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Energy system modelling for studying flexibility on industrial sites

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ABSTRACT

With an increasing share of non-dispatchable renewable energy sources in the European grid, energy flexibility will be key for the industrial sector to support the green transition. The EU-project Flex4Fact aims at finding solutions for energy and process flexibility for industry, using SINTEF's open-source energy system model EnergyModelsX to quantify the potential benefits. This work presents some extensions done in EnergyModelsX, denoted as EnergyModelsFlex, to accommodate energy and industrial flexibility, adding new functionalities to assist with industrial flexibility potential. The extended EnergyModelsX model is described and demonstrated through two case studies in the plastic and polymeric products manufacturing sector to evaluate their potential for increasing renewable generation and flexibility. The first use case, being energy intensive, consumes both natural gas and electricity. This site enables the use of heat recovery and utilization, hydrogen blending, on-site hydrogen production, which can reduce CO2 emissions. The second use case relies solely on electricity consumption, and the considered flexibility is energy shifting by electric batteries and production flexibility. The focus of this case study is on the interplay between energy storage, on-site energy production and process flexibility to increase the degree of self-produced renewable energy in the energy mix. Together, the two case studies demonstrate how the extended EnergyModelsX framework can be used to explore process and energy flexibility in the industry to aid the transition from a fossil-based society to a renewable based society.

Keywords: Industrial demand-side flexibility, Energy transition

INTRODUCTION

To meet the ambitious net zero target of the EU by 2050, it is a top priority to transition from fossil fuels to renewable sources [1]. However, unlike traditional fossil fuel power plants, which can adjust output to match demand, non-dispatchable renewable sources like solar and wind are subject to natural variability and cannot be controlled to meet immediate demands. This is a challenge in the industrial sector where consistent and predictable energy usage is crucial. The EU project Flex4Fact aims to develop solutions to leverage energy and process flexibility in industry to meet a future with high renewable energy penetration [2].

A part of this project seeks to identify optimal investment strategies for enhancing energy flexibility, i.e. the capability of an industry to adapt to variable energy production. The investment strategies arise from energy system modelling, where the key is to understand how different technologies, such as solar power and electric batteries (BESS), complement the industrial site and potential process flexibility. To enable these assessments, SINTEF's open-source energy system model, EnergyModelsX (EMX) [3] has been used and further developed to specifically address flexibility requirements at industrial sites. The considered flexible aspects modelled through Flex4Fact include process flexibility modelled as energy load shifting, allowing multiple energy carriers to cover the demand of single processes, and energy storage technologies. Synergies between these mentioned flexibilities and integrated on-site renewable expansions are focused upon within this work. Sensitivity analyses are conducted to assess the robustness of the investment strategies towards changes in market prices or scaled production, to capture optimal use of flexibility and investment decisions to the energy system.

This work is structured as follows. We first describe EMX alongside the new flexible functionalities towards industrial flexibility, then present two use cases that is related to the Flex4Fact projects alongside their implementations. Finally, we demonstrate the results regarding the new functionalities on the use cases.

ENERGY SYSTEM MODELLING

There exist multiple other toolboxes that represent the energy system, but some are more focused on large scale energy systems with details on regional constraints like TIMES [4]. As described in [3], an advantage with EMX compared to other models for the representation and optimization of energy systems at specific sites, such as SpineOpt [5], GenX [6], and the Tulipa Energy Model [7], is the modular structure - by splitting the full model framework into separate, installable packages - with the high focus on extensibility and alternative technology formulations.

EnergyModelsX

EnergyModelsX (EMX) is an open-source energy system modelling toolbox developed by SINTEF [3]. The toolbox is written in the Julia programming language using the JuMP modelling framework, enabling a fast and modular framework for multiple dispatch models. Emphasis is made on giving modelers a high level of flexibility. Detailed description of the model and its use can be found in [8]. The following will give an overview of the features of EMX relevant for the assessments performed in the presented work.

EMX mirrors real energy systems through generic representations of different technologies. These representations are defined in EnergyModelsBase, and include sink, source, generation and storage technologies, and links between the different technologies. Generic representations can be assigned features specific to the energy system in question such that specifications of that energy system are captured. A source can for instance be assigned emission features to mimic a natural gas source. The technologies are referred to as nodes. Three different fundamental nodes exist; source, sink and network nodes. Interactions between nodes are defined by creating links between them. Source and sink nodes can only give or receive input from the surroundings (i.e. is only linked one way) while network nodes can have two-way interactions.

