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# Flexibility from Industrial Demand-Side Management in a Net-Zero Sector-Coupled Energy System

***Patricia Mayer[a], Mario Heer[a], David Yang Shu[a], Nik Zielonka[a], Ludger Leenders[a], Florian Baader[a], André Bardow[a]***

[a] *Energy Process Systems Engineering, ETH Zurich, Zurich, Switzerland, abardow@ethz.ch*

**Abstract:**
Energy systems require flexibility to help with the penetration of variable renewable energy. A promising solution for flexibility provision is demand-side management (DSM) from industry. However, the extent of flexibility from industrial DSM depends on the characteristics of industrial processes. In this work, we investigate the potential of industrial DSM as a flexibility provider to a net-zero sector-coupled energy system. Specifically, we investigate the cost reductions and the change in deployment of other flexibility options due to industrial DSM. We examine three system configurations for the Swiss sector-coupled energy system, varying the attractiveness of alternative flexibility options. To consider the characteristics of industrial processes, we parameterize the study with three representative industrial process characteristics: load-shifting potential, storage capacity, and losses. Our results show that the value of flexibility from industrial DSM highly depends not only on the process characteristics, but also on the system's flexibility alternatives, particularly for flexibility over longer time horizons. Due to differences in flexibility alternatives, the maximum cost reductions from industrial DSM vary between 2% and 27%. Additionally, we find that the effects of the three investigated characteristics on cost reductions also depend on the interactions with the alternative flexibility options. Depending on the interactions, cost reductions may stagnate as flexibility from industrial DSM is enhanced. Our study shows that while industrial DSM can serve as a flexibility provider to a net-zero sector-coupled energy system, the value of industrial DSM highly depends on both the characteristics of industrial processes and the system's alternative flexibility options. Both aspects must be considered when evaluating the extent of flexibility from industrial DSM.

**Keywords:**
Demand-Side Management, Flexibility, Sector-Coupling, Energy System, Net-Zero, Industry, Switzerland

## 1. Introduction

Countries are increasingly setting net-zero emissions targets to address climate change [1]. To meet these targets, fossil fuels must be replaced by renewable energy sources in all energy-consuming sectors [2], and direct air carbon capture and storage (DACCS) must be implemented to abate residual emissions. As energy-consuming sectors transition away from fossil fuels, electrification becomes increasingly important as the medium for integrating renewables into other sectors. For example, the heating sector can be electrified by heat pumps and the mobility sector can be electrified by battery electric vehicles [3]. The resulting reliance of all energy sectors on the electricity sector leads to sector-coupling, where the electricity sector becomes the central pillar for the overall energy system. However, most renewable energy is intermittent, such that flexibility is needed for systems with a high share of variable renewable energy. Flexibility refers to an energy system's ability to cope with the variability and unpredictability that variable renewable energy introduces in different time scales, while reliably supplying all the demanded energy to end users [4]. Shaner et al. [5] show that the need for flexibility increases rapidly after 80% variable renewable energy share.

Flexibility can be provided from the supply side through storage, imports, and fossil-based electricity with carbon capture and storage (CCS). However, each of these options has limitations: storage technologies, such as batteries, are expensive and not suitable for long duration energy storage due to their self-discharge characteristic. [6–8]. Power-to-hydrogen is a storage technology that is stable over long time horizons, but has a low round-trip efficiency [8, 9]. Pumped hydro storage, while efficient, is subject to high capital costs, topographic limitations, and environmental concerns regarding surrounding areas [10]. Electricity imports are subject to availability abroad. Fossil fuel imports are also subject to availability abroad. Additionally, the required CCS is not widely accepted and can thus be difficult to scale due to both social and physical constraints [11].

Due to the limitations of supply-side flexibility, demand-side management (DSM) serves as a promising alternative. Demand-side management refers to the shifting of energy consumption patters to obtain a desired

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energy consumption profile [12]. A good candidate for demand-side management is the industry sector due to its large energy demand, its potential for storing products over long time horizons, its already-existing metering infrastructure, and the avoidance of consumer behaviour change [13]. An example of industrial demand-side management is the shifting of production schedules to better-follow the availability of renewable electricity. For instance, an industrial process can over-produce during the daytime hours to take advantage of low prices caused by photovoltaic availability, store the overproduction, and under-produce during night-time hours such that the overall production stays the same. Promising example processes for industrial DSM are aluminum electrolysis, cement and raw mills, air separation, electric arc furnace and pulp production due to their high electricity demands and technical possibilities for load shifting [14].

The extent of flexibility from industrial DSM depends on several characteristics of industrial processes:

- **Load-shifting potential**: The percentage of the base industrial energetic demands that can be shifted to another time interval in response to volatility.
- **Storage capacity**: The amount of product that can be stored at a time.
- **DSM losses**: The losses associated with demand-side management, such as efficiency losses from off-design operation and product losses from storage.

These three characteristics influence the potential value from industrial DSM for the overall system. Promising industrial candidates can be identified by identifying promising combinations of these characteristics. Additionally, some of these characteristics can be influenced via financial incentives, e.g. the installation of larger storage capacities. Therefore, understanding the characteristics' effects on industrial DSM can help guide financial incentives.

Studies have shown how industrial DSM can affect the costs and environmental impacts for individual industrial sites [15–17]. Studies have also considered the contributions of industrial DSM from an overall system perspective [18, 19]. However, these studies have typically focused only on the electricity sector. For instance, Paulus et al. [18] analyzed the economic benefits of industrial DSM from energy-intensive industries to electricity markets. Papadaskalopoulos et al. [19] also studied the economic benefits of industrial DSM to the European power system by varying the load shifting potential. Thus far, to the best of our knowledge, no study has resolved the potential contributions of industrial DSM to a net-zero sector-coupled energy system.

