energy carriers ($\forall e \in E$), and time steps ($\forall t \in T$) through input/output power flows $\dot{E}_{k,e,t}^{in/out}$, ensuring demand requirements $\dot{E}_{e,t}^{D}$ are met (Eq. (4b)).

Integration of the PEM electrolysis system into the energy system model occurs through its input/output power flows $\dot{E}_{PEM,H_2,t}^{in/out}$ (Eqs. (4c) and (4d)).

Methanation pressure variation (i.e., hydrogen demand pressure; hereafter termed methanation pressure for brevity) is governed by Eq. (4e). The methanation process operates at a characteristic curve, which is obtained through a pre-processing step (cf. System assumptions). This characteristic curve provides electricity demand changes $\Delta \dot{E}_{MP,el}^{in}$ in relation to methanation pressure changes Δp_{MP} for each hydrogen demand level. Within the optimization, time-dependent hydrogen demand $\dot{E}_{MP,H_2,t}^{in}$ serves as an exogenous input parameter, associated with the corresponding reference electricity

Table 2: Optimization modes (LP: Low-pressure, MP: Methanation process, EL: Electrolyzer).

Mode	EL LP outlet	MP pressure	EL temperature	EL pressure
Ref-seq		Fixed	80 °C	30 bar
Ref-int	✓	1 to 20 bar	80 °C	30 bar
pT-opt-seq	✓	Fixed	20 to 80 °C	1 to 30 bar
pT-opt-int	✓	1 to 20 bar	20 to 80 °C	1 to 30 bar

demand $\dot{E}^{in,ref}_{MP,el,t}$ and reference methanation pressure $p^{ref}_{MP,t}$. By applying linear interpolation, Eq. (4e) determines actual electricity demand through the adjustment of methanation pressure $p_{MP,t}$ relative to the reference pressure $p^{ref}_{MP,t}$.

Eq. (4f) ensures that electrolyzer pressure $p_{cat,t}$ is at least equal to the methanation pressure at the low-pressure outlet.

The constraint vector $\mathbf{g}$ encompasses all additional restrictions (e.g., energy storage capacities, load limitations, material balances). Decision variables include electrolyzer operating parameters (i.e., temperature $T_{stack,t}$, pressure $p_{cat,t}$, current density j_t), methanation pressure $p_{MP,t}$, and input/output power flows $\dot{\mathbf{E}}$ of all system components.

Solution of the resulting nonlinear programming optimization problem employs the open-source solver IPOPT, obtaining a local optimum. Identical initialization values are applied across all optimizations to ensure reliable, reproducible results and maintain consistency between different operating modes (cf. Scenario definition).

SYSTEM ASSUMPTIONS AND SCENARIO DEFINITION

System assumptions

Weather data from Hamburg, Germany, serves as time-dependent input for calculating PV system power availability [5]. Additionally, day-ahead electricity market prices are utilized, with both data sets based on the year 2023. Electricity prices comprise purchase prices and feed-in tariffs, with feed-in tariffs corresponding directly to day-ahead market prices [6]. Purchase prices include additional charges for non-household customers (i.e., grid fees and taxes) [7]. Hourly year-round data are aggregated into seven representative typical days (24 h each) using a hierarchical clustering method [8], yielding 168 time steps. To account for long-term storage, the storage formulation from [9] is applied.

Based on these temporal input data, pre-processing employs the energy system model and optimization approach from [4] to derive the methanation process operating strategy and generate an operating characteristic curve. The operating strategy provides time-dependent hydrogen $\dot{E}^{in}_{MP,H_2,t}$ and electricity demands $\dot{E}^{in,ref}_{MP,el,t}$, along with corresponding methanation pressures $p^{ref}_{MP,t}$, as exogenous input time series. The operating characteristic curve relates methanation pressure variations to electricity consumption across different load levels, enabling pressure adjustment according to Eq. (4e).

Table 1 presents the nominal capacities of all energy system components. The sizing of the PEM electrolysis system, PV unit and hydrogen storage reflect a cost-optimal hydrogen supply configuration [3], while methanation process capacities are derived from [4] with adjustments to match the electrolyzer capacity. The electrolyzer is assumed to operate at a maximum current density of 2 A/cm² at its nominal capacity of 1 MW [3].

Table 1: Nominal capacity of energy system components based on [3, 4].

Component	Nominal capacity
PEM electrolysis system	1 $\mathrm{MW_{H_2}}$
PV unit	2.5 MW
Hydrogen storage	49.3 MWh
Methanation processes	2x 0.45 $\mathrm{MW_{CH_4}}$

Scenario definition

Four optimization modes are defined to investigate the influence of integrated operating strategies (Table 2). These modes distinguish between the electrolyzer's intrinsic operational flexibility and its coordination with downstream methanation processes.

