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Optimization of energy systems sizing and operation including heat integration and storage

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Abstract:

Sustainable energy solutions are highly dependent on the availability and costs of resources during their operation. For instance, power output of solar cells and wind turbines vary over time which impacts the technical, economic, and environmental feasibility of Power-to-X (P2X) systems. In addition, efficient system solutions for energy conversion will require an optimal heat integration between several technologies and conversion routes. Thus, several methods have been proposed to conceptualize and optimize the design and operation of process plants. However, the possibilities of heat integration and storage during dynamic operation of different P2X-processes have been rarely evaluated by existing methods in literature. In this context, this research aims to provide an optimization framework, based on linear optimization and pinch analysis, to fill this knowledge gap, crucial to the development of dynamic renewable systems. The novel method is exemplified in the optimization of a Power-to-Methanol plant using solid oxide cells (SOCs) subjected to varying electricity production of wind turbines. The optimization estimates a minimal methanol production cost of 1772-1793 USD/ton for integrated scenarios and 1820-1807 USD/ton for non-integrated cases. Thus, heat integration plays a crucial role in cutting up to 2% of fuel production cost, while storage and optimal operation reduces further 3.3 % of the electrolysis size compared with reference scenarios.

Keywords:

energy integration; energy storage; optimization; pinch analysis; power-to-methanol.

1. Introduction

The increasing capacity of renewable electricity generation, combined with goals to reduce the dependency on fossil fuels in the global economy, has driven interest in the electrification of the industry. For instance, by replacing natural gas with wind or solar power as the main source of energy in hydrogen production, several chemical products (such as ammonia, methanol, natural gas, etc.) could be produced sustainably, with regional security and possibly at a lower cost. Processes plants that focus on using electricity to produce chemical goods have been called Power-to-X plants in the literature. Recent studies indicate that Power-to-X systems will play a major role in energy storage and industry decarbonization, and several large-scale projects are currently under development [1].

In this context, research has been focusing on different challenges associated with the design and optimization of Power-to-X plants. Most of these studies rely on thermodynamic models and mixed integer linear optimization problems (MILP) to estimate and optimize key performance indicators of novel system solutions. With regards to the optimization framework, these works can be categorized by their methods into two major types: energy integration and multi-period optimization studies. The first aims to assess the best technology types and sizes that can be integrated using a heat exchanger network [2,3]. On the other hand, the second type focus on optimizing equipment sizes under variable production profiles and market prices [4,5].

However, energy integration studies usually disregard the effects of intermittent resources, partial load efficiencies and storage solutions. In addition, multi-period optimization usually oversimplifies the heat integration problem (i.e., reduced number of temperature levels) or assume lumped models with fixed heat connections. Thus, each optimization approach has gaps that could be fulfilled by combining the two approaches. For instance, recently Li et. al [6] has proposed a complex optimization that merges both approaches to optimize distributed energy systems. Nonetheless, the optimization of Power-to-X systems including the variability of resources, storage and detailed heat integration opportunities have seldom been studied in literature. For example, a Power-to-X operating solely with wind power may benefit from power

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and heat storage to stabilize energy supply. However, the optimal size of storage and utility systems is interconnected with operation and therefore both aspects should be considered to minimize production costs.

Thus, this research aims to address this research gap by proposing a simple and generalized optimization framework merging pinch analysis and multi-period optimization for energy systems like Power-to-X plants. The method allows to select and size technologies while ensuring an optimal heat integration at each time step. To exemplify the method and assess its possible gains, the design and optimization of a Power-to-Methanol system is evaluated using the optimization framework and the results are compared with non-integrated solutions.

2. Case study: Power-to-methanol

The optimization framework proposed in this section is applied to design an off-grid Power-to-Methanol plant comprised of wind turbines, solid oxide electrolysis system, methanol synthesis and distillation, as illustrated in Fig. 1. Each technology is represented by a linear model based on previous investigations using different modelling environments (e.g., Julia, Aspen Plus, etc.) [7]. The lists of every technology input, output, heat transfer and costs considered in this analysis are provided in Appendix A. In addition, a brief description of the main technologies employed in this case study is given in this subsection.