In this study, we evaluate how varying degrees of industrial DSM affect the costs and the needs for other flexibility options of a net-zero energy system considering multiple sectors. Varying degrees of industrial DSM are modelled by varying the industrial process characteristics listed above. We aim to answer the following research questions:

1. What are the potential cost reductions of a net-zero sector-coupled energy system from industrial DSM?
2. How does industrial DSM interplay with other flexibility options?

To answer these research questions, we model the Swiss sector-coupled energy system using the linear optimization framework SecMOD [20]. We use a snapshot approach, constrain the system to net-zero emissions, and determine the system's cost-optimal investments and operation for varying degrees of industrial DSM. We do not consider costs associated with industrial DSM to determine an upper bound on the potential cost reductions. We consider three scenarios with varying assumptions regarding natural gas prices and use in power plants. By considering three scenarios, we can compare the contributions from industrial DSM across systems with varying flexibility alternatives. Of particular importance are the alternatives for long-duration flexibility, referring to durations longer than 12 hours. To represent industry, we create a generic, process-agnostic model comprised of the Swiss industry's electricity and heat requirements. This approach allows us to vary DSM characteristics without the need to model specific industries and processes. To model the varying degrees of industrial DSM, we perform a parameterized study by introducing parameters representative of industrial process characteristics. Our approach allows us to study the potential of industrial DSM as a flexibility provider to a net-zero sector-coupled energy system.

In Section 2., we briefly introduce the energy system model and discuss the modeling of industrial DSM in detail. Section 3., presents the results of the parameterized study. Finally, Section 4., summarizes the most important points of this study.

## 2. Modelling industrial DSM in Sector Coupled Energy Systems

As the focus of this study is industrial DSM, we only briefly summarize the Swiss energy system modelling in Section 2.1.. We describe the modelling of industry and the industrial DSM characteristics in more detail in Section 2.2.. Section 2.3. introduces the three scenarios.

## 2.1. Swiss Sector-coupled Energy system

The Swiss sector-coupled energy system is modelled with the open-source linear optimization framework SecMOD [20]. We consider the electricity, heat, and private mobility sectors within the energy system and focus on the year 2050 with an exogenous net-zero operational emissions constraint. Within the heat sector, we consider civil heating along with industrial heating at three temperature levels. Industry also has en electricity demand which we consider together with industrial heat demands (Section 2.2.). The optimization framework determines the cost-optimal investment and operation decisions to reach the net-zero emissions target, while ensuring that exogenous demands are met. Demands for civil electricity, civil heat, and private mobility are provided separately, while demands for industrial electricity and heat are provided in an aggregated fashion to represent Swiss industrial demands. Only operational emissions are considered for the net-zero target. The technology options included in the model of the sector-coupled energy system are shown in Table 1.

The energy system is modelled as a 1-node system. Hourly time series are provided and aggregated with a temporal resolution of 25 typical days. To allow for seasonal storage, the typical days are interlinked using the method developed by Kotzur et al. [21]. Note that Switzerland today has 8.8 TWh of seasonal storage from hydro reservoirs [22], comprising 14% of the overall electricity demand in 2019 [23].

**Table 1**: Technology options provided for modelling the Swiss sector-coupled energy system

| **Electricity** | **Civil heat** | **Transportation** |
|---|---|---|
| photovoltaics<br>onshore wind<br>natural gas combined cycle*<br>run-of-river<br>large dam hydro<br>geothermal<br>biogas | thermal insulation<br>electrode boiler<br>heat pump<br>natural gas boiler | battery electric vehicle |
| **Low-temperature heat** | **Medium-temperature heat** | **High-temperature heat** |
| electrode boiler<br>heat pump | electrode boiler<br>natural gas boiler | natural gas boiler |
| **Storage technologies** | **Negative emission technologies** | **Power-to-X** |
| Li-ion batteries<br>pumped hydro storage | direct air capture | power-to-methane |

* *CCS_lowprice* and *CCS_highprice* scenarios

## 2.2. Implementation of Industrial Demand-side Management

In this section, we explain how industry is modelled within the energy system and how the industrial DSM characteristics were represented by three parameters. The hourly electricity and heat demands of Swiss industry are aggregated into a generic industrial process. This aggregated process produces 1 "good/hour", while consuming the hourly industrial energy demands for Switzerland. We use an industrial electricity demand of 6 TWh [24] and a heat demand of 20 TWh [25] in 2050. The heat demand is split into three temperature levels (Table 2) according to a report from the Swiss Federal Office of Energy [24]. The demands in Table 2 represent the base industrial energy demands, $d^{base}_{energy}$, from which the benefits of industrial DSM are explored. Industrial production is assumed constant throughout the year, such that an exogenous demand of 1 good/hour, or $d^{base}_{goods}$, is introduced. Thus, without industrial DSM, the hourly electricity and heat demands of Swiss industry must be supplied for every hour of the year. This assumption introduces a basis from which to measure the benefits from industrial DSM. However, the benefits may be greater or smaller depending on how the actual industrial energy demand profiles follow renewables availability.