While links between any nodes can be defined, modelling ease and flexibility are best achieved by defining an Availability node. The Availability node does not have any features assigned to itself but acts as a collector of all links as illustrated as the "av"-node in Figure 1. That way, new nodes can be defined in the framework without changing all the links between the existing nodes.

The modularity of the EMX framework is achieved by Julia's multiple dispatch functionality when extending the EnergyModelsBase package. Several such extensions have been implemented to ease geographical representation (EnergyModelsGeography) and investments (EnergyModelsInvestments). In the Flex4Fact project a graphical user interface has also been developed for EMX (EnergyModelsGUI). A series of technology specific extensions has also been developed (e.g., for non-dispatchable renewable energy sources like PV power, CO2, Hydrogen and Heat).

Building upon such extensions this work has resulted in a unified extension called EnergyModelsFlex which will be described in the following.

EnergyModelsFlex

The EnergyModelsFlex extension provides a series of technology node types for EMX enabling energy and process flexibility modeling. The following nodes are described for the present work.

StorageEfficiency

The StorageEfficiency node enables storage efficiency control compared to RefStorage. It's storage resource can be any EMX Resource, and can be used for both the battery technology and the hydrogen storage technology. As for the RefStorage node, investment can be made in both charge/discharge (i.e. the inverter for batteries) and the storage level. Moreover, its generic storage behavior is also inherited from the Base-package but only CyclicStrategic has been considered in the present study. That is, the storage requires cyclic behavior within a strategic period.

ChargeRateCapacity

The ChargeRateCapacity node is a further development of the StorageEfficiency node where a coupling between the charge rate and capacity has been added. The ChargeRateCapacity node thus mimics a BESS where the charge rate can be limited by the capacity of the battery and ensures that completely decoupled investments into charge rate and battery capacity are avoided. While the node was developed to mimic an electric battery, other types of energy storage, such as thermal storage, is also a enabled.

PayAsProducedPPA

The PayAsProducedPPA node considers pay-as-produced power purchase agreement (PPA) from off-site solar PV. This non-dispatchable renewable energy source is similar to the node AbstractNonDisRES from the EnergyModelsRenewableProducers extension, but need to dispatch on this type in order to modify the OPEX constrain to extend to all power produced (including curtailed production).

LimitedFlexibleInput

The LimitedFlexibleInput node dispatches on the NetworkNode but modifies the flow in constraints by setting upper limits of the input resources. This is needed when hydrogen is to partly replace natural gas but is limited. An upper limit of 20% hydrogen volume (corresponding to a 7.01 % energy fraction) in the H2-NG gas mix is often used as it would not require major alteration in the machinery.

LoadShifting

The LoadShifting node dispatches on the Sink node where the demand can be altered by load shifting, i.e. the transfer of a predefined quantity of energy (power and duration) from one time to another. This quantity of energy is given as an input to the node, together with the allowed time slots from and to where the load shifting can occur. The load shifting thereby represents a flexible energy demand, but the flexibility is based on (external) constraints rather than a cost benefit or penalty, meaning that the flexibility cannot be optimized from a cost perspective.

DESCRIPTION OF THE USE CASES

In the Flex4Fact project, a total of five case studies are investigated. We here focus on two that covers much of the goal of investigating both energy and process flexibility. The two use cases are briefly described in the following.

SPS

Standard Profil Spain (SPS) is a Spanish company specializing in automotive sealing systems for major OEMs (Ford, GM, Renault, etc.). To reduce their carbon footprint, the factory considers onsite renewable energy for hydrogen production via electrolyzers and electricity demands, while gradually replacing natural gas in furnaces with green hydrogen. Hydrogen, process flexibility and BESS storage are also under consideration to maximize energy self-consumption.

Figure 1 illustrates SPS's existing energy system along with potential extensions through investments, as represented in our EMX model implementation. Investment options are marked with dashed lines, and the red text indicates the investments being carried out in the optimization. Energy flows between nodes have a unique colors per energy carrier. The representation of the energy system is based on information provided by SPS to the project and has also been discussed with SPS.

We consider four energy sources: electricity grid, representing electricity purchase under the current contract, PPA, which is an alternative contract for electricity supplied through the grid and produced by PV, on-site PV generation, and natural gas. Four consumption sinks are considered: machinery gas consumption, electricity-specific needs, space heating, and waste heat. Additionally, the model implicitly accounts for curtailed PV and for CO_2 emissions.

The energy sources and energy sinks are connected through three node types: energy conversion, energy storage, and energy distribution. However, most of the connections shown in Figure 1 are logical links rather than representing a specific physical distribution system.