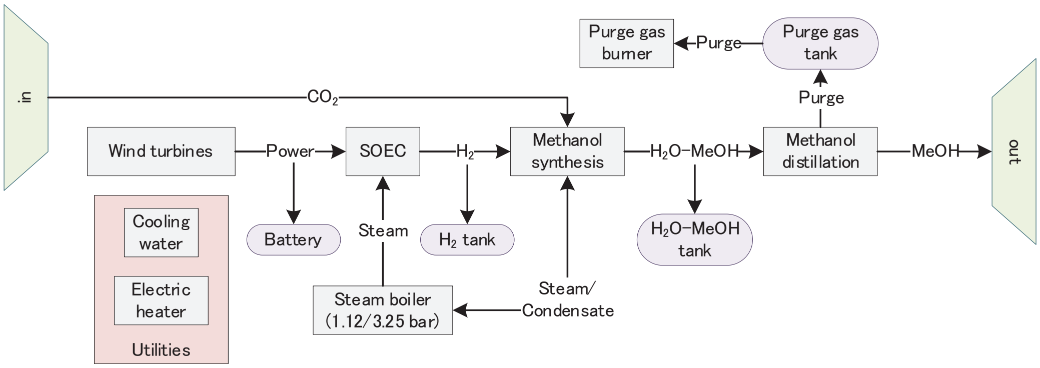

Figure. 1. Flowchart of the study case for a Power-to-Methanol plant (some resources and heat transfer were omitted for clarity)

The data of wind power generation reported by Champion, et al. [4] for an onshore wind turbine located in Esbjerg, Denmark was used to simulate the hourly power generation of a wind turbine. The main information about the wind turbine is reproduced in Table 1 from the source reference [4].

Table 1. Reference wind turbine parameters

Parameter	Value
Nominal power generation	3.15 MW
Rotor diameter (D)	142 m
Hub height	100 m
CAPEX	1.76 M€$_{2019}$/MW
Fixed OPEX	14.4 €$_{2019}$/kW/y
Variable OPEX	1.56 €$_{2019}$/MWh

The electrolysis system, Fig. 2, uses solid oxide cells to efficiently convert steam at high temperature (750 °C) and close to atmospheric pressure (1.12 bar) into hydrogen, which is compressed for storage and methanol production. A small portion of the products from the cathode of each cell are recirculated to maintain a minimal hydrogen concentration of 10% vol. in the reactants, which helps to control the electrochemical reaction, degradation, and thermal management. A detailed description of the process and modelling assumptions can be referenced in our previous works [7–9].

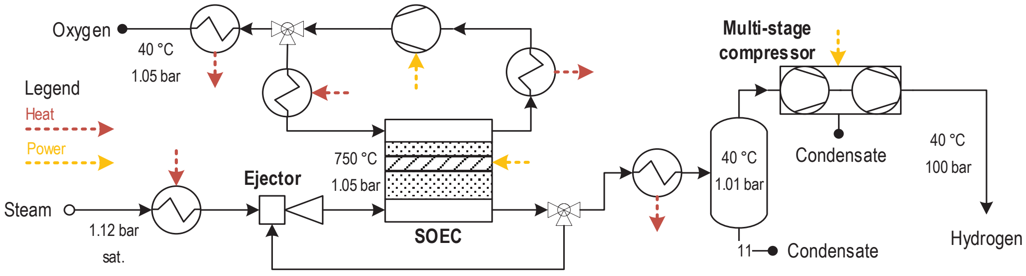

Figure. 2. Flowchart of the electrolysis system based on solid oxide cells (SOEC)

Methanol is produced in a quasi-isothermal reactor (265 °C, 90 bar) from the stoichiometric mixture of carbon dioxide and hydrogen ($CO_2+3H_2 \rightarrow CH_3OH+H_2O$). The chemical reactor is designed to achieve the same product's composition of 20 °C below the chemical equilibrium condition, as it is reported by previous works [10]. The reaction rate is estimated based on the model proposed by Bussche and Froment [11] for a copper/zinc oxide catalyst [12]. The methanol synthesis and distillation are divided as shown in Fig. 3 to include the possibility to store the water-methanol mixture (H_2O-MeOH) and operate the distillation on demand. Methanol distillation is an energy intensive process with little operational flexibility, therefore modelling it separately allows the optimization to reach more precise solutions. The detailed description of the process parameters and additional assumptions can be referenced in our previous work [7].