**Table 2**: Base energy demands of Swiss industry, $d^{base}_{energy}$, for the production of 1 $\frac{good}{hour}$, or $d^{base}_{goods}$

| Input/Output | Temperature Range | Value (MW) |
|---|---|---|
| electricity | – | 685 |
| low temperature heat | $< 200°C$ | 750 |
| medium temperature heat | $200°C - 800°C$ | 907 |
| high temperature heat | $> 800°C$ | 571 |

The contributions from industrial DSM are evaluated by performing a parameterized study on three parameters

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representative of the industrial process characteristics introduced in Section 1. An industrial goods storage tank is introduced to serve as a buffer for industrial over and under-production (Figure 1). No investment or operating costs are associated with storage capacity to evaluate an upper bound on cost reductions from industrial DSM. The calculated cost reductions can then be compared to the real costs associated with the necessary storage capacities. The three modelled parameters are described below:

- **Load-shifting potential** (*iflex*): The load-shifting potential, referred to as *iflex*, represents to the fraction of the base load, $d_{energy}^{base}$, that can be shifted up or down at a given time step, $t$, similar to [19]. *Iflex* can take any value between 0 and 1, as shown in Equation (1).

  $$0 \leq iflex \leq 1 \tag{1}$$

  An *iflex* value of 0 corresponds to no load-shifting potential and an *iflex* of 1 corresponds to the ability to shift 100% of the base load at a given time step, ranging from a complete shutdown to the doubling of base production.

- **Storage capacity** ($t_{SC}$): The storage capacity refers to the maximum amount of goods in the industrial storage tank, and limits the amount of goods can be stored at a time. We parameterize the storage capacity, $SC$, with the time interval $t_{SC}$ over which the base demand of $1 good/hour$, or $d_{goods}^{base}$, can accumulate (Equation (2)).

  $$SC = t_{SC} \cdot d_{goods}^{base} \qquad t_{SC} \in [12\ hours, 6\ months] \tag{2}$$

  For example, with a $t_{SC}$ of $1 day$ the storage capacity is constrained to a day's worth of industrial demand. We range $t_{SC}$ from 12 hours to 6 months in our parameterized study. Throughout this text, we refer to $t_{SC}$ as the storage capacity.

- **DSM losses** ($\eta$): DSM losses refer to production lost as a result of industrial DSM. Losses can arise from off-design operation as well as storage leakage. To study the effect of DSM losses, we introduce the discharge efficiency, $\eta$, that represents the amount of goods that can be withdrawn from the storage of industrial goods per goods stored. A lower efficiency means that less goods can be withdrawn per goods stored and therefore more goods need to be produced to meet the overall demand. The discharge efficiency, $\eta$, can take any value from 0 to 1 as shown in Equation (3).

  $$0 \leq \eta \leq 1 \tag{3}$$

  An $\eta$ value of 0 corresponds to 100% product losses and an $\eta$ value of 1 corresponding to no product losses. Note that while $\eta$ only represents discharge efficiency associated with storage in our mathematical formulation, the wide $\eta$ range investigated can be interpreted as also considering additional efficiency losses.

The relationship between the three parameters (*iflex*, $t_{SC}$, and $\eta$), the industrial production, and the storage can be seen schematically in Figure 1 as well as in Equations (4) to (8). Equation (4) constrains the production used at a given time step, $P(t)$, between the range defined by the *iflex* parameter.

$$d_{goods}^{base} \cdot (1 - iflex) \leq P(t) \leq d_{goods}^{base} \cdot (1 + iflex) \tag{4}$$

Equation (5) prevents the industry storage from acting as a source or sink for industrial products by setting the initial and final storage levels ($SL$) equal, similar to [15].

$$SL_{t=0} = SL_{t=T} \qquad T = 8760h \tag{5}$$

Equation (6) models the stored product. $in(t)$ refers to the product stored at time $t$ and $out(t)$ refers to the product withdrawn.

$$SL(t+1) = SL(t) + in(t) - \frac{out(t)}{\eta} \tag{6}$$

Equation (7) shows how the demand of industrial goods is met at every time step with a combination of production, $P(t)$, and storage.

$$d_{goods}^{base} = P(t) - in(t) + out(t) \quad (7)$$

Finally, Equation (8) constrains the storage level with respect to the parameterized storage capacity, $t_{SC}$.

$$SL(t) \leq t_{SC} \cdot d_{goods}^{base} \quad (8)$$

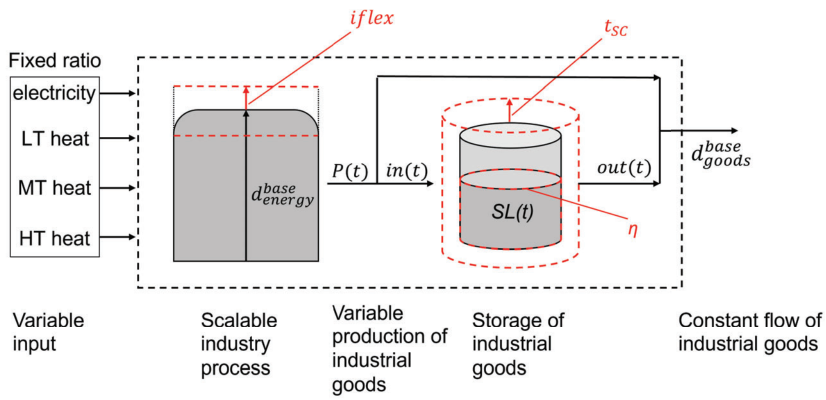


**Figure 1**: Schematic representation of the relationship between the industrial DSM parameters (*iflex*, $t_{SC}$, and $\eta$), industrial production, and storage of industrial goods. The three parameters are shown in red. *iflex* corresponds to load-shedding potential, $t_{SC}$ correspods to the time interval over which the base industrial demand of $1 good/hour$, or $d_{goods}^{base}$, can accumulate. $\eta$ corresponds to the storage discharge efficiency. LT, MT, and HT correspond to low, medium, and high temperature heat demands for Swiss industry. $P(t)$ is the production of industrial goods at time $t$. $in(t)$ and $out(t)$ are the product stored and withdrawn, respectively, and $SL(t)$ is the storage level.

### 2.3. Scenarios

Three scenarios represent different assumptions on natural gas prices and on the utilization of natural gas power plants as a flexibility option. The three scenarios, described below, allow us to compare the contributions from industrial DSM across systems with varying flexibility alternatives.