The energy conversion nodes are the existing gas oven for space heating, electrolyzers, and heat recovery that convert waste heat into usable space heating. Two heat recovery options are considered: From gas usage in the machinery of the facility, and from the hydrogen production in the electrolyzer. The model also includes two types of energy storage investments: batteries and hydrogen storage. One physical distribution investment is represented: The transport of recycled heat to the space heating site. Finally, there is a conversion node representing the mixing of natural gas and hydrogen to create the energy carrier "gas", which is a blend of natural gas and hydrogen with non-fixed proportions - but with a 20% hydrogen volume cap in the gas mix. For this case study, the dimensioning of each investment option, i.e. MW invested, is a continuous variable with an upper constraint.

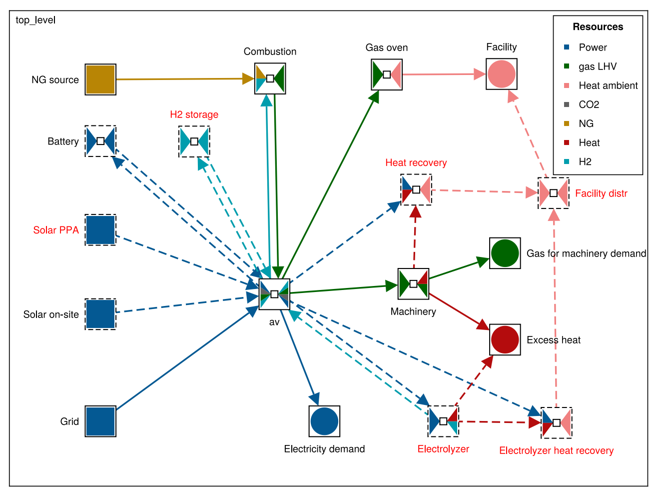

Figure 1. Graphical representation of the SPS energy system (current and all investments included) in EMX.

The operation of the energy system is optimized on an hourly basis across the entire year, 8760 sequential hours in total. That annual simulation is conducted for five strategic periods: 2024, 2025 - 2026, 2027 – 2030, 2031 – 2040, and 2041 – 2050. Investments carried out for a strategic period are assumed to be in operation from the start of that strategic period.

SEAC

SEAC is an Italian producer of diving equipment. The production processes are based on molding, and run solely on electricity, which is therefore the only energy form considered in the energy system analyses. Electricity can be delivered from the power grid or on-site PV panels. The energy demand is divided into process consumption (“Production”) and building and factory heating, cooling and lighting (“Base load”) as illustrated in Figure 2. In the base case, the Production node is a regular sink. Load shifting-type energy flexibility is enabled by changing the Production node to LoadShifting. Load shifting is constrained to two times per week, with a duration of 8 hours and magnitude of 15 kW. Investment options (PV and BESS) are illustrated with dashed lines in Figure 2. The ChargeRateCapacity node is used to represent the BESS, ensuring that a round-trip efficiency of 0.98 is implemented, and that investments into charge rate follows the investment in charge capacity.

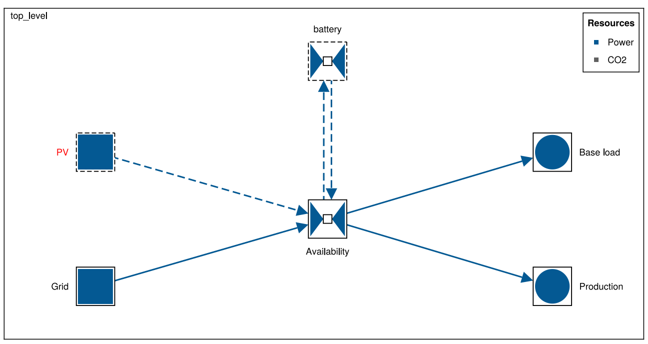

Figure 2. Graphical representation of the SEAC energy system (current and all investments included) in EMX.

The operation of the energy system is optimized on an hourly basis across the entire year, 8760 sequential hours in total. That annual simulation is conducted for seven strategic periods: one for each year in the timespan 2024-2030. The CAPEX of the PV and BESS technologies decrease linearly from 1000 €/kWp to 870 €/kWp, and 400 €/kWh to 200 €/kWh, respectively, in the time span 2024 to 2030 [9], [10].

Herein, the SEAC use case illustrates the utilization of load shifting within the EMX framework as a means to enhance renewable energy utilization in industry. Hence the presented results focus on and discuss the load shifting. Other aspects related to the energy system of SEAC, such as which, when and why investments are profitable, will not be discussed although they could be of interest in a different context.

