FLEXIBILITY MANAGEMENT FOR INDUSTRIAL ENERGY SYSTEMS

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Abstract: This paper proposes a decision model for the optimized scheduling of energy flexibility and the assessment of different energy purchase strategies for industrial facilities. The decision model refers to a deterministic, mixed-integer linear programming (MILP) optimization problem with a time interval of 15 minutes. A case study covers flexible loads, energy storage units, and the load profile of an industrial production cycle. The objective function includes operational costs, energy purchase costs, and network charges. Furthermore, the annual peak load is constrained to reduce network charges. This allows for the flexible use of energy in a cost-efficient way. The flexible use of energy makes it possible to reduce energy costs and allows for accomplishing further cost benefits due to peak power reduction. A comparison of energy purchase strategies shows the cost advantage from investigating alternative strategies.

Keywords: Energy flexibility measure, Flexibility management, Multi market participation, Peak power reduction

1 Introduction

Demand-side flexibility [1] presents added benefits for the energy grid. For instance, reduction of generation capacity requirements, a higher security of supply and a widened competition for the provision of balancing services [2]. Through demand-side flexibility, consumers can also benefit from reduced energy supply costs and higher grid reliability [3]. The higher levels of consumption in the industrial sector compared to other sectors [4] implies that greater flexibility for industrial facilities would significantly contribute to extending the demand-side capabilities of the grid. Fundamental, from the industrial consumer's point of view, is to first identify and characterize the energy flexibility measures for local industrial processes, and second to evaluate to which market segments or tariff schemes the flexibility can be offered. Finally, it is important to assess the economic benefits of flexibility.

With regard to the first step, the German research project SynErgie [3] described the flexibility of industrial processes through *energy flexibility measures (EFM)*. The description through EFM offers a simple and effective way to compare the identified flexibility potentials executable in an industrial production site [5].

The second step requires deep knowledge of the energy market and tariff structure. Currently, consumer awareness of opportunities provided by demand response actions has yet to be fully established [1]. A methodical classification for market segments or tariff schemes has been carried out in literature describing where marketing energy flexibility is possible [6]. Bianchini et al. [6] characterized so-called *market options* to support industrial consumers. The potential for cost reduction or profit increase was also evaluated, showing that the highest potential can be ascribed to the reduction of network charges and the day-ahead market (DAM) [6].

Finally, it takes quantitative assessments for different market options and possible combinations to identify the most profitable market combination. To this end, a decision model needs to be designed to determine the cost-efficient utilization of EFM. In literature, decision models or energy management systems for industrial flexibility have been proposed, e.g. by [7–9]. However, these approaches mostly lack a generic definition of industrial flexibility and require specific modelling for each energy flexibility measure. Moreover, they focus on assessing only a single configuration of energy markets and tariffs. This paper designs a decision model for the cost-efficient use of EFM in multiple market options. EFM activation is simulated, modifying the electricity consumption profile measured at the consumer's connection point to the public grid. The aim is to decide whether a specific point in time is the optimal point for activating EFMs to reduce energy costs. Cost reduction is achieved by reducing network charges and/or purchasing electricity on the DAM [6]. Using EFM definition, the designed decision model is applicable to different industrial facilities. The paper is organized as follows. Section 2 provides a background overview of related fields. Section 3 describes the decision model and the scenario assessment model. Section 4 presents a case study. The results are outlined and discussed in section 5, followed by the conclusion and an outlook in section 6.

2 Background

2.1 Energy Flexibility in Industrial Systems

Energy flexibility on the consumer side can be defined as the ability of a production system to adapt quickly and with little financial effort to changes in the energy market [10]. Energy flexibility is implemented in practice through EFM, defined as concrete and conscious actions on industrial processes ending up in a variation of consumption at the grid connection point [11]. Energy flexibility on the consumer side benefits the grid in multiple ways. The most relevant benefit is the option to ensure a balance between power supply and demand in grids with large penetration of renewable energy sources (RES) and the possibility to reduce curtailments [12, 13]. However, barriers related to availability, technical and regulatory aspects, as well as uncertain or low compensation, limit the exploitation of energy flexibility on the consumer side [1, 13, 14].