**CCS_lowprice**: This scenario includes the cheapest flexibility alternative to industrial DSM by allowing for electricity production from natural gas power plants with carbon capture and storage (CCS). It assumes a natural gas import price of 31€/MWh, representative of a stable historical average [26].

**CCS_highprice**: This scenario also allows for electricity production from natural gas power plants with carbon capture and storage (CCS) while assuming a high natural gas import price of 135 €/MWh, representative of the average for 2022 [26].

**minCCS**: This scenario includes the most expensive flexibility alternative to industrial DSM by only allowing for electricity production from renewable energy sources. This scenario represents an extreme case where both the use of CCS and fossil fuel imports are minimized. Natural gas can still be imported at a price of 31 €/MWh, but only for use in natural gas boilers for high and medium temperature heat. In this scenario, batteries become important as the flexibility alternative to industrial DSM.

## 3. Results and Discussion

The contributions from industrial DSM depend on both the industrial DSM characteristics, represented by the three parameters (*iflex*, $t_{SC}$, and $\eta$), and on the system characteristics, represented by the three scenarios. The most influential system characteristics are the alternative flexibility options, particularly over time horizons greater than 12 hours. Our results show that the system cost reductions from industrial DSM range from 1.7% to 27% due to the differing flexibility alternatives across scenarios. The flexibility alternatives also influence the relationships between the industrial DSM characteristics and the industrial DSM contributions.

In subsection 3.1. we discuss the effect of the load-shifting potential on the contributions from industrial DSM. In subsection 3.2., we discuss the effect of storage capacity, and in subsection 3.3. we discuss the effect of DSM


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losses. We place particular emphasis on how the contributions vary depending on the system's alternative flexibility options.

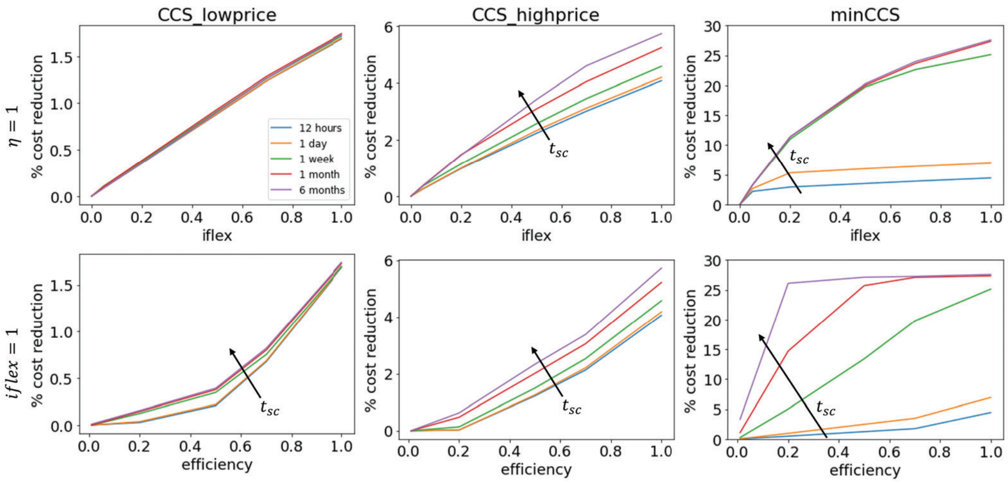


**Figure 2**: Top row: % cost reduction compared to a system with no industrial DSM as a function of load-shifting potential, *iflex*, for 100% discharge efficiency ($\eta$ = 1). Bottom row: % cost reduction compared to a system with no industrial DSM as a function of discharge efficiency, $\eta$, for 100% load-shifting potential (*iflex* = 1). The columns correspond to scenarios and the colors correspond to storage capacities, $t_{SC}$. Arrows point in the direction of increasing storage capacity. The ranges for % cost reduction vary across scenarios.

## 3.1. Load-shifting Potential

Load-shifting potential can decrease the overall system costs for all scenarios (Figure 2). However, the magnitude of the maximum cost reduction differs significantly depending on the scenario: for the *CCS_lowprice* scenario, the maximum cost reduction is 1.7% whereas for the *minCCS* scenario, the maximum cost reduction is 27%. This magnitude difference is mainly driven by the attractiveness of industrial DSM as a flexibility provider over longer time horizons, as shown by the jump in cost reduction for the *minCCS* scenario between 1 day and 1 week storage capacities (Figure 2, top row, third column).

Additionally, the relationship between cost reduction and load-shifting potential differs across scenarios: the *CCS_lowprice* and *CCS_highprice* scenarios show a more linear relationship between cost reduction and *iflex* whereas the *minCCS* scenario shows a non-linear relationship (Figure 2, top row). The relationships are driven by the effect of increasing load-shifting potential on the implementation of the alternative flexibility options as explained in detail in the subsections below.

### 3.1.1. CCS_lowprice

In the *CCS_lowprice* scenario without industrial DSM, electricity from natural gas is used to balance both the intraday and the seasonal fluctuations in renewables availability. To help with the seasonal imbalance of PV availability, which peaks in the summer, direct air capture (DAC) with carbon capture and storage (CCS) is deployed flexibly, maximizing its $CO_2$ capture in the summer following PV availability (Figure 3, Reference). Once DAC capacity is installed, it can be deployed flexibly throughout the year while incurring no additional costs for the flexible operation. DAC capacity thus serves as a seasonal flexibility alternative to industrial DSM.