Regarding the electrolyzer, a distinction is made between fixed state-of-the-art operating parameters (i.e., 80 °C, 30 bar [3]; 'Ref' cases) and dynamically adjustable temperature and pressure within specified limits ('pT-opt' cases). The electrolyzer operating range spans 20 to 80 °C and 1 to 30 bar.

The optimization modes further differentiate the coordination approach. In the sequential approach ('seq'), the methanation process operating strategy (i.e., electricity demand, methanation pressure) is predetermined ($\dot{E}^{in}_{MP,el,t} = \dot{E}^{in,ref}_{MP,el,t}; p_{MP,t} = p^{ref}_{MP,t}$), and the electrolyzer subsequently determines its operating strategy accordingly. In the integrated approach ('int'), the electrolyzer operating strategy and methanation pressure (and consequently electricity demand) are determined

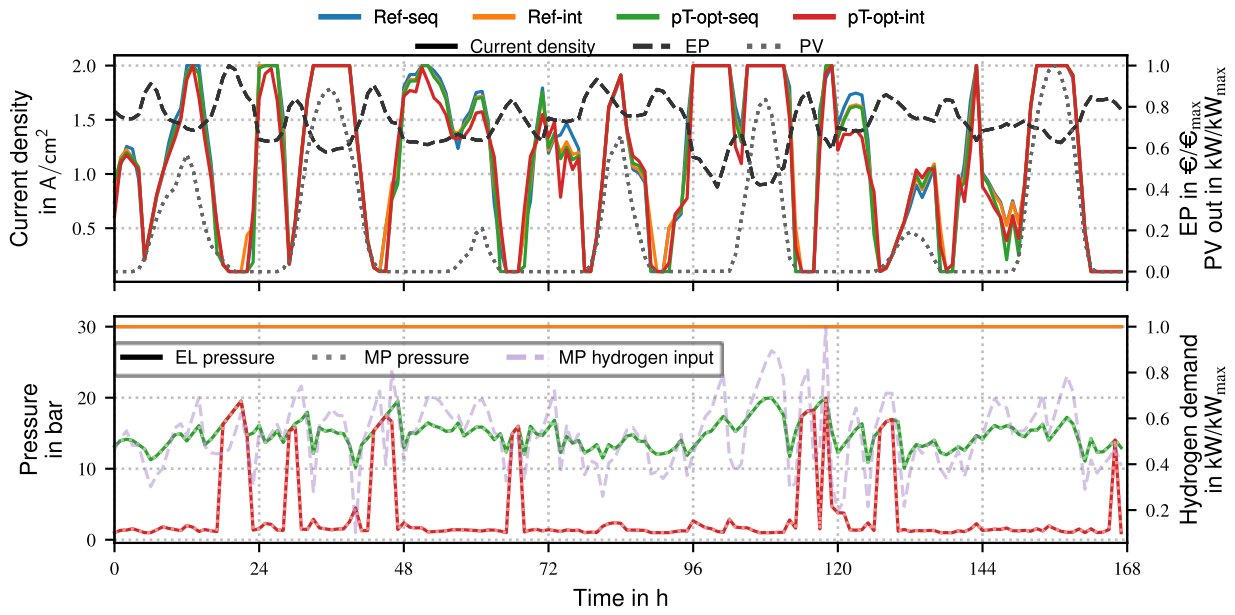

Figure 2: Temporal progression of current density, electrolyzer (EL) pressure, and methanation (MP) pressure across the four optimization modes. Electricity price (EP), photovoltaic (PV) output, and methanation hydrogen input are shown for reference, normalized to their respective maximum values. The blue, orange, and green MP pressure curves overlap.

simultaneously, enabling coordinated system-level optimization. Methanation pressure can be adjusted between 1 and 20 bar [4]. Lower pressure selection necessitates additional hydrogen compression within the methanation process to achieve the desired reaction pressure. These effects are captured in the operating characteristic curve derived from the methanation process model [4]. The time-dependent hydrogen demand of the methanation processes remains fixed across all optimization modes.

RESULTS AND DISCUSSION

Operational planning

Figure 2 illustrates the electrolyzer operating strategies across the four optimization modes, based on current density (i.e., load indicator) and operating pressure.

Current density. The current density of all modes is presented as solid lines in the upper part in Figure 2. Current density profiles—and thus hydrogen production timing and quantities—remain largely consistent across all optimization modes. High current densities (i.e., high operating loads) predominantly occur during periods of low electricity prices (e.g., at 32 h, 100 h) and/or high PV generation (e.g., at 84 h, 156 h).