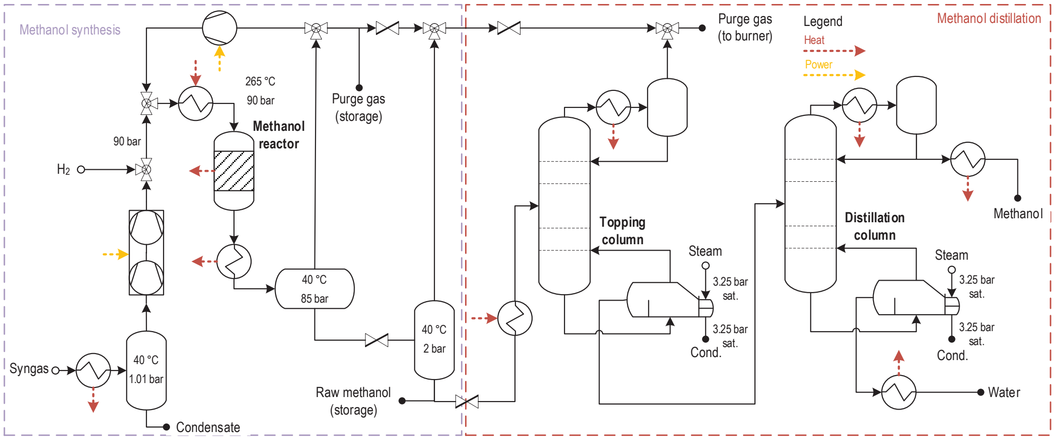

Figure. 3. Flowchart of the methanol synthesis and distillation units based on the isothermal reactor design.

The same technology and storage solutions shown in Fig. 1 and detailed in Appendix A are assumed to analyse optimal configurations under the same conditions, which are summarized in Table 2. In total, five scenarios are proposed to examinate how the wind power profile, heat integration and storage impact on the results. A summary of these scenarios is provided in Table 3.

Table 2. Summary of common parameters for optimization scenarios

Parameter	Value
Annual production of methanol (t/year)	54750
CO_2 cost (USD/ton)	30
Plant lifetime (years)	20
Interest rate of return (%/year)	8 %/year
Partial load limits (% nominal capacity)	0-100%
Installed capacity limits	≥ 0
Storage efficiency	100%
Ramping limits (% nominal capacity / h)	
Solid oxide electrolysis system	20 %/h
Methanol synthesis	20 %/h
Methanol distillation	20 %/h

Table 3. Summary of scenarios description

	Scenario acronym				
Characteristics	*AVG*	*NI-NS*	*NI-S*	*I-NS*	*I-S*
Wind power profile	No	Yes	Yes	Yes	Yes
SOEC/Methanol heat integration	Yes	No	No	Yes	Yes
Storage technologies	No	No	Yes	No	Yes

The base scenario, AVG, represents the usual energy integration optimization at steady-state conditions, where only an average of the power supply and costs is assumed. The other four scenarios include the possibility to heat integrate the electrolysis and fuel production (I – integrated; NI – non-integrated), as well as the use of storage to allow the processes to operate out of sync (S – storage; NS – no storage).

2. Methods

The objective function of the proposed optimization problem is the operating revenues of a process plant over a year discounting the amortized investment cost and fixed expenses, as expressed in Eq. (1). In this equation, $r_{i,t}^{in}$ and $r_{i,t}^{out}$ represent the rate of resources imported and exported by the process plant, respectively, while $c_{i,t}^{in}$ and $c_{i,t}^{out}$ denote their associated cost. In addition, the investment repayment and fixed expenses are estimated based on the grassroot cost for each technology (C_{GR}^{τ}) multiplied by the scale factor (f^{τ}) and capital recovery factor (β_{CRF}).

$$\max\left\{\sum_{t}^{T}\left[\sum_{i}^{I}\left(r_{i,t}^{out}c_{i,t}^{out}-r_{i,t}^{in}c_{i,t}^{in}\right)\right]-\sum_{\tau}^{\tau_n}f^{\tau}C_{GR}^{\tau}\beta_{CRF}\right\} \tag{1}$$

Technologies are divided into two categories, conversion and storage, which are denoted by the superscripts κ and σ, respectively. Each converting technology (κ) is represented by a black-box model consisted of a set of inlet resources ($r_i^{\kappa,in}$), outlet resources ($r_i^{\kappa,out}$) and heat transfers divided into temperature intervals (Q_k^{κ}), as exemplified in Figure 1. The main constraints of the optimization problem, Eq. (2) and (3), represent the balance of resources and heat between the boundary conditions of the process plant and its components (i.e., technologies). Moreover, resources and heat balances are influenced by transfers between technologies, which are affected by a temporal size factor (f_t^{κ}). This reflects the partial-load conditions of a technology in a particular timeframe (t).

