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Conceptual design of energy storage systems for continuous operations in renewable-powered chemical processes

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ABSTRACT

This work aims to develop an energy storage system that allows fluctuating energy inputs (*i.e.* from process sections driven by renewable sources) to power two process units that are operated continuously at different temperatures. The system consists of two vessels storing diathermal mediums: one for the hotter- and the other for the colder-energy fluxes. The investigated solutions include sensible-heat-, latent-heat-, and thermochemical-TES (thermal energy storage). Organic Rankine cycles (ORCs) with lithium-ion batteries and thermoelectric generators were also assessed. Indeed, all these technologies allow the exploitation of low-temperature thermal energy to supply the high-temperature unit during periods of energy scarcity. Both vessels aim for total self-sufficiency; however, the option to rely on external utilities has been included to meet the energy demand of both units when sufficient process-side power is unavailable. Two energy profiles were investigated to assess the proposed storage systems' performance: one showing only solar energy inputs and the other showing only wind energy inputs. Finally, an optimization problem was formulated to estimate the optimal size of both storage vessels. Indeed, increasing their capacities would lead to higher capital expenses (CAPEX) and lower operating expenses (OPEX). As a result, the assessed process-integrated configurations (*i.e.* those featuring any energy storage system) proved competitive with the non-integrated solution (*i.e.* the one fully relying on external sourcing of electricity) only if referring to high electric energy prices (300 USD/MWh). Conversely, when considering an electricity price of 100 USD/MWh, all the assessed process-integrated configurations proved more expensive than the non-integrated solution.

Keywords: Energy storage, Heat recovery, Process integration, Renewable energy, Solar power, Wind power.

INTRODUCTION

Powering the chemical industry with renewable energy represents a significant challenge for process engineers today. The primary obstacle to achieving a fully integrated green solution lies in harmonizing inherently intermittent energy production with processes that require predominantly continuous operation. Energy storage has emerged as a highly effective approach to address this challenge, with various methods aiming to regulate oscillatory renewable energy inputs for processes requiring operational steadiness. Scientific literature offers several innovative energy storage methods, such as fluid heating via electrical resistances [1], or storage by batteries [2] or reversible reactions (being exothermic or endothermic according to the direction taken) [3], *i.e.* electrochemical storage. Other technologies involve evaporating liquefied air to drive turbines for electricity generation during the discharge phase, complemented by compression cycles during the energy storage charging phase [4]. Lastly, even Brayton cycles and subsequent storage of working fluids may play a role in continuous electricity production [5]. This work aims to model and optimize the heat recovery system powering two different process units (*aka* "users") relying entirely on the thermal energy recovered from upstream process sections exposed to significant

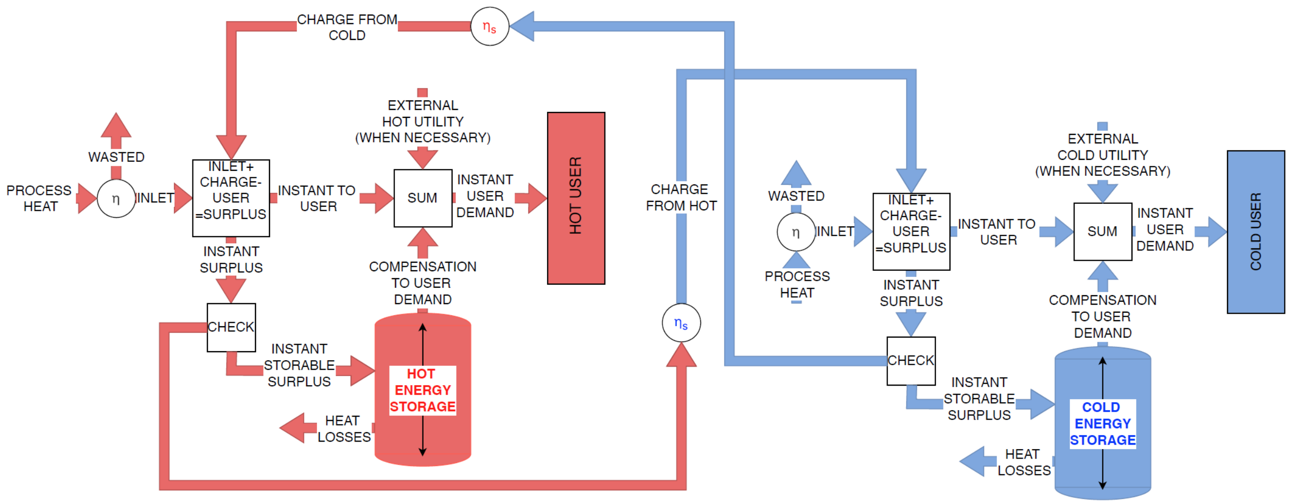

Figure 1: Block flow diagram of the integrated system model.