The 'pT-opt-int' (cf. red line) mode exhibits minor deviations compared to other modes, with slightly lower current densities at certain times (e.g., at 50 h, 124 h) and higher values at others (e.g., at 134 h). This reduction stems from the electrolyzer's higher electrical efficiency at lower loads. Unlike other operating modes, operation at these lower loads is enabled by reducing diffusion losses through lower pressure, allowing the same usable hydrogen production to be maintained despite a lower current density.

Pressure. The lower part in Figure 2 illustrates electrolyzer and methanation pressure as solid and dotted lines, respectively.

The electrolyzer operates at a constant pressure of 30 bar in both 'Ref-seq' and 'Ref-int' modes by definition (cf. blue and orange lines, respectively). In the 'pT-opt-seq' mode (cf. green lines), pressure is reduced to match the methanation pressure within a variable range of ca. 10 to 20 bar. In all three modes, methanation pressure is prescribed exogenously and not optimized. In the 'Ref-seq' and 'pT-opt-seq' modes, this constraint results from the sequential optimization approach, whereas in the 'Ref-int' mode, the electrolyzer pressure necessarily exceeds the methanation pressure. Adjusting the electrolyzer pressure would not yield efficiency gains in this configuration (i.e., the methanation pressure already corresponds to the energetically optimal operating point from a methanation perspective).

Pressure optimization behavior differs in the 'pT-opt-int' mode (cf. red lines). Here, the electrolyzer operates predominantly at substantially lower pressures between 1 and 2 bar, with the methanation pressure adjusted accordingly. The reduced electrolyzer pressure

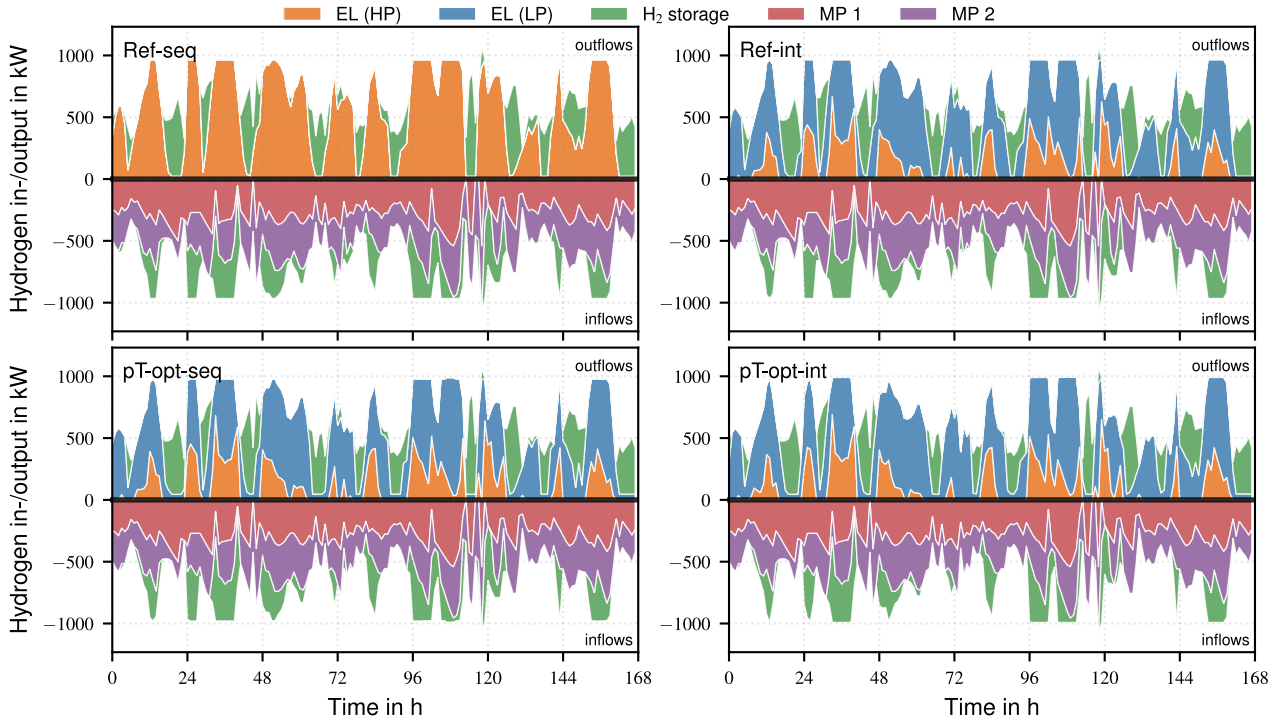

Figure 3: Temporal profiles of hydrogen inflows and outflows for production and utilization across all four optimization modes (EL: Electrolyzer, LP: Low-pressure outlet, HP: High-pressure outlet, MP: Methanation process).