As load-shifting potential is introduced (assuming $\eta$ = 1, $t_{SC}$ = 12 *hours*), the electricity from natural gas needed to balance the intraday fluctuations reduces substantially due to the shifting of industrial production to daytime hours. Maximum load-shifting potential (*iflex* = 1) and a storage capacity of 12 hours ($t_{SC}$ = 12 *hours*) reduces both natural gas imports and $CO_2$ stored by 19%. The cost reduction of 1.7% is mainly due to the decrease in natural gas imports. The imports decrease linearly for increasing load-shifting potential, driving the linear cost reduction observed in Figure 2.

Increasing storage capacity does not lead to significantly higher cost savings relative to the 1.7% observed for a 12 hour storage capacity. Increasing storage capacity leads to a flatter operation of DAC throughout the year (Figure 3, 6 months), decreasing DAC capital expenditures slighty. However, the decrease in capital expenditures is much smaller than the 1.7% cost reduction associated with intraday natural gas imports and therefore increasing storage capacity does not greatly enhance the cost savings from industrial DSM in the CCS_lowprice scenario (Figure 2 top row, first column).

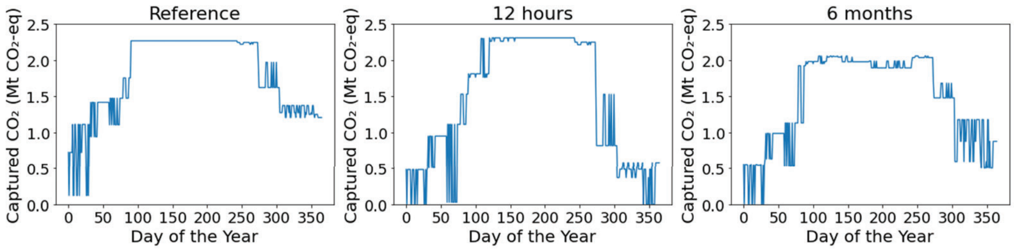


**Figure 3**: CCS_lowprice scenario: daily $CO_2$ captured across storage capacities. The Reference case corresponds to no industrial DSM. The 12 hour and 6 month storage capacity plots assume 100% load-shedding potential (*iflex* = 1) and 100% discharge efficiency ($\eta$ = 1).

### 3.1.2. CCS_highprice

In the *CCS_highprice* scenario without industrial DSM, batteries are used in the winter to balance renewables fluctuations over several days. Additionally, electricity from natural gas is needed in the winter to supplement the lower renewables availability (Figure 4, Reference). As load-shifting potential is introduced (assuming $\eta$ = 1, $t_{SC}$ = 12 *hours*), the system no longer needs batteries to balance fluctuations over several days, but rather only to balance intraday fluctuations. Additionally, less electricity from natural gas is needed in the winter, reducing natural gas imports by to 25% (Figure 4, 12 hours). The reduction in battery capacity and in natural gas imports are the main drivers for cost reductions as industrial DSM is introduced. Because of the decreased need for natural gas combustion for electricity, less direct air capture is needed in the summer, thus freeing up some renewable electricity to produce methane for industrial heating. This effect further reduces the need for natural gas imports. As storage capacity increases, the long-duration flexibility offered by industrial DSM further decreases the amount of natural gas imports needed for electricity production in winter (Figure 4, 6 months). Thus, the maximum cost reduction for full load-shifting potential results from the long-duration flexibility offered by industrial DSM, displacing batteries at smaller storage capacities and electricity from natural gas at larger storage capacities.

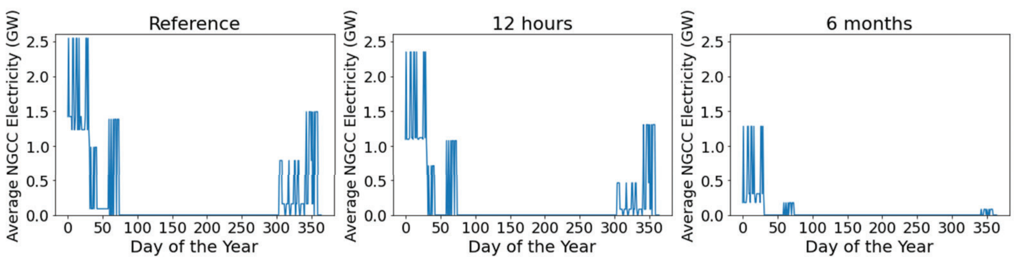


**Figure 4**: CCS_highprice scenario: average daily electricity production from natural gas combined cycle (NGCC) across storage capacities. The Reference case corresponds to no industrial DSM. The 12 hour and 6 month storage capacity plots assume 100% load-shedding potential (*iflex* = 1) and 100% discharge efficiency ($\eta$ = 1).

### 3.1.3. minCCS

In the *minCCS* scenario without industrial DSM, battery storage is needed over several months to balance the fluctuations in renewables availability (Figure 5, Reference). Investment in Li-Ion battery capacity comprises 41% of the total system costs and is the largest cost contributor. As load-shifting potential is introduced (assuming $\eta$ = 1, $t_{SC}$ = 12 *hours*), the required battery capacity decreases, reducing costs by 4.4%. However, the reduction in installed battery capacity stagnates at low load-shifting potential (*iflex* = 0.05) (Figure 2): small load-shifting potential is sufficient to shave off peak battery capacity. Thus, for smaller storage capacities, a small amount of load-shifting potential yields most of the benefits from industrial DSM. As storage capacity increases, the battery capacities decrease significantly due to the long-duration flexibility that industrial DSM provides: a 6 month storage capacity reduces the battery capacity required for inter-day storage by 59% relative


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to a 12 hour storage capacity (Figure 5, 6 months). The large reduction in battery capacity drives the highest cost reductions across all three scenarios of 27%. It must be noted that the *minCCS* scenario represents an extreme scenario with no imports of electricity or natural gas for electricity production. Thus, the magnitude of the cost reduction serves as an upper bound on reductions from industrial DSM.