thermal load fluctuations due to renewable energy inputs. To ensure the continuous operation of the investigated process units, it is crucial to identify the optimal configuration according to the technologies employed and the storage capacities to be installed (as it concerns the CAPEX). Also, such an integrated solution should minimize the reliance on external utilities (as it concerns the OPEX).

METHODOLOGY

Operating at two different temperatures, the two users are supplied by two streams at distinct temperatures: the "hot" (*i.e.* 185 °C) and the "cold" (*i.e.* 95 °C) one. The system incorporates two storage tanks amidst the users' incoming energy inputs and departing energy demands. Both tanks are interconnected to optimize energy integration, allowing energy transfer between them in cases where a surplus exceeds the storage capacity. In this regard, the "hot-to-cold" energy transfer efficiency is approximately 90% [6]. Conversely, the "cold-to-hot" energy transfer efficiency significantly changes according to the technologies employed for energy conversion.
Three distinct energy storage technologies are evaluated: latent-heat-, sensible-heat-, and thermochemical-TES (thermal energy storage). On the other hand, an organic Rankine cycle (ORC), combined with an electric resistance and a battery to manage short-term fluctuations and ensure the continuous operation of the turbine, has been assessed to convert cold thermal energy into hot thermal energy. Also, a process configuration featuring a thermoelectric reactor coupled with thermal resistance has been considered. **Figure 1** illustrates how the system was modeled. To run the optimization problem, the sizes of the storage tanks act as degrees of freedom. Larger tanks would increase capital investment costs but reduce external energy purchases. Conversely, smaller tanks would reduce investment costs but increase operational costs and emissions, as they require more external energy, which might also be associated with a high carbon footprint. Going into the modeling details of both energy storage systems (*i.e.* the "hot" and the "cold" ones), $Instant\ Surplus$ is a variable of key importance, accounting for the difference between the energy demand of the users and the energy supplied by the heat recovery system (plus any eventual energy coming from the other vessel). Accordingly, it is defined as:

$$InstantSurplus(t) = Inlet(t) \cdot \eta - User(t) + ChargeFromSystem(t) \cdot \eta_c \tag{1}$$

where η accounts for the energy losses due to storage, and η_c is the conversion efficiency (*i.e.* "hot-to-cold" or "cold-to-hot"). Hot-to-cold energy transfers typically feature near-unity efficiencies, while cold-to-hot energy transfers generally show much lower efficiencies due to thermodynamical and conversion limitations. Hereafter, the $ChargeFromSystem$ variable is defined as:

$$ChargeFromSystem(t) = max\big(InstantSurplus(t) - (MAXEnergyStorage - EnergyStorage(t)), 0\big) \tag{2}$$

Equation 2 quantifies the energy that can be transferred between the systems when immediate use or storage is not possible, according to the installed capacity of the storage system ($MAXEnergyStorage$). The $EnergyStorage$ variable tracks the filling and emptying of storage vessels over time, incorporating heat losses:

$$EnergyStorage(t) = \min(\max(EnergyStorage(t-1) + InstantSurplus(t), 0), MAXEnergyStorage) \cdot (1 - HeatLosses) \tag{3}$$

This ensures full compliance with physical and operating limitations in both storage systems. When neither stored

Table 1: The proposed technologies for energy storage and conversion.

Technology	Medium (hot and cold storage)	Plant section	Efficiency	Lifetime	Ref.
Latent heat	KNO_3 KOH $H_2C_2O_4$	Energy storage	η = 90% Heat losses = 1%/h	15 y	[7]
Sensible heat	$NaNO_3$ NaOH $H_2C_2O_4$	Energy storage	η = 90% Heat losses = 1%/h	15 y	[7]
Thermochemical	$CaAl_{0.02}Mn_{0.8}O_{2.68}+0.16O_2 \leftrightarrow CaAl_{0.02}Mn_{0.8}O_3$ [Unfeasible]	Energy storage	η = 90% Heat losses = 1%/h	15 y	[8]
ORC + Battery	–	Energy conversion	η_c = 30%	20 y	[9]
Thermoelectric generator	–	Energy conversion	η_c = 5%	12 y	[10]

nor transferred energy is enough to meet the users' demand, any remaining imbalance is compensated by the $ExternalUtility$ variable, calculated as:

$$\begin{aligned}
&\boldsymbol{if}\ InstantSurplus < 0 \quad AND \\
&|InstantSurplus(t)| > EnergyStorage(t) \\
&\qquad ExternalUtility(t) = |InstantSurplus(t)| - EnergyStorage(t) \\
&\boldsymbol{else} \\
&\qquad ExternalUtility(t) = |InstantSurplus(t)| - EnergyStorage(t)
\end{aligned} \tag{4}$$