increases electrolyzer efficiency, while the lower methanation pressure leads to higher electricity consumption in the methanation process. Overall, the absolute electricity savings of the electrolyzer outweigh the additional electricity demand of methanation during these periods. However, this trade-off is not universally beneficial. At isolated times when the electrolyzer operates at minimum load (e.g., at 20 h, 44 h), no pressure reduction is applied. Under these conditions, the absolute electricity savings of the electrolyzer are insufficient to compensate for the potential increase in methanation electricity consumption, particularly when methanation operates at elevated load.

Hydrogen production and storage. Figure 3 illustrates the temporal profiles of hydrogen inflows and outflows for production and utilization across all four optimization modes. Consistent with the current density profiles, electrolyzer hydrogen production remains nearly identical across all optimization modes (cf. orange and blue). As hydrogen demand from the methanation processes is additionally inflexible (cf. red and violet), hydrogen storage utilization exhibits very similar patterns across all modes (cf. green).

Consistent with current density patterns, the electrolyzer operates highly dynamically, switching between full load under favorable conditions (e.g., high PV output or low electricity prices) and minimum load under less favorable conditions. Full-load periods serve both direct methanation supply and hydrogen storage, whereas minimum-load periods rely primarily on storage discharge to meet methanation demand. This strategy ensures a stable and continuous hydrogen supply to the methanation processes over the entire time horizon.

All optimization modes except 'Ref-seq' allow the electrolyzer to supply hydrogen via both the low-pressure (LP) and high-pressure (HP) outlets. Hydrogen is either provided exclusively via the LP outlet (i.e., for direct methanation supply) or simultaneously via both outlets (i.e., for methanation supply and storage). At no point is hydrogen supplied solely via the HP outlet. This indicates that compression to 200 bar for storage is energetically unfavorable compared to direct supply at lower pressure levels, leading to a clear preference for maximizing direct hydrogen utilization.

Nevertheless, hydrogen storage remains economically attractive during periods of high PV availability and/or low electricity prices. The additional energy demand for compression is accepted during these periods, even though the electrolyzer capacity would, in principle, be sufficient to supply the methanation processes continuously without storage reliance.

The 'pT-opt-int' mode exhibits minor storage differences compared to other modes. At isolated time steps, less hydrogen is supplied via the HP outlet and thus

stored (e.g., at 60 h, 74 h). Over the entire period, only 21.3% of the produced hydrogen is provided via the HP outlet in the 'pT-opt-int' mode, compared to 23.3% in the 'Ref-int' mode and 24.2% in the 'pT-opt-seq' mode. As the 'pT-opt-int' mode operates the electrolyzer at significantly lower pressures, the subsequent compression effort is correspondingly higher. For specific time steps, the benefits of storage don't outweigh this increased compression energy demand, rendering high-pressure operation economically unattractive more frequently compared to the other modes.

Discussion. The optimization mode does not fundamentally influence the electrolyzer operating strategy with respect to current density. Instead, electrolyzer operation is primarily driven by cost-optimal production conditions, such as low electricity prices or high PV availability, rather than by temporal hydrogen demand. As a result, hydrogen production profiles and storage utilization remain largely consistent across all optimization modes, ensuring a stable hydrogen supply to the methanation processes despite highly dynamic electrolyzer operation.

Regarding pressure, the results indicate that the electrolyzer tends toward the lowest feasible operating pressure when sufficient flexibility is available. When integrated optimization is applied, information exchange between the electrolyzer and the methanation processes enables the determination of an energy- and cost-efficient hydrogen pressure at the overall system level. This leads not only to increased electrolyzer efficiency but also to changes in hydrogen routing, with a clear preference for direct low-pressure supply and a reduced reliance on energy-intensive high-pressure storage.

Consequently, integrated optimization approaches can yield substantial deviations from sequential approaches in optimal operating parameters, including pressure levels and storage usage. Although such approaches require increased planning effort and information exchange, they can enhance system-wide efficiency and contribute to a more cost-effective hydrogen supply and overall energy provision from an integrated energy system perspective.

Costs and electricity consumption

The economic and energetic implications of these operational strategies are quantified through operating cost and electricity consumption. Figure 4 presents the operating cost of the overall energy system as well as the electricity consumption of the electrolysis system and the methanation processes for all modes.