$$r_{i,t}^{in}+\sum_{\sigma}^{\sigma_n}s_{i,t-1}^{\sigma}\eta_i^{\sigma}+\sum_{\kappa}^{\kappa_n}f_t^{\kappa}\left(r_i^{\kappa,in}-r_i^{\kappa,out}\right)=r_{i,t}^{out}+\sum_{\sigma}^{\sigma_n}s_{i,t}^{\sigma}\quad\forall i,t \tag{2}$$

$$R_{k-1,t}+\sum_{\omega}^{\Omega}f_t^{\omega}\left(\sum_{n}^{N}Q_k^{\omega}\right)=R_{k,t}\quad\forall k,t \tag{3}$$

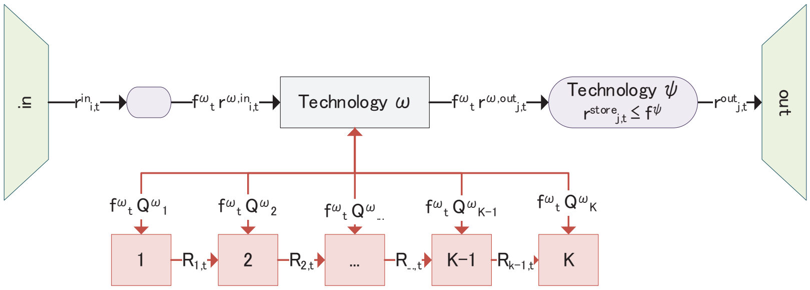

Figure. 2. Generalized sketch of a technology model in the optimization framework (where multiple technologies are coupled).

The heat cascade constraint, Eq. (3), is based on the work of Marechal and Kalitventzeff [13] and recently adapted by Li, et al. [6]. The heat transferred in a temperature interval, *k*, in a specific timestep ($R_{k,t}$) is positive to indicate a possible exchange from higher to a lower temperature level, and null in the extremes of the heat cascade (0 and K) [14]. These variable limits are represented in Eq. (4).

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$$R_{k,t} = 0, \qquad k = 0, K$$
$$R_{k,t} \geq 0, \qquad otherwise \tag{4}$$

On the other hand, storage technologies relate to accumulation variables ($s_{i,t}$) in Eq. (2) by limiting their maximum value to a size factor (f^{σ}), as written in Eq. (5). It's important to notice that storage losses can be modelled throughout an efficiency factor (η_i^{σ}) in Eq. (2), while inefficiencies in charging and discharging processes can be described by conversion technologies with an unequal balance of resources ($r_i^{\kappa,in} \geq r_i^{\kappa,out}$).

$$s_{i,t}^{\sigma} \leq f^{\sigma} \tag{5}$$

Resources can be imported or exported by the process plant under limited conditions that may vary depending on the problem analysed. For instance, a certain amount of product "*i*" may be delivered after a finite number of time steps (e.g., yearly demand of fuel), which can be represented by a constraint like Eq. (6). Another common scenario is that the supply and/or demand for each timestep is defined (e.g., hourly power generation or heat demand), as exemplified in Eq. (7).

$$\sum_{t} r_{i,t} = cte \tag{6}$$

$$r_{i,t} = cte \tag{7}$$

The technology size factors (f) are limited by upper and lower bounds, Eq. (8), while the temporal size factors for converting technologies (f_t) are restricted by maximum and minimal loads relative to their size (l_{min} and l_{max}, respectively), Eq. (9). In addition, some converting technologies may have ramping limits proportional to their size (r_{down} and r_{up}), which can be represented by Eq. (10).

$$f_{min} \leq f \leq f_{max} \tag{8}$$

$$l_{min} f \leq f_t \leq l_{max} f \tag{9}$$

$$r_{down} f \leq f_t - f_{t-1} \leq r_{up} f \tag{10}$$

The constraints described in Eq. (8) and (9) have been proposed by different authors [4,15] and they allow to optimize the technology sizes and operation loads simultaneously. However, these constraints don't allow to model operational discontinuities such as shutdown and standby periods without fixing the technology size. A possible alternative is to use a reformulation strategy as proposed by Voll et. al. [16] and recently employed by Li et al. [6].

3. Results

The main results for the optimization of each scenario are presented in Table 4. The cost estimates for methanol production and CAPEX excluding wind turbines vary between 1290-1820 USD/ton and 5123-8918 USD/t/y, respectively. Due to the current high investment of SOECs ($/kg$_{H2}$), these numbers are in the upper end range of those reported by IRENA and Methanol Institute [17] for e-methanol production through CO_2 from renewable sources (820-1620 USD/ton and 2000-9720 USD/t/y). The optimization results also exemplify how the variability of wind, heat integration and storage solutions can lead to different designs and costs.