Thus, the optimizer iteratively adjusts the maximum hot and cold storage capacities ($MAXEnergyStorage$) through an exhaustive grid-search to identify the configuration minimizing the total costs. Such calculations, based on the energy demand vs. production profiles, describe the storage dynamics, the power needed for the conversion technology, and the utility requirements accounted for by the objective function. The maximum storage size matches to $MAXEnergyStorage$, the maximum required conversion power corresponds to the highest value by the $ChargeFromSystem$ time-array, and the total external utility demand comes from integrating the $ExternalUtility$ vector throughout the assessed time frame.

Two distinct objective functions have been considered. The former distributes the investment costs over the lifetime (LT) of each process unit:

$$\begin{aligned}
\Phi_{OBJ}^{(1)} &= HotMediumCost/LT_{HotMedium} + HotTankCost/LT_{HotTank} \\
&+ColdMediumCost/LT_{ColdMedium} + ColdTankCost/LT_{ColdTank} \\
&+\left(\sum_{t=1}^{t_{end}} ColdUtility(t) + \sum_{t=1}^{t_{end}} HotUtility(t)\right) \cdot ElectricityCost \\
&+EnergyConversionCost/LT_{conversion}
\end{aligned} \tag{5}$$

The latter incorporates a Capital Recovery Factor (CRF), calculated as $\frac{IR(1+IR)^{LT-1}}{(1+IR)^{LT}-1}$, with an 8% interest rate (IR) to account for the time value of money. Several factors may influence the interest rate, including project risk (higher perceived risk results in higher interest rates), financial market considerations, and the type of financing used (as equity and debt involve different costs). Consequently, a range between 5% and 8% (hence the 8% choice has a conservative nature) is suggested for the interest rate as green projects often benefit from incentives and more favorable conditions compared to traditional sectors, though frequently facing major risks related especially to technological innovation or regulatory variability.

$$\begin{aligned}
\Phi_{OBJ}^{(2)} &= HotMediumCost \cdot CRF_{HotMedium} + HotTankCost \cdot CRF_{HotTank} \\
&+ColdMediumCost \cdot CRF_{ColdMedium} + ColdTankCost \cdot CRF_{ColdTank} \\
&+\left(\sum_{t=1}^{t_{end}} ColdUtility(t) + \sum_{t=1}^{t_{end}} HotUtility(t)\right) \cdot ElectricityCost \\
&+EnergyConversionCost \cdot CRF_{conversion}
\end{aligned} \tag{6}$$

For both objective functions (defined in Equations 5 and 6, respectively), an operating time of 8760 hours per year (*i.e.* assuming non-stop plant operations) was assessed. Indeed, as the upstream process sections (*i.e.* those providing the "process heat" reported in **Figure 1**) are powered by renewable energy inputs, they typically exhibit large oscillations throughout the year, especially due to solar and wind seasonal trends. In this regard, **Table 1** reports all the technologies proposed for the investigated system and their respective efficiencies and lifetimes. Finally, the optimization problem was assessed through a brute-force but exhaustive grid-search routine in MATLAB™ R2024a. As mentioned above, this problem shows two continuous degrees of freedom (*i.e.* decision variables): the installed capacity of the hot and the cold energy storage systems.

RESULTS AND DISCUSSION

The model underwent two distinct input thermal-

Table 2: The investigated process configurations.

#	Hot storage	Cold storage	Energy conversion
1	Sensible	Sensible	ORC + Battery
2	Latent	Sensible	ORC + Battery
3	Thermochemical	Sensible	ORC + Battery
4	Sensible	Sensible	TEG
5	Latent	Sensible	TEG
6	Thermochemical	Sensible	TEG
7	Sensible	Latent	TEG
8	Latent	Latent	TEG
9	Thermochemical	Latent	TEG
10	Sensible	Latent	ORC + Battery
11	Latent	Latent	ORC + Battery
12	Thermochemical	Latent	ORC + Battery

energy profiles, "A" and "B", based on solar (the former) and wind (the latter) energy inputs. In both cases, the primary purpose of the optimization process is to identify the most effective process-integration technique and determine whether energy storage is more cost-effective than relying on external utilities. Please note that both objective functions disregard carbon emissions entirely. However, integrated heat recovery systems typically reduce carbon intensity due to their lower dependence on external utilities (which usually are highly carbon-intensive, especially those used for heating).