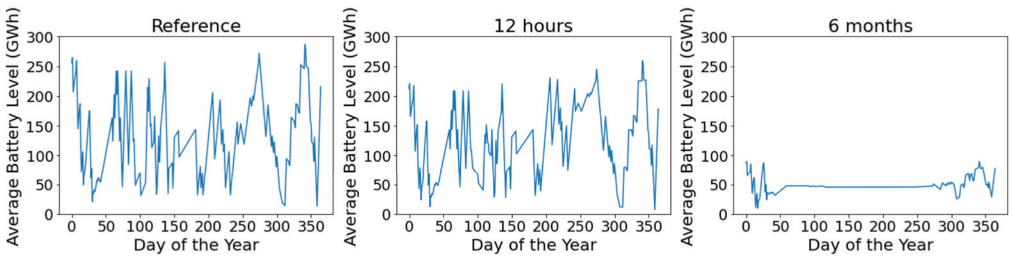


**Figure 5**: minCCS scenario: average daily battery storage level across storage capacities. The Reference case corresponds to no industrial DSM. The 12 hour and 6 month storage capacity plots assume 100% load-shedding potential (*iflex* = 1) and 100% discharge efficiency ($\eta$ = 1).

## 3.2. Storage Capacity

The effect of storage capacity on the contributions from industrial DSM differs for each scenario and depends on whether industrial DSM provides a beneficial alternative for flexibility over longer time horizons. Storage capacity exhibits a saturation, above which contributions from industrial DSM stagnate. The saturation capacity is qualitatively determined based on the results and explained in the subsequent paragraphs.

In the *CCS_lowprice* scenario, storage capacity has little impact on the cost reductions associated with industrial DSM, as explained in section 3.1.1. The saturation capacity for the *CCS_lowprice* scenario can thus be observed at 12 hours. In the *CCS_highprice* scenario, natural gas imports exhibit a step decrease at a storage capacity of 1 month, indicating the displacement by industrial DSM for long-duration flexibility. The saturation capacity for the *CCS_highprice* scenario can thus be observed at 1 month. In the *minCCS* scenario, the installed battery capacity exhibits a step decrease at a storage capacity of 1 week. This phenomenon explains the jump in % cost reduction between 1 day and 1 week for the *minCCS* scenario shown in Figure 2. Storage capacities larger than 1 week do not lead to significant additional cost reductions for a system with 100% discharge efficiency. At lower discharge efficiencies, however, the effect of storage capacity can be more significant, as explained in section 3.3. and shown in Figure 2 (bottom row, third column).

All scenarios exhibit a maximum useful storage capacity determined by the duration, $t_{SC}$, at which industrial DSM displaces the long-duration flexibility alternatives. If industrial DSM contributes no long-duration flexibility benefits relative to the flexibility alternatives, then small storage capacities are sufficient to obtain the maximum cost reductions from industrial DSM.

## 3.3. DSM Losses

For all scenarios, efficiencies must be above a certain threshold to obtain benefits from industrial DSM. However, the threshold efficiency varies depending on the scenario, and can also be affected by the storage capacity. For the sake of comparison, we focus the following discussion on an *iflex* value of 1 and define a threshold efficiency as the efficiency at which 20% of the maximum cost reductions are reached (Figure 6, red lines).

In the *CCS_lowprice* and *CCS_highprice* scenarios, the threshold efficiency decreases by approximately 10% from a 12 hour to a 6 month storage capacity. However the threshold efficiencies differ. The *CCS_lowprice* scenario exhibits threshold efficiencies between 45% and 55% whereas the *CCS_highprice* scenario exhibits threshold efficiencies between 30% and 40%. In the worst case across both scenarios, corresponding to the *CCS_lowprice* scenario with a 12 hour storage capacity, cost reductions up to 20% can still be obtained with discharge efficiencies below 55%.

In the *minCCS* scenario, storage capacity has a more significant effect on the threshold efficiency (Figure 2, bottom row, third column). The threshold efficiency decreases from 37% to 3% from a 12 hour to a 6 month storage capacity (Figure 6, row 3). In the case of a 6 month storage capacity and low efficiencies around 3%, the system shifts its use of renewable electricity in the summer from synthetic methane production to additional industrial production. The system overproduces industrial goods throughout the summer, requiring large storage capacities. As a result of reducing synthetic methane production, more natural gas for heat production is imported. However, importing additional natural gas is significantly cheaper than the battery capacities needed without industrial DSM, and thus large cost reductions are seen even at low efficiencies when storage capacities enabling seasonal storage are available. For smaller storage capacities, the significant overproduction during the summer is not possible and thus higher efficiencies are needed to yield comparable cost reductions to the 6 month storage capacity.

Our results show that industrial DSM can reduce costs even for efficiencies as low as 3%, depending on the costs of the system's flexibility alternatives. Therefore, even processes with high storage losses or low part-load efficiencies could reduce system costs through industrial DSM.