In the last years, steps have been taken towards reducing barriers for energy flexibility, also thanks to the German project “SynErgie”, which is part of a program called “Kopernikus projects for the Energiewende” [3]. The “SynErgie” project aims at synchronizing industrial energy demand with fluctuating RES power supply [3]. In this context, EFM are defined by three categories: power, time and costs. In addition, a method for identifying and characterizing EFM has been developed and applied to different industrial consumers [5]. A data model aiming at a standardized description of energy flexibility measures has been proposed as an essential basis for flexibly automating industrial processes [12]. Integrating flexibility into production planning and control (PPC) has been investigated by [15]. The authors develop a methodology to integrate energy flexibility planning and marketing in conventional PPC systems that are not able to consider flexibility measures. Kaymakci et al. [16] introduce a method for implementing flexibility measures down to the machine level, applying it to a compressed air system that fills the gap between EFM management level and machine level (shop floor). The representation of flexibility through standard parameters allows for comparing different flexible processes and devices, representing both flexible loads and storage systems. It helps provide a common basis for information exchange between different subjects, such as flexible consumers and market operators, for commercializing flexibility measures on the energy market [12]. It also contributes to assessing suitable marketing opportunities [6]. This paper applies the standard definition of EFM introduced in [3, 5], representing local flexibility in a simple but effective way (table 1).

Table 1: Descriptive parameters of energy flexibility measures (EFM) based on power, time and costs [3, 5].

Parameter	Unit	Description
Direction	↕, ↑, ↓	Load variation: load reduction (↓), load increase (↑), load shift (↕)
$\boldsymbol{P_{EFM,min}}$	kW	Minimum EFM activation power
$\boldsymbol{P_{EFM,max}}$	kW	Maximum EFM activation power
$\boldsymbol{t_{EFM,active,min}}$	s	Minimum EFM activation time
$\boldsymbol{t_{EFM,active,max}}$	s	Maximum EFM activation time
$\boldsymbol{t_{EFM,regen,min}}$	s	EFM regeneration time
$\boldsymbol{SOC_{EFM,min}}$	%	Minimum state of charge of EFM, if modelled as a storage system
$\boldsymbol{SOC_{EFM,max}}$	%	Maximum state of charge of EFM, if modelled as a storage system
$\boldsymbol{C_{activation}}$	€/kWh	EFM activation costs based on the activated flexible energy

2.2 Market Options

Consumers benefit from the marketing of flexibility measures for demand response through reduced energy costs [3]. In Germany, different ways for marketing flexibility have been identified. One option is oriented towards making a profit on the ancillary services market, and a second option reduces the energy bill [6]. These options are defined here as *market options* as in [6]. In the market options for profit increase, flexibility can be offered to the grid operator by way of a power increase or decrease coming with a monetary gain. These Market options have frequently been investigated in literature [9, 17–19]. However, due to frequent regulatory changes and strong price fluctuations over the last years, the potential remains uncertain and will not be further investigated in this paper [6].