The technologies listed in **Table 2** were combined to assess the three storage methods for both (*i.e.* "hot" and "cold") tanks with the proposed two conversion methods. Considering all possible combinations, 18 configurations (*i.e.* = 3·3·2) were obtained. However, excluding those 6 featuring thermochemical energy storage for the cold tank (since the investigated scientific literature does not report any storage medium available at such temperatures) resulted in 12 viable and technically feasible configurations.

From the proposed optimization problem, one can expect two opposite scenarios: the former, minimizing the OPEX, almost nullifies the need for external utilities by contemplating heavy energy transfer from the cold to the hot tank through a conversion technology; the latter, minimizing the CAPEX, rejects any integrated conversion feature: *i.e.* it increases reliance on external utilities (thus potentially leading to higher emissions) but also reduces investment costs and spatial requirements associated with the energy conversion system.

Another critical aspect of the analysis concerns the competitiveness of the process integration compared to purchasing external energy whenever needed to mitigate renewable energy fluctuations. Therefore, even buying electrical energy from an external power grid has been evaluated as a reference benchmark (such configuration has been referred to as "NI", *i.e.* "non-integrated"). Accordingly, we assumed an electricity cost equal to 100 USD/MWh. However, we also performed a parallel estimation referring to the European peak electric price of 300 USD/MWh, as reported by Eurostat [11] for the last decade, to account even for scenarios with high energy prices.

Figure 2 shows the results for those two different electricity prices in the case of Profile A. The first couple of columns report the costs associated with the non-integrated configuration. In this context, when the instantaneous energy supply is insufficient to meet user requirements, any deficit is compensated by purchasing electricity from the grid. A similar trend can be observed when referring to Profile B. While Profile A leads to process configurations ranging between 118.1 kUSD/y and 707.7 kUSD/y (100 USD/MWh) and 200.2 kUSD/y and 795.6 kUSD/y (300 USD/MWh), Profile B leads to process configurations ranging between 125.1 kUSD/y and 543.5 kUSD/y (100 USD/MWh) and 262.3 kUSD/y and 695.2 kUSD/y (300 USD/MWh). Concerning Profile A, when referring to 100 USD/MWh, all the assessed energy storage technologies lead to higher costs than the non-integrated configuration (NI). However, when considering 300 USD/MWh, all the configurations except #4, #5, and #6 are cheaper than NI. Concerning Profile B, when referring to 100 USD/MWh, all the assessed energy storage technologies lead to higher costs than the non-integrated configuration (NI). However, when considering 300 USD/MWh, only the #8 and #11 configurations are cheaper than NI.

Therefore, the assessed case study does not show remarkable economic benefits from integrating energy storage systems into the process compared to external sourcing of electricity (*e.g.*, from the power grid) unless significant electric energy price increases.