Compared to the reference case 'Ref-seq', the 'Ref-int' mode achieves operating cost savings of 2%. These savings are primarily attributable to the availability of the low-pressure outlet, which eliminates the need to compress the entire hydrogen output. As a result, the electricity consumption of the electrolysis system is reduced by 2.7%, while the electricity demand of the methanation processes remains unchanged.

The 'pT-opt-seq' mode enables 7.3% savings in total operating cost. These savings mainly result from reducing the electrolyzer operating pressure to the methanation pressure and optimizing the operating temperature. Both adaptions increase electrolyzer efficiency and reduce the electrolysis system's electricity consumption by 5.3%. As in the previous case, no impact on the electricity consumption of the methanation processes is observed.

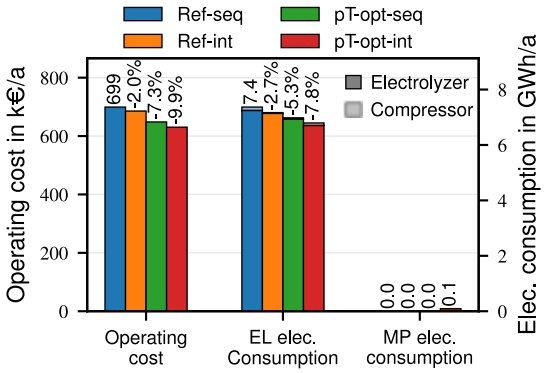

Figure 4. Operating cost and electricity consumption of the electrolysis system (EL) and methanation processes (MP) across all optimization modes.

The 'pT-opt-int' mode yields the highest operating cost savings, amounting to 9.9%. A further decrease in operating pressure drives the additional reduction compared to the 'pT-opt-seq' mode, as the methanation pressure is also adjusted under integrated optimization. While this results in a 7.8% reduction in the electricity consumption of the electrolysis system, the lower methanation pressure leads to an increase in the electricity demand of the methanation processes. In absolute terms, however, the electricity savings achieved by the electrolyzer outweigh the additional electricity consumption of the methanation processes.

Discussion. No single operating strategy is uniformly optimal for all energy system components within the analyzed energy system configuration. Instead, achieving a system-wide optimum requires balancing the differing sensitivities of the involved processes. In the considered optimization modes, electrolyzer electricity consumption is markedly more sensitive to operating pressure than methanation process electricity consumption. Consequently, operating strategies that prioritize electrolyzer performance—while accepting minor efficiency losses in methanation processes—prove advantageous from a system perspective. While sequential optimization approaches already enable noticeable cost and energy savings, the results demonstrate that additional

benefits can be realized through integrated planning by explicitly accounting for interactions between electrolyzer and methanation operation.

CONCLUSIONS

"Green" hydrogen production via PEM electrolyzers remains energy- and cost-intensive, limiting the competitiveness of renewable hydrogen-based energy systems. While adaptive operating strategies have demonstrated efficiency improvements in simple systems with constant hydrogen demand, their effectiveness in complex power-to-X configurations with dynamic downstream synthesis processes and variable pressure requirements has remained unclear. This study addresses this research gap by analyzing integrated optimization of PEM electrolyzer parameters in conjunction with downstream methanation processes, demonstrating that operating cost reductions of up to 9.9% are achievable compared to conventional fixed-parameter operation, with electrolysis system electricity consumption reduced by 7.8%.

Sequential optimization approaches, which adjust electrolyzer parameters independently based on predetermined downstream requirements, achieve 7.3% operating cost savings. In contrast, integrated optimization approaches that simultaneously coordinate electrolyzer and methanation operating conditions achieve an additional 2.6%-point reduction. This superior performance stems from the bidirectional information exchange between system components, enabling the determination of system-wide optimal operating pressures rather than component-specific set points. The operating pressure emerges as the most critical parameter, with electrolyzer electricity consumption exhibiting markedly greater sensitivity to pressure variation than methanation process electricity consumption. This results indicates that system-level optimization should prioritize electrolyzer efficiency, even at the cost of minor electricity consumption penalties in downstream synthesis processes.

These findings demonstrate the significant potential of system-wide optimization approaches for enhancing the cost-competitiveness of "green" hydrogen supply. Implementing control architectures that enable real-time coordination between electrolyzers and downstream synthesis units offers substantial economic benefits, particularly when electrolysis systems are designed for wide operating pressure ranges to fully exploit efficiency optimization potential. Future research should extend this analysis to additional synthesis pathways (e.g., Fischer-Tropsch synthesis and Haber-Bosch synthesis) to further enhance the system-level efficiency and economic viability of renewable hydrogen-based energy systems.

DIGITAL SUPPLEMENTARY MATERIAL

The model code and input data will be made available later in an online repository.

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