The market options for cost reduction refer to reducing electricity supply prices and network charges (NC) without considering other taxes and fees [20]. The electricity supply price represents the cost of energy consumed and purchased directly from the energy market or through a third party, called a retailer. The energy market is divided into the forward market (FM), day-ahead market (DAM) and intraday market [21]. The FM deals with long-term electricity trading up to six years in advance, while DAM and intraday market have to do with short-term trading for one day up to 5 minutes in advance [22, 23]. Due to the price risk on the DAM and the intraday market, industrial consumers prefer to buy electricity in advance through bilateral contracts via "over-the-counter" trading. Another option is to purchase on the FM through a retailer [22]. However, the price fluctuations that characterize the DAM and intraday market make the marketing of flexibility on these markets a promising business [24]. Long-term purchase is not considered a marketing opportunity for flexibility, as explained in [6], and is therefore defined as a *purchase strategy*. NC cover costs for construction, operation, and maintenance of the grid. The grid operator raises NC for every consumer connected to the grid [25]. NC can be reduced by limiting the maximum power peak over a given period of time. This strategy is called peak shaving (PS). Further options for reducing network charges are individual network charges allowed by regulation [25]. For atypical network usage (AN), the consumer is required to reduce consumption during peak load time windows (PLTW). The required reduction depends on the voltage level of the consumer´s grid connection and is required to be not less than 100 kW. If the required reduction has satisfied every PLTW, the maximum peak load generated during the PLTW is considered [25]. The third bill component gathers any further legal taxes and fees the consumers pay to the state [20]. Flexibility can reduce some of the taxes or fees by taking advantage of reliefs and exceptions. However, as these criteria are diverse, their reduction requires case-by-case examination, and so they will not be further evaluated here.

2.3 Literature Review

Decision models or purchase strategies for market players to activate flexibility measures on energy markets are present in the literature. A portfolio optimization strategy for sellers (generators) acting in multiple markets has been proposed in [25]. With this strategy, the seller decides where and how to offer energy in various markets, considering price forecasts. [19] proposes and investigates an optimal bidding methodology for flexibility aggregators operating in multiple markets. A unit commitment of flexibility units is obtained considering forecasted prices for the FM, the DAM, and the balancing market using stochastic MILP. The results show that bidding on multiple markets increases the economic potential of demand response.

Decision models evaluating consumers' market participation in multiple markets can be found in the literature. Here, four examples are summarized. The authors of [9] introduce a stochastic programming strategy, which can optimize the bidding on energy markets of an energy-flexible factory in Germany for profit maximization. Here, bidding on the balancing market and on the DAM are sequentially considered, and the strategy includes a risk evaluation. A stochastic programming approach to optimize the production planning of a cement milling process is developed in [17]. A sequential bidding process, first on the balancing market and then on the DAM is depicted as part of the optimization problem. The authors use flexibility measures for industrial process to minimize the expected costs, i.e. the costs for procuring energy on the DAM without the profits from the tertiary reserve offers. In [8], a stochastic MILP is described determining the optimal bidding strategy for an aluminium smelter offering its flexibility across several markets. It considers various markets, in particular the DAM and the spinning reserve market. It results in bidding curves for each hour and the availability of spinning reserve. An additional decision model for large flexible industrial consumers is proposed in [7]. This MILP-based model can simultaneously optimize the activation of energy flexibility and the energy portfolio procurement from different market options, including bilateral contracts and energy markets. Flexibility measures are storage systems, flexible load, and onsite generation. These examples, however, do not compare the profit from single markets and different market combinations to the market combination investigated in the respective paper.

Existing approaches rarely evaluate the effect of flexibility activation or maximum withdrawal on taxes and fees, not even for multiple market participation. [18] simulates the bidding strategy for a cooling process of an energy-flexible factory in three Danish submarkets: the DAM, the intraday market, and the balancing market. The three markets are considered individually and in combination. It shows that consumers benefit from bidding in multiple markets due to the price difference between markets. However, the authors assume that taxes and fees are constant and only related to the consumed energy. For the Danish electricity market, the authors of [27] investigate the potential for demand response of an industrial process (roller presses). The study evaluates the potential for demand response including profit from the balancing market, the energy costs, and the taxes, but it does not compute any specific cost reduction or profit for a single company. The grid's maximum power load is considered for optimal energy scheduling of a flexible microgrid in [28]. Here, energy scheduling defines how energy is purchased from and sold to the public grid, depending on energy-flexible devices available and the maximum power load constraint. The hydrogen systems, which are the most expensive system devices in the paper, are activated primarily in dependence of the maximum power load constraint. This shows that the maximum power load constraint is relevant for activating flexibility. However, the paper does not consider the combination of this constraint with further market options.