RESULTS

The following highlights the results from the two use cases that illustrate the features added to the EMX framework throughout the present work. Hence, results related to the energy system of the use cases, but not specifically the added features, are not discussed herein.

SPS

For SPS the optimal investments are presented in Table 1. The investment in hydrogen is only profitable in the last two periods, where CO_2-prices increases significantly (which is not expected to happen before 2030).

Table 1: Optimal investments in the base case for SPS.

Period	Type	Amount
2024		
2025 - 2026	PPA contract, solar*	4778 kWp
2027 - 2030		
2031 - 2040	On-site PV generation	418 kWp
	Electrolyzer	3 kW
	Hydrogen storage	49 kWh
2041 - 2050	Electrolyzer	520 kW
	Hydrogen storage	9790 kWh

*) Upper constraint for invested amount is binding

For the current analysis we consider a pay-as-produced PPA at 50€/MWh, which is well below the price in the current electricity contract for use of grid electricity. The maximum permitted investment is therefore selected from the start (no investments allowed in 2024). Since this contract is pay-as-produced, and the model does not include a sell back to market option, there is curtailment at the weekends when there is no production in SPS’s facility. This can be seen in Figure 3 where 168 hours of data have been extracted from the strategic period of 2025-2026. This thus makes “free” electricity available, but this is not enough to make hydrogen production profitable in that period.

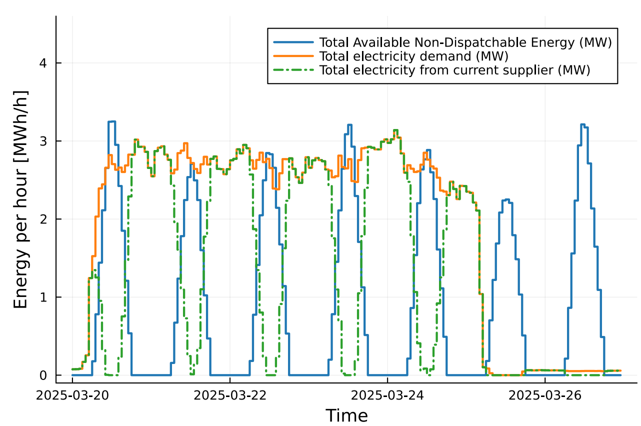

Figure 3. Example hours, showing PPA and electricity consumption. The difference is curtailment when PPA is highest and import through grid when electricity consumption is highest.

One of the goals of SPS is to cut CO_2 emissions, but with a hard limit of 20% volume of hydrogen in the H2-NG gas mix there is quite limited reduction potential even when the CO_2-prices reaches 500€/tCO_2eq [11] in the strategic period 2041-2050. This can be illustrated in Figure 3 where the 7.01% energy limit of hydrogen (corresponding to the 20 % volumetric share) is reach with "inf" CO_2 prices. The further reduction of CO_2 to 11.79% in total is due to investments in excess heat utilization (resulting in lower gas consumption).

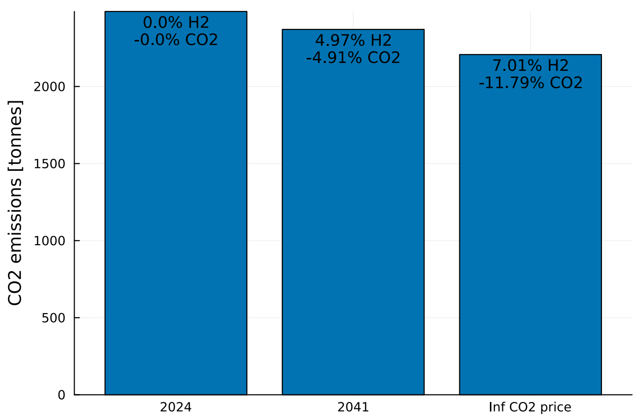

Figure 4. Total CO_2 emissions annually for the current system (2024), the final period of our analysis (2041-50), and for a case where the CO_2 cost is set very high. The share of hydrogen in total gas consumption (natural gas plus hydrogen) and the CO_2 reduction relative to the 2024 case is printed on each bar.

SEAC

In the SEAC use case, energy flexibility modelled through the LoadShifting node is in focus. Figure 5 illustrates the implementation of load shifting, where a quantity of energy ("Energy shifted" in green), corresponding to a production batch in SEAC, may be shifted from of time of the day to another, or even to another day. In the this case, two load shifts are allowed within a working week, and only within the working hours. The figure illustrates that batches are shifted from the afternoon to the morning or midday. This corresponds relatively well with the availability of renewable energy from the PV panels as well as the price of electricity from the power grid.