For instance, the estimated costs for fuel production in the base scenario (AVG) are 27-29 % lower than other cases in which the influence of the wind power variability is considered. This difference can be explained by the need to oversize wind turbines, to compensate curtailment losses, and the Power-to-MeOH system, to match the varying rating of power generation, as it can be observed in Table 4. Figure 5 illustrates the distribution of CAPEX investments among all the technologies in each scenario. It is noticeable that the increase of SOEC size, due to the variability of wind power, represents the lion share (56-59%, 2766-2981 USD/t/y) of the CAPEX increase relative to the AVG scenario.

The optimization results also indicate the possibility to reduce 1-2% of methanol costs by integrating high temperature electrolysis with a methanol plant. This cost reduction can be attributed to the lower power consumption in the electric heaters for the integrated cases, as depicted in the Figure 6, which lowers the wind turbine sizes and, consequently, the total CAPEX investment. As can be observed by the integrated composite curves, heat provided by the condensation of the methanol reactor's products could be used to generate steam for the electrolysis system, reducing approximately 22% of electric heaters rating at steady state conditions (~1.5 MW).

Table 4. Main optimization results for each scenario proposed

	Scenarios				
Result	*AVG*	*NI-NS*	*NI-S*	*I-NS*	*I-S*
Size factors					
Wind turbine	1.00	1.25	1.24	1.22	1.21
SOEC	1.00	1.74	1.71	1.73	1.67
MeOH synthesis	1.00	1.74	1.71	1.73	1.66
MeOH distillation	1.00	1.74	1.59	1.73	1.66
Steam boiler (1.12 bar)	1.00	0	0	1.73	1.67
Steam boiler (3.25 bar)	1.00	1.74	1.59	1.73	1.66
Purge gas burner	1.00	1.74	2.00	1.73	3.48
Electric heaters	1.00	0.18	0.59	1.73	2.30
Cooling water	1.00	1.47	1.41	1.73	1.66
Battery (MWh)	0	0	6.79	0	3.85
Hydrogen (m^3)	0	0	0	0	1.49
Purge gas (m^3)	0	0	6.33	0	13.18
Water-MeOH (m^3)	0	0	167	0	57.32
*Economics**					
Annual costs (MMUSD/y)	70.62	99.65	98.9	98.16	96.99
CAPEX (MMUSD)	625.97	919.49	911.98	905.58	894.29
CAPEX (USD/t/y)	11433	16794	16537	16540	16334
CAPEX excluding wind turbines (USD/t/y)	5124	8919	8846	8857	8705
Methanol cost (USD/t)	1290	1820	1807	1793	1772

*The year base for economic values presented in this research is 2022

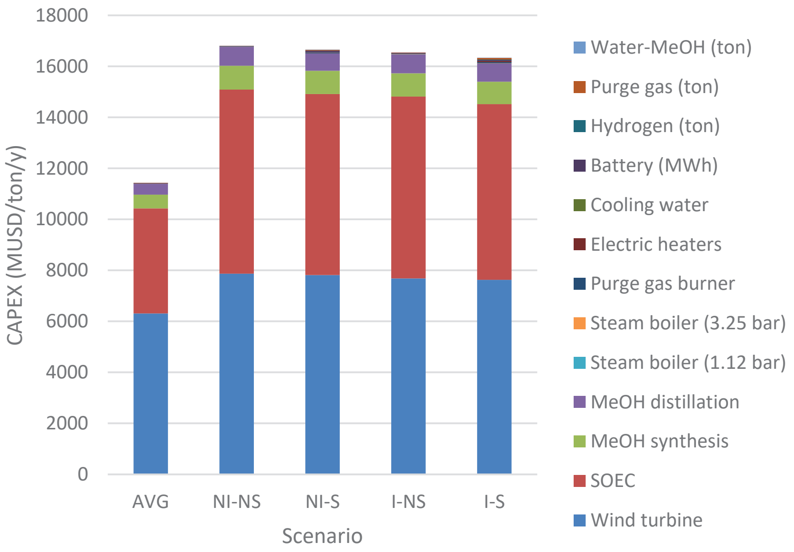


Figure. 5. Distribution of CAPEX investment for each scenario

The inclusion of storage solutions in scenarios NI-S and I-S allows an additional reduction in size of the wind turbines and electrolysis system and, consequently, lower the fuel costs in 0.7-1.2% compared with NI-NS and I-NS scenarios. It is important to highlight that a larger reduction in the electrolysis size is observed for the integrated scenario (3.3% against 1,6% for the non-integrated), which indicates that excluding heat integration during operating optimization could hide significant improvement opportunities. In particular, the I-S scenario operates differently depending on the wind power availability, as can be observed in Figure 7. For instance, the system stores purge gas when wind power is close to maximum to be used when electricity availability is diminished. In addition, the optimal configuration also shuts-down the distillation process to reduce power consumption in electric heaters. This effect on the utility's consumption can be more clearly examined from the integrated composite curves depicted in Figure 8