This paper investigates the cost-effectiveness of the marketing of flexibility measures considering day-ahead market (DAM) and network charges reduction, in particular peak shaving (PS) and atypical network usage (AN). Both DAM prices and network charges have been increasing over the last years [6]. Thanks to a limited complexity of market participation and a stable regulatory structure, the authors have come to prioritize the investigation of these market options [6]. The relevance and structure of network charges for German electricity prices likewise makes it fundamental to investigate cost reduction due to multiple market participation, including flexibility activation effects on taxes and fees. The results are compared to the purchase of energy for a fixed price through a retailer and to the purchase on the FM. The comparison with purchase strategies allows examining which advantage each combination of market option and purchase strategy offers to the marketing of flexibility.

3 Methodology

3.1 Flexibility Management Decision Model

The decision model uses the electrical energy E per time interval t, E_t, to model the energy flows in the system. The power output P_t of each system component is assumed to be constant over the applied time intervals t of 15 minutes. While the fixed system demand $P_{d,t}$ is known, the MILP solver calculates the remaining energy flows, $E_{EFM,i,t}$, resulting from the EFM activation $P_{EFM,i,t}$. The objective of the decision model is to minimize system energy costs. The system load is $P_{system,t}$. The EFM activation cost is defined by the respective activation costs $C_{activation,i}$, the current market value $C_{market,t}$, and the network charges power price C_{power}.

$$\min z_t = \sum_{i=1}^{n} E_{EFM,i,t} \cdot \left(C_{market,t} + C_{power} + C_{activation,i}\right) \tag{1}$$

In Eq. (1), $E_{EFM,i,t}$ is calculated for each time step t for each $i-th$ EFM. The total number of EFM is represented by n. The energy flexibility power of the EFM is transferred to the decision model taking the form of maximum and minimum value constraints shown in expression (2).

$$P_{EFM,i,min} \leq P_{EFM,i,t} \leq P_{EFM,i,max} \quad \forall t \in [1,T] \tag{2}$$

EFM availability is constrained by a maximum activation duration $t_{EFM,i,active,t}$ and a regeneration duration $t_{EFM,regen}$, which follows an activation as shown in expressions (3-4).

$$t_{EFM,i,active,min} \leq t_{EFM,i,active,t} \leq t_{EFM,i,active,max} \quad \forall t \in [1,T] \tag{3}$$

$$t_{EFM,i,regen,min} \leq t_{EFM,i,regen} \quad \forall t \in [1,T] \tag{4}$$

The EFM availability of energy storage systems depends on their state of charge $SOC_{EFM,i,t}$. This is calculated using the energy flowing in and out of the storage system (Eq. (5)). The $SOC_{EFM,i,t}$ is constrained by a maximum and minimum value, as shown in expression (6).

$$SOC_{EFM,i,t} = SOC_{EFM,i,t-1} + E_{EFM,i,t-1} \quad \forall t \in [2,T] \tag{5}$$

$$SOC_{EFM,i,min} \leq SOC_{EFM,i,t} \leq SOC_{EFM,i,max} \quad \forall t \in [1,T] \tag{6}$$

Also, the system load $P_{system,t}$ and the reduction of network charges are constrained. To consider the network charges, a binary value NC is introduced and the system is constrained to $P_{NC,t,max}$. When network charges are not considered in the optimization, the system energy state is constrained to the maximum load capacity of the systems grid connection point $P_{grid,max}$, as shown in expression (7).

$$\sum_{i=1}^{n} P_{EFM,i,t} + P_{d,t} = P_{system,t} \leq \begin{cases} P_{NC,t,max} & if\ NC = 1 \\ P_{grid,max} & if\ NC = 0 \end{cases} \quad \forall t \in [1,T] \tag{7}$$

The value of $P_{NC,t,max}$ is defined depending on the considered reduction of NC, being PS or AN. For PS, $P_{NC,t,max}$ is a constant value P_{PS}. In the case of AN, the binary value $PLTW$ is introduced. It determines whether the current time step t is in a peak load time window. In that case, $P_{NC,t,max}$ is set to an adaptive value $P_{AN,t}$, in accordance with the AN qualification criteria described in section 2; otherwise $P_{NC,t,max}$ is set to $P_{grid,max}$ (Eq. (9)).

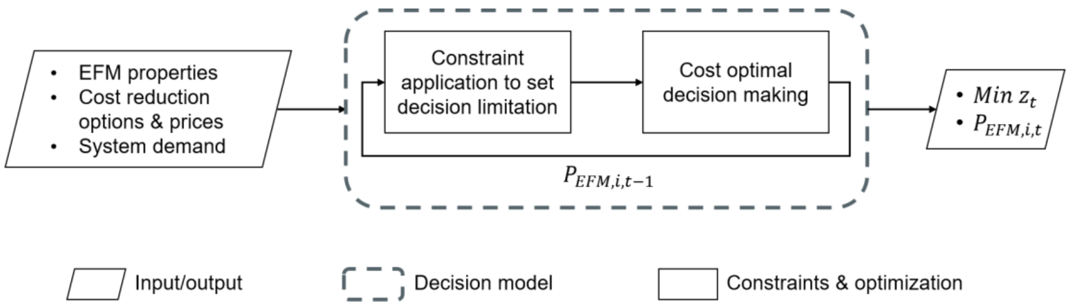


Figure 1: Overview of the decision model logic determining optimal EFM activation for each time step t.

$$P_{NC,t,max} = \begin{cases} P_{AN,t} & if\ PLTW = 1 \\ P_{grid,max} & if\ PLTW = 0 \end{cases} \quad \forall t \in [1,T] \tag{9}$$

An overview of the logic implanted in the decision model is shown in figure 1. EFM properties, the considered cost reduction options and their prices, as well as the system demand, are sent to the decision model as input data. In accordance with the given constraints and input data, the decision model determines the cost optimal activation of each available EFM $P_{EFM,i,t}$ for every regarded time step $t \in [1,T]$. After each time step t, the decision is sent to the next time step as additional input. So, temporal continuity and dependency is achieved.

3.2 Assessment Approach

To investigate market options and purchase strategies, a branch graph was created (figure 2). This graph serves as a basis for simulation. It establishes the possible combinations of market options and purchase strategies allowed by the regulation, hereafter referred to as scenarios. Among the purchase strategies, a fixed market price (FIX) is considered for taking into account the energy purchase through bilateral contracts or through a retailer. The combinations are forwarded to the decision model, which then applies the corresponding input parameters and constraints.

Each simulated scenario is evaluated according to the resulting overall costs $C_{overall}$ Eq. (10).

$$C_{overall} = \sum_{t=1}^{T} (E_{system,t} \cdot C_{market,t} + \sum_{i=1}^{n} E_{EFM,i,t} \cdot C_{activation,i}) + NC \tag{10}$$

For comparison, the reference scenarios (RS) were simulated in which no EFM were activated, serving as a basis for assessing the profitability of EFM activation. The assessment parameter $Index$ enables a clear comparison between scenarios and RS. Here, the scenario overall costs are examined in relation to those of the corresponding RS. This allows quantifying the respective cost difference in percentage (Eq. (11)).

$$Index = \left(\frac{C_{overall,scenario}}{C_{overall,RS}} - 1\right) \cdot 100 \tag{11}$$

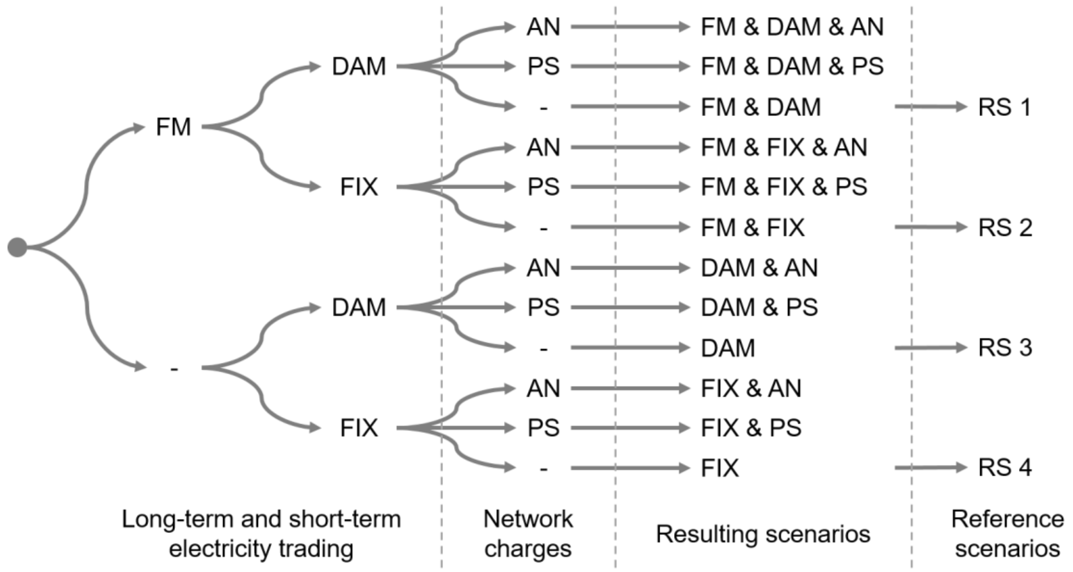


Figure 2: Branch graph of examined purchase strategies and cost reduction options.

Additionally all scenarios and RS2 were compared to each other to contrast the standard purchase strategy adopted by the investigated company (FM & FIX) with other possible purchase strategies.

4 Case Study

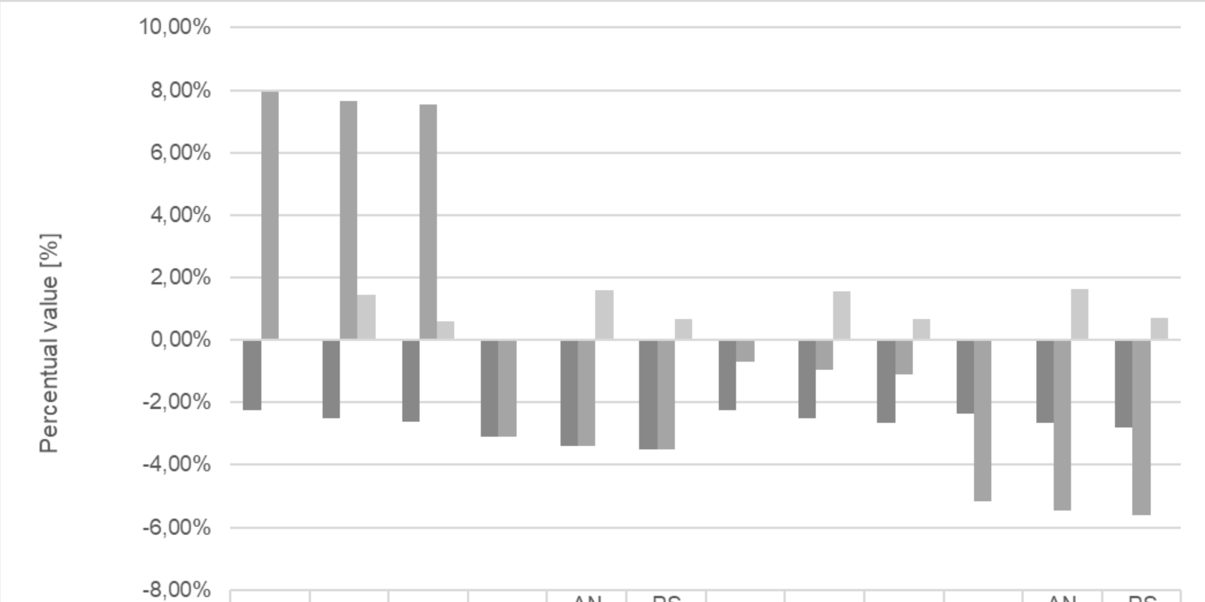
The decision model was tested on an industrial facility, which includes an electrical storage system, a flexible ventilation system, and unidirectional charging stations for electrical vehicles (EV) (Table 2). The simulation considers an exemplary load profile of the industrial facility [3] and historical energy prices [23]. The ventilation system can either be used as load increase (EFM1) or load decrease EFM (EFM2). EV charging stations are available only during working hours. The EV are modelled to arrive at 8 a.m. with a state of charge of 50% and leave fully charged at 5 p.m., leaving the time of charging free for cost-efficient activation (EMF3). The storage system is a load shifting energy flexibility measure (EFM4). Charging and discharging levels are limited to extend the life expectancy of the component.