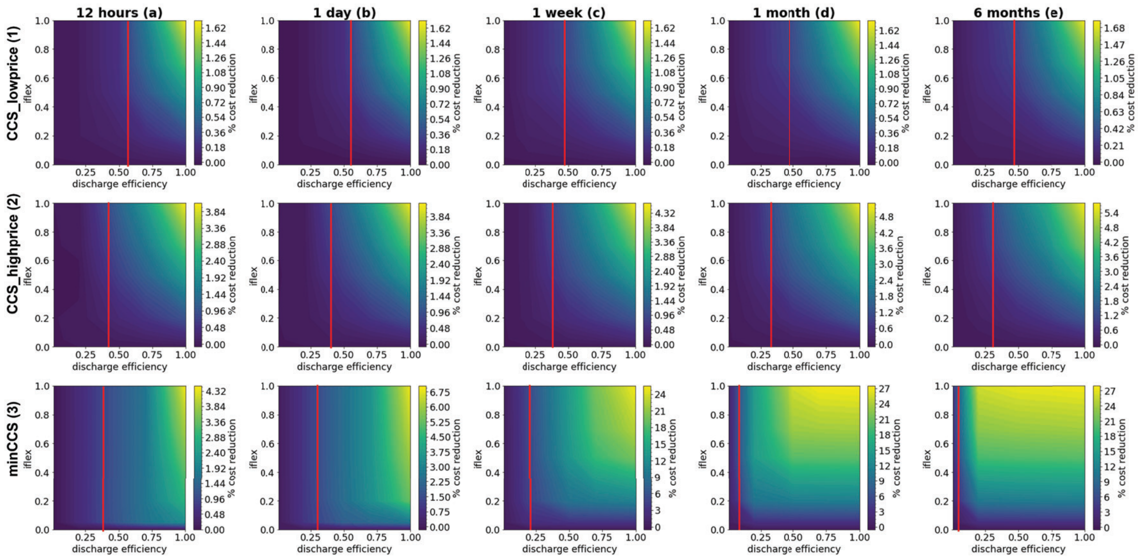


**Figure 6**: % cost reduction for the net-zero sector-coupled system for different values of iflex and discharge efficiency, $\eta$, vs. the reference case of zero iflex and $\eta$. Rows correspond to scenarios (numbers) and columns correspond to the storage capacity in terms of the storage capacity time interval, $t_{SC}$, over which the demand for goods, $d^{base}_{goods}$, is accumulated (lower case letters). Red lines indicate the efficiency corresponding to 20% of the maximum cost reduction, when considering *iflex* = 1.

## 4. Conclusions

In this study, we investigate the potential of industrial DSM as a flexibility provider to a net-zero sector-coupled energy system. Specifically, we investigate cost reductions and the change in deployment of other flexibility options due to industrial DSM. We focus on the Swiss sector-coupled energy system comprised of the electricity, heating, and private transportation sectors. To study the effects of industrial DSM, we carry out a parameterized study with three parameters representative of industrial DSM characteristics: load-shifting potential, storage capacity, and DSM losses. We consider three scenarios ranging from cheapest alternative flexibility to industrial DSM to most expensive.

We find that industrial DSM reduces costs for all three scenarios. However, the magnitude of the cost reduction depends on the system's alternative flexibility options, particularly for flexibility over time horizons longer than 12 hours. Thus, the value of industrial DSM must be evaluated within the context of the overall energy system. In a system with inexpensive natural gas imports and the ability to produce electricity from cheap natural gas with CCS (*CCS_lowprice* scenario), industrial DSM reduces costs by up to 1.7%. In a system with electricity only from renewable energy sources (*minCCS* scenario), the maximum cost savings from industrial DSM are 27%. The difference arises because in the *CCS_lowprice* scenario, direct air capture serves as an inexpensive alternative long-duration flexibility option whereas in the *minCCS* scenario, batteries serve as an expensive long-duration flexibility option. Therefore, potential cost reductions from industrial DSM for the *minCCS* scenario are much higher.

We also find that while cost reductions from industrial DSM depend on the industrial DSM characteristics, the influence of the characteristics on cost reductions depends on the interactions with the system's alternative flexibility options. For example, increasing load-shifting potential can have either a linear or a non-linear effect on cost reductions depending on the resulting deployment of the alternative flexibility options. Depending on

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the relationship, small load-shifting potential may be sufficient to yield large cost reductions for the system. Storage capacity reaches a saturation capacity, above which contributions from industrial DSM stagnate. The saturation capacity depends on the long-duration flexibility benefits that industrial DSM provides. If industrial DSM provides little to no long-duration flexibility benefits, such as in the *CCS_lowprice* scenario, smaller storage capacities are sufficient to obtain most cost reductions from industrial DSM. Otherwise, contributions stagnate beyond the capacity at which industrial DSM displaces the alternative long-duration flexibility options. Regarding DSM losses, industrial DSM can reduce system costs despite high DSM losses depending on the costs of the alternative long-duration flexibility options. The *minCCS* scenario exhibits 20% of the maximum cost reductions from industrial DSM with only 3% efficiency due to the high costs of Li-ion batteries.

Based on our study, we conclude that while industrial DSM can serve as a flexibility provider to a net-zero sector-coupled energy system, the magnitude of the contributions highly depends on the flexibility alternatives for the system. Particularly, industrial DSM is most beneficial when industrial products can be stored seasonally and long-duration flexibility options are missing or expensive. Therefore, both the characteristics of industrial processes and the system's characteristics must be considered when evaluating flexibility provision from industrial DSM.

In this work, we aggregate all Swiss industry energy demands and assume that the energy demands can be shifted all together. As our results show potential, future research should focus on obtaining a more precise estimate of the potential flexibility provision from industrial DSM in Switzerland. We suggest differentiating between industries and introducing industry-specific, time-dependent energy demand profiles. The ranges of the considered industrial DSM parameters can also be adapted to better-fit the operation of the specific industries. Additionally, we suggest comparing the resulting system cost reductions from industrial DSM to the costs that industries would incur to implement DSM measures, such as investments in over-capacities and storage containers. This comparison would allow for a better estimate of the cost benefits from industrial DSM to the Swiss energy system.

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## References

[1] United Nations. *For a livable climate: Net-zero commitments must be backed by credible action* Available at: https://www.un.org/en/climatechange/net-zero-coalition [accessed 12.1.2023].

[2] Ramsebner J., Haas R., Ajanovic A., Wietschel M. *The sector coupling concept: A critical review*. WIREs Energy Environ. 2021;10(4):e396.