Table 2 compares the load shifting to product-based rescheduling performed by SEAC. Contrary to the energy-based load shifting, the production-based rescheduling of SEAC accounts for costs, such as man hours, associated with rescheduling of production, and optimizes the production of unique products. One advantage with the production-based rescheduling compared to the load shifting is that production schedules are developed, giving additional information on the operation of the facility. However, complexity increases since detailed information on each product's energy demand and production time is necessary, along with personnel requirements, work hours and salaries. Insignificant differences between the rescheduling and the load shifting in the overall facility performance are found. We notice, however, that the load shifting is sensitive to the input, and that the energy of producing the batch must be predefined. Extensive preprocessing of data may therefore be necessary.

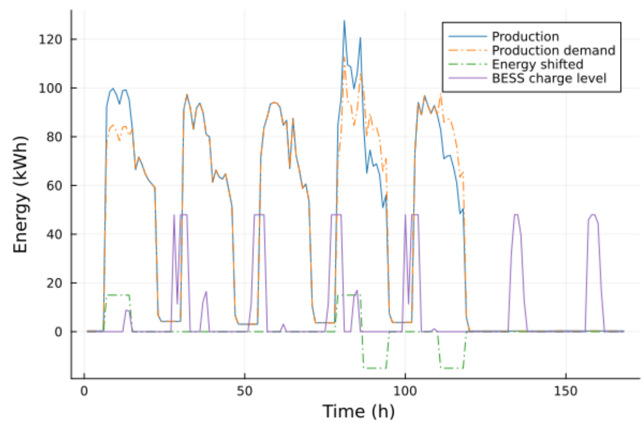

Figure 5. Illustration of load shifting over a week in the SEAC use case. The energy shifted (in green dashdotted) represents a production batch. The original production demand (in orange dashdotted) is optimised relative to the energy availability from on-site PV panels and the power grid prices, and results in the production (in blue). The charge of the BESS (in purple) follows the balance between energy availability and demand, and is thus affected by the load shifting.

Table 2: Comparison between load shifting and the production-based rescheduling of the production.

	Cost (€/MWh)	PV consumption (%)	Grid consumption (%)
Base case	110.4	50.2	49.8
Production-based rescheduling	107.7	51.7	48.3
EMX load shift	107.7	51.5	48.3

An advantage of EMX's implementation of load shifting is that the impact of flexibility on investments on a longer timescale can be explored. In SEAC, the load shifting was coupled with investments in BESS and PV. Table 3 displays the results for the load shifting-coupled investment model compared to an investment model without the load shifting. Investments in PV and BESS investments increased by 1.7 % and 4.5 %, respectively, with load shifting compared to without. While the difference between the two models is relatively small due to the limited magnitude of the load shifting in SEAC, the increased BESS investments are interesting. Typically, we expect that the load shifting reduces the investments into BESS systems since the consumption can be shifted according to the availability of the PV power.

Table 3: Optimal investments in SEAC in 2030 using energy systems modelling in EMX as set up in Figure 2 with and without load shifting.

	PV (kWp)	BESS (kWh)	Flexibility (kWh/year)
EMX without load shift	294.8	194.6	0
EMX load shift	299.8	203.3	12 480

The reason for this behavior in SEAC can be that the constraint on the duration and timing of the load shifting inhibits a perfect match between the shifted production and the PV energy generation. Figure 5 illustrates how making use of BESS therefore is necessary to exploit the full potential of the load shifting, and to increase the utilization of the renewable energy from the PV panels.

CONCLUSIONS

The EnergyModelsX framework provides a high level of flexibility in modelling energy systems. Its primary strength lies in the exploitation of the multiple dispatch feature provided by the Julia programming language. New technologies can be introduced in the model by dispatching on existing implementations resulting in less complex code.

The application of EnergyModelsX to industrial settings has proven to provide the flexibility needed to model the goals of the analysis. The main challenge is to achieve the correct data and the implementation of these into constraints.

The present work has demonstrated that the implementation of load shifting can adequately represent the production flexibility of industrial settings. One of the major advantages with load shifting is the relative incomplexity compared to production-based rescheduling algorithms, which ultimately enable investigations into the impact of process and energy flexibility on a long timescale. In industries where the magnitude of the load shifting is larger than in SEAC, this can have a significant impact. This is, however, given that the load shifting represents the process flexibility of the industry, which may require extensive preprocessing of data and industry information and remains one of the key challenges with the representation of process flexibility through load shifting.

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