Table 2: Case study EFM specifications according to the descriptive parameters discussed in section 2 [3].

Parameter	**Unit**	**EFM1: Ventilation system**	**EFM2: Ventilation system**	**EFM3: Charging stations**	**EFM4: Storage system**
Direction	↕, ↑, ↓	load increase	load decrease	load increase	load shift
$\boldsymbol{P_{EFM,min}}$	kW	0	0	0	0
$\boldsymbol{P_{EFM,max}}$	kW	300	300	350	2.500
$\boldsymbol{t_{EFM,active,min}}$	s	0	0	0	0
$\boldsymbol{t_{EFM,active,max}}$	s	432.000	1.800	SOC dependent	SOC dependent
$\boldsymbol{t_{EFM,regen}}$	s	0	1.800	SOC dependent	SOC dependent
$\boldsymbol{SOC_{EFM,min}}$	%	-	-	50	10
$\boldsymbol{SOC_{EFM,max}}$	%	-	-	100	90
$\boldsymbol{C_{activation}}$	€/MWh	5,83	2,55	22,62	1.073,22

5 Simulation Results and Discussion

First, the total costs of the reference scenarios were compared. Purchase on the FM and the DAM in RS1 is the only reference scenario to perform better than RS2, with a total cost reduction of 2.9%. The two reference scenarios RS3 and RS4 are not profitable in comparison to RS2, with a total cost increase of 1.58% and 10.43%, respectively. In particular, the total cost increase of more than 10% in RS4 is mainly due to the considered high fixed price assumed in the simulations. The investigated effect of the EFM activation (figure 3) leads to energy cost reductions for all cases with a reduction between 2.2% and 3.5% (in figure 3 “comparison with respective RS”). The consumers benefit from EFM activation as costs are reduced, even if no reduction of network charges is intended. Comparing the results to RS2, the best scenario remains RS1 (FM-DAM), where cost reduction reaches 5%. The worst scenario is still the purchase through fixed prices, with an increase of costs of up to 8%. As regards the purchase on the DAM, this scenario becomes profitable with EFM activation, offering a cost reduction of 1% compared to RS2. Activating the relatively expensive EFM, as in the storage system EFM 4, does not depend on energy prices but only on the NC strategy. As in [28], the most expensive EFM is rarely activated in the absence of NC reduction strategies such as PS (two activations). This explains that activation costs for scenarios with the same market option for NC reduction are similar (figure 3 “Activation costs over the total”). In presence of PS, the storage is activated more often than with AN (100 and 78 activations, respectively) but with less energy activated, since AN requires fulfilling a higher energy level. Despite the high activation costs, these two options remain more profitable than not including NC as a market option. Considering PS and AN results in further cost reduction. Market options for NC reduction are therefore a concrete way for industrial consumers to reduce energy costs, and using storage systems for this scope is a viable strategy. On the other end, the relatively cheap EFM are activated depending on the purchase prices. The ventilation system as a load increase EFM1 is only activated if the DAM is considered. The activation takes place if prices at the DAM are negative, creating an incentive for this kind of EFM. If FM