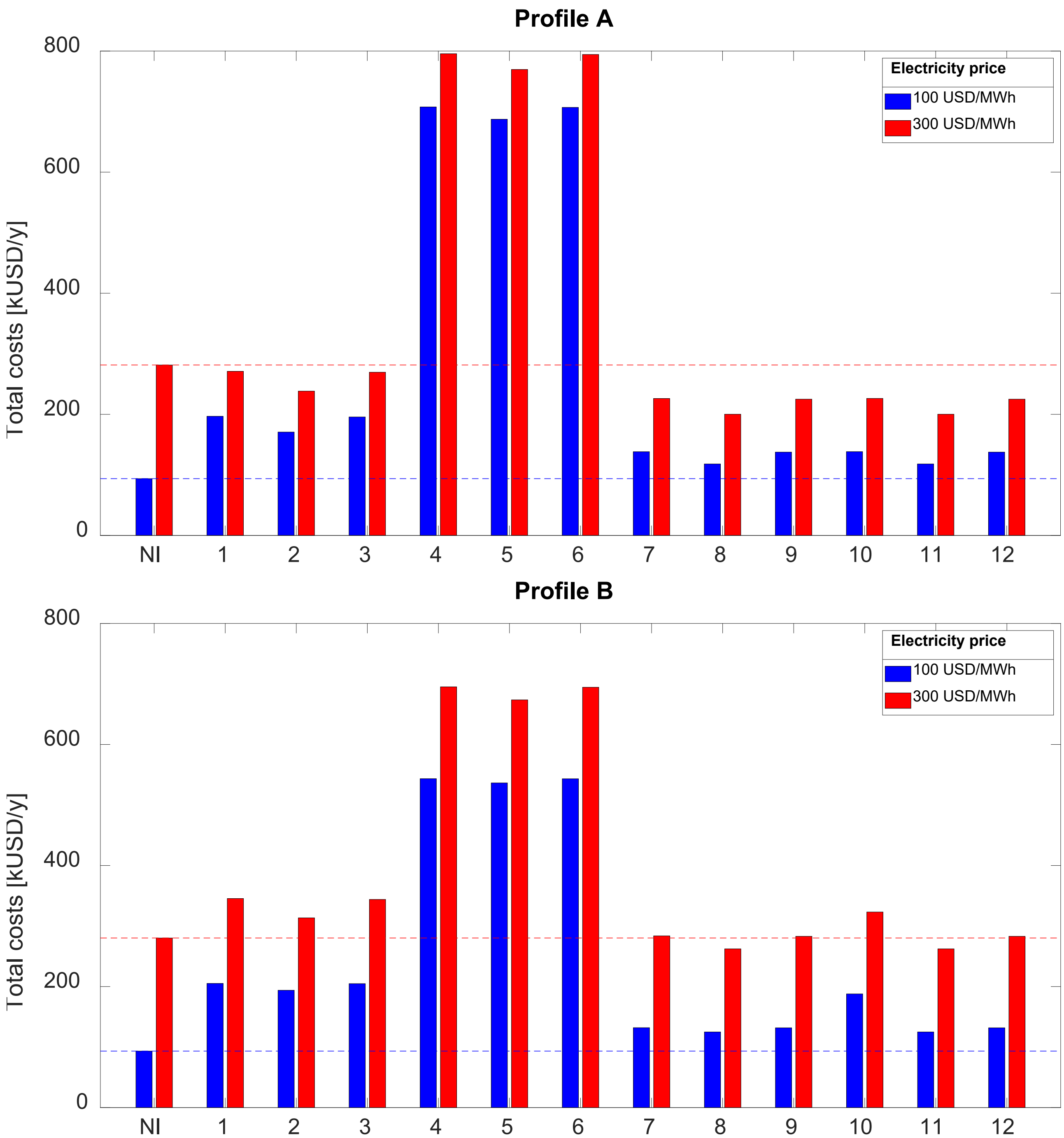

Figure 2: Annual total costs ($\Phi_{OBJ}^{(2)}$) by the 12 assessed configurations (see **Table 2**) compared to the non-integrated one (NI) when referring to Profile A (Panel A, top) or Profile B (Panel B, bottom).

CONCLUSIONS

This study highlights the critical role of energy storage in improving both economic and environmental outcomes in chemical plants. Process integration and energy storage systems allow for reducing carbon emissions and even operating costs when energy prices are particularly high. The results underscore that large-scale integration of renewable energy into chemical processes is only feasible through effective storage systems that consistently outperform external energy purchases during peak demand and production shortfalls. Also, higher economic benefits are expected due to the environmental benefits of process integration (*e.g.*, less dependence on external electricity and/or heat sourcing, which is typically carbon-intensive).

The presented optimization demonstrated the potential benefits of process-integrated energy storage solutions. While this work performed a sensitivity analysis of electricity prices, dynamic conceptual design techniques accounting for price variations over time may provide additional insights. Nevertheless, including energy storage consistently resulted in reduced external utility consumption when renewable energy sources were used.

An innovative aspect of this study lies in assessing energy conversion between two interconnected tanks whose sizes are to be optimized. Although promising, the feasibility of this method depends heavily on energy profiles and economic factors, as shown by the different results obtained with the two objective functions, two profiles, and two electricity prices. As such, industrial-scale implementation of energy conversion must be rigorously evaluated, accounting for several techno-economic assumptions.

Lastly, this work proves that coupling renewable energy inputs with energy storage systems allows for the operation of large-scale chemical processes according to the need for smooth variations in mass and energy flows by only calling for minor modifications to existing units. This approach aligns with process sustainability goals, especially the transition to greener industrial solutions.

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