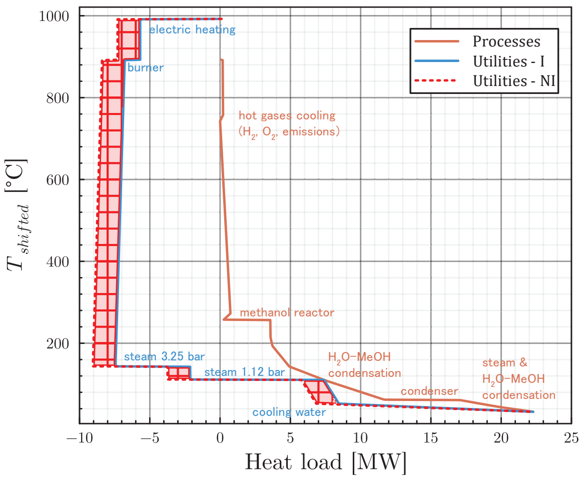


Figure. 6. Heat integration between utilities and processes for scenarios I and NI

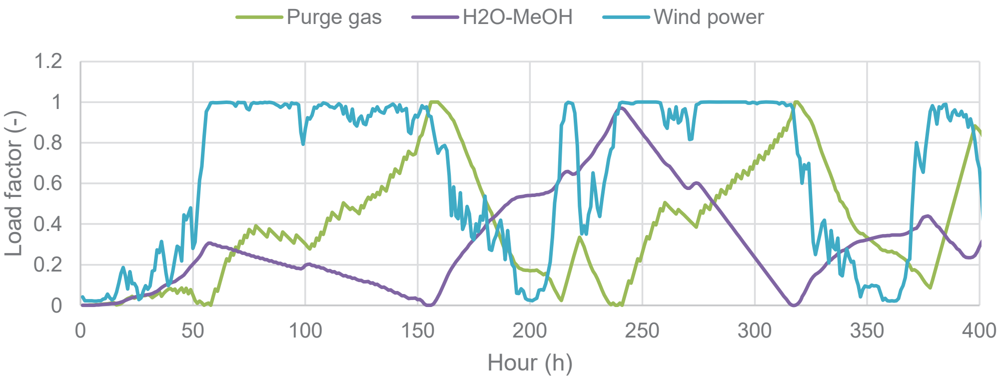
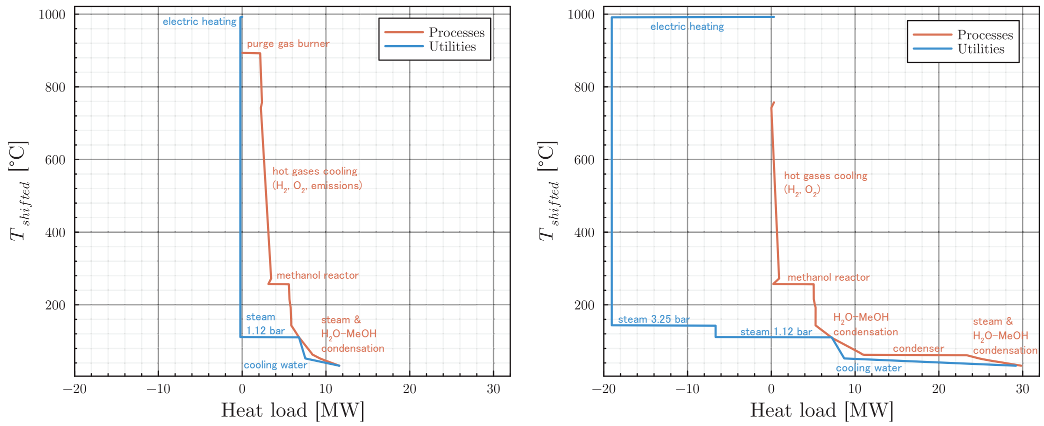


Figure. 7. Wind power and storage load variation of purge gas and H_2O-MeOH for the I-S scenario



(a) Low wind power (t = 170 h)

(b) High wind power (t = 277 h)

Figure. 8. Integrated composite curves for I-S scenario at different hours

3.1. Discussions

The results of the optimization study presented in the previous subsection exemplify how the steady-state assumption may hide costs and inefficiencies linked with the variability of renewable energies such as wind and solar power. This underestimation may also diminish the possible benefits of using biomass energy, which is usually less efficient than wind/solar power, but it can supply a stable source of energy. For instance, a possible alternative to further reduce the SOECs and wind turbine sizes is to complement wind power with biomass energy. The impact of this hybridization in the product costs, which could be assessed by the optimization framework proposed here, can't be fully evaluated from traditional steady-state integration studies.

In addition, the Power-to-Methanol example also demonstrates how heat integration is a crucial part of high temperature electrolysis systems such as SOECs. On the other hand, this may not be an important factor for traditional technologies, such as alkaline electrolysis, which may lead to unfavourable designs of Power-to-X plants for the future. For example, choosing to produce hydrogen separated from its use may not impact on product's cost today, but it may hinder the possibly benefits of switching from alkaline/PEM electrolysis to SOEC technology in the future. A similar observation can be drawn from the storage optimization scenarios, which may require oversized process parts (e.g., distillation and burners) from conception to reduce operating costs.

Previous studies have also pointed to possible improvements by generating steam from heat integration and proposed to reduce steam consumption by using co-electrolysis [2]. Other suggested modification indicated by Zhang et al. [3] is to operate at strongly exothermal conditions (0.9-1.1 A/cm^2, 1.42 V, 750-870 °C) to provide enough heat for steam generation and reduce cells size. However, the operation under exothermal conditions may severely increase cells degradation, which mostly likely will limit this optimization solution. On the other hand, the impacts of wind power variability and storage in the optimization of plant design and operation, as demonstrated in this study, have seldom been evaluated.

The optimization framework proposed in this study has several limitations, which can be overcome by including additional modelling strategies. For instance, the nonlinear properties of certain systems (e.g., efficiency and costs) can be approximated by a series of lines for specific intervals [16]. Another example is the details of the heat exchanger network, which can be designed to minimize the number of units to indirectly reduce the cost of the energy integration [8,14]. An extended version of this research work will focus on including these improvements and extending the Power-to-Methanol analysis.

4. Conclusions

An optimization framework is proposed to evaluate opportunities for heat integration on energy conversion and storage systems operating at dynamic conditions (e.g., fluctuating power loads, seasonal resources, etc.). The method aims to merge techniques from multi-period optimization with energy integration methods derived from pinch analysis to assist in the optimization of size and operation of future energy systems such as Power-to-X. The optimization of a Power-to-Methanol plant operating off-grid using wind power is used to exemplify the different insights provided by the optimization framework. For instance, the results indicate that conventional heat integration studies assuming constant power supply and costs may significantly underestimate technology sizes and costs (27-29 %). In addition, heat integration between high temperature electrolysis and methanol production may reduce up to 2% of fuel costs by reducing the required electric heating for steam generation. Moreover, a reduction of up to 4% in the electrolysis systems can be achieved by optimizing storage and operation including heat integration. This is possible by storing purge gas during high wind power periods and shutting down methanol distillation during low wind power generation. It is important to highlight that this size reduction is reduced by half in the case without including the possibility of heat integration, exemplifying the hidden opportunities for design in Power-to-X compared with previous studies of multi-period optimization.

Acknowledgments

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Appendix A – Technologies details

The main details of each technology and storage options assumed in the optimization study are presented in Tables 5-8. The balance of resources and heat transfer, Tables A.1 and A.2, are based on thermodynamic models described in a previous study. The cost of investment, maintenance, and operation (Tables A.3 and A.4) were estimated following the equations proposed by Turton, et. al. [18] and Seader et. al. [19], except for the SOEC system and storage, which was determined based on values proposed by Refs. [4,20].

Table A.1. Balance of resources for each technology at reference size

	Inputs			Outputs		
Technology	*Type*	*Qnt.*	*Unit*	*Type*	*Qnt.*	*Unit*
Wind turbines				Electricity	0-130.5	MW
SOEC thermoneutral	Steam 1.12 bar	365.37	ton/d	Hydrogen	29.84	ton/d
	Electricity	46.06	MW			
SOEC thermoneutral / independent system	Electricity	52.91	MW	Hydrogen	29.84	ton/d
Methanol synthesis	Hydrogen	29.84	ton/d	H2O-MeOH	237.07	ton/d
	CO2	217.02	ton/d	Purge gas	4.76	ton/d
	Electricity	1.19	MW			
Methanol distillation	H2O-MeOH	237.07	ton/d	MeOH	150.00	ton/d
	Steam 3.25 bar	212.63	ton/d	Cond. 3.25 bar	212.63	ton/d
Steam boiler (1.12 bar)				Steam 1.12 bar	365.31	ton/d
Steam boiler (3.25 bar)	Cond. 2.5 bar	212.63	ton/d	Steam 3.25 bar	212.63	ton/d
Purge gas burner	Purge gas	4.76	ton/d			
	Electricity	3.79	kW			
Electric heater	Electricity	5.77	MW			
Cooling water	Electricity	0.19	MW			

Table A.2. Heat transfers associated with each technology at reference size

	Heat transfers			
Technology	*Type*	*Rate (MW)*	*T source (K)*	*T target (K)*
SOEC thermoneutral	Steam heating	5.77	376	1023
	H2 cooler	-5.05	1023	344
	H2 condenser	-2.66	344	313
	O2 1st cooling	-4.56	1023	473
	O2 2nd cooling	-0.43	481	313
	O2 reheat	2.96	480	1023
	H2 compression	-3.80	473	313
Methanol synthesis	CO2 compression	-1.37	422	313
	Preheater	7.71	308	538
	Reactor	-3.35	538	537
	Cooling	-3.66	537	424
	Condenser	-7.94	424	313
Methanol distillation	Preheater	0.16	314	328
	1st Condenser	-0.01	323	322
	2nd Condenser	-5.17	343	342
	MeOH cooling	-0.20	343	313
	H2O cooling	-0.35	388	313
Steam boiler (1.12 bar)	Liquid heating	1.38	298	376
	Phase change	9.51	376	377
Steam boiler (3.25 bar)	Evaporating	5.30	408	409
Purge gas burner	Air preheater	0.06	304	398
	Radiative	-1.10	1174	1173
	Convective	-0.65	1173	433
Electric heater	Heating	5.77	1273	1272
Cooling water	Cooling	13.46	298	318

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Table A.3. Estimated costs for each technology at refence size

Technology	Costs *Type*	*Value (MMUSD)*	*Lifetime (years)*
Wind turbines	C_{GR}	345.45	20
SOEC thermoneutral	C_{GR}	225.76	20
SOEC thermoneutral / independent system	C_{GR}	227.45	20
Methanol synthesis	C_{GR}	29.16	20
Methanol distillation	C_{GR}	23.49	20
Steam boiler (1.12 bar)	C_{GR}	0.13	20
Steam boiler (3.25 bar)	C_{GR}	0.07	20
Purge gas burner	C_{GR}	0.70	20
Electric heater	C_{GR}	1.21	20
Cooling tower	C_{GR}	0.54	20

Table A.4. Estimated costs for each storage technology at reference size

	Resource			**Cost**		
Technology	*Type*	*Qnt.*	*Unit*	*Type*	*Cost (MMUSD)*	*Lifetime*
Battery	Electricity	100	MWh	C_{GR}	54.43	20
H2 tank	Hydrogen	1	T	C_{GR}	0.69	20
Purge gas tank	Purge gas	1	t	C_{GR}	0.25	20
Raw MeOH tank	Raw MeOH	1000	t	C_{GR}	3.24	20

Nomenclature

c	specific cost, USD/kg or USD/MWh or -
C_{GR}	investment cost, USD
β_{CRF}	capital recovery factor $(i/(1-(1+i)^{-years}))$, year^{-1}
D	rotor diameter, m
f	size factor, -
r	resource amount, kg or MWh or m^3, or rate, kg/h or MW or USD/h.
$ramp$	ramp limit factor, -
R	heat transfer rate between temperature intervals, kW
s	stored amount, kg or MWh or m^3.
$\dot{Q}$	heat transfer rate, kW

Greek symbols

κ	converting technology index
κ_n	number of converting technologies
σ	storage technology index
σ_n	number of storage technologies
η	efficiency, -
ρ	specific mass, kg/m^3
v	velocity, m/s

Subscripts and superscripts

$down$	discharge rate
fix	fix rate
i	resource index

I	number of resources
in	inlet
k	temperature interval index
K	number of temperature intervals
$rate$	design condition
T	number of time frames
t	time index
n	stream index
N	number of streams
min	minimal size or load
max	maximum size or load
out	outlet
up	charging rate

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