[3] Baumgärtner N., Deutz S., Reinert C., Nolzen N., Kuepper L.E., Hennen M., Hollermann D.E., Bardow A. *Life-Cycle Assessment of Sector-Coupled National Energy Systems: Environmental Impacts of Electricity, Heat, and Transportation in Germany Till 2050*. Front. Energy Res. 2021;9:621502.

[4] IRENA. *Power System Flexibility of the Energy Transition.* 2018, Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Nov/IRENA_Power_system_flexibility_1_2018.pdf [accessed 08.05.2023].

[5] Shaner M.R., Davis S.J., Lewis N.S., Caldeira, K. *Geophysical constraints on the reliability of solar and wind power in the United States*. Energy Environ. Sci. 2018;11(4):914–925.

[6] Sepulveda N.A., Jenkins J.D., Edington A., Mallapragada D.S., Lester R.K. *The design space for long-duration energy storage in decarbonized power systems*. Nat Energy. 2021;6(5):506–516.

[7] Albertus P., Manser J.S., Litzelman S. *Long-Duration Electricity Storage Applications, Economics, and Technologies*. Joule. 2020;4(1):21–32.

[8] Gabrielli P., Poluzzi A., Kramer G.J., Spiers C., Mazzotti M., Gazzani M. *Seasonal energy storage for zero-emissions multi-energy systems via underground hydrogen storage.* Renewable and Sustainable Energy Reviews. 2020;121:109629.

[9] Pellow M.A., Emmott C.J.M., Barnhart C.J., Benson, S.M. *Hydrogen or batteries for grid storage? A net energy analysis*. Energy Environ. Sci. 2015;8(7):1938–1952.

[10] Koohi-Fayegh S., Rosen M. A. *A review of energy storage types, applications and recent developments*. Journal of Energy Storage. 2020;27:101047.

[11] Budinis S., Krevor S., MacDowell N., Brandon N., Hawkes A. *An assessment of CCS costs, barriers and potential*. Energy Strategy Reviews 2018;22:61–81.

[12] Meyabadi A. F., Deihimi, M. H. *A review of demand-side management: Reconsidering theoretical framework*. Renewable and Sustainable Energy Reviews. 2017;80:367–379.

[13] Zhang Q., Grossmann I.E. *Enterprise-wide optimization for industrial demand side management: Fundamentals, advances, and perspectives*. Chemical Engineering Research and Design. 2016;116:114–131.

[14] Arnold K., Janssen T. *Demand side management in industry: necessary for a sustainable energy system or a backward step in terms of improving efficiency?*. Europ. Council for an Energy Efficient Economy. 2018.

[15] Schäfer P., Daun T.M., Mitsos A. *Do investments in flexibility enhance sustainability? A simulative study considering the German electricity sector*. AIChE J. 2020;66(11).

[16] Torabi R., Gomes A., Lobo D., Morgado-Dias F. *Modelling demand flexibility and energy storage to support increased penetration of renewable energy resources on Porto Santo*. Greenhouse Gas Sci Technol. 2020;10 (6):1118–1132.

[17] Klaucke F., Karsten T., Holtrup F., Esche E., Morosuk T., Tsatsaronis G., Repke J. *Demand Response Potenziale in der chemischen Industrie*. Chemie Ingenieur Technik. 2017;89 (9):1133–1141.

[18] Paulus M., Borggrefe F. *The potential of demand-side management in energy-intensive industries for electricity markets in Germany*. Applied Energy. 2011;88(2):432–441.

[19] Papadaskalopoulos D., Moreira R., Strbac G., Pudjianto D., Djapic P., Teng F., Papapetrou M. *Quantifying the Potential Economic Benefits of Flexible Industrial Demand in the European Power System*. IEEE Trans. Ind. Inf. 2018;14(11):5123–5132.

[20] Reinert C., Schellhas L., Mannhardt J., Shu D.Y., Kämper A., Baumgärtner N. et al. *SecMOD: An Open-Source Modular Framework Combining Multi-Sector System Optimization and Life-Cycle Assessment*. Front. Energy Res. 2022;10:Article 884525.

[21] Kotzur L., Markewitz P., Robinius M., Stolten D. *Time series aggregation for energy system design: Modeling seasonal storage*. Applied Energy. 2018;213:123–135.

[22] Swiss Federal Office of Energy (SFOE). *Schweizerische Elektrizitätsstatistik 2019*. 2020, Available at: https://www.bfe.admin.ch/bfe/de/home/versorgung/statistik-und-geodaten/energiestatistiken/elektrizitaetsstatistik.html [accessed 12.1.2023].

[23] Swissgrid AG. *Energy Statistic Switzerland 2019*. 2020, Available at: https://www.swissgrid.ch/en/home/operation/grid-data/generation.html [accessed 12.1.2023].

[24] Swiss Federal Office of Energy (SFOE), Prognos AG, TEP Energy GmbH, INFRAS AG. *Analyse des schweizerischen Energieverbrauchs 2000-2019 nach Verwendungszwecken*. 2020, Available at: https://www.bfe.admin.ch/bfe/en/home/supply/statistics-and-geodata/energy-statistics/analysis-of-energy-consumption-by-specific-use.html [accessed 12.1.2023].

[25] Marcucci A., Guidati G., Giardini D. *Swiss Energy Scope - ETH - Swiss Energy Scope with hourly resolution.*,tech. rep., ETH Zürich, Joint Activity Scenarios and Modelling (JASM), 2021, Available at:https://sccer-jasm.ch/JASMpapers/JASM_SES_ETH_documentation.pdf [accessed 12.1.2023].

[26] Trading Economics. *EU Natural Gas* Available at: https://tradingeconomics.com/commodity/eu-natural-gas [accessed 12.1.2023].

 https://doi.org/10.52202/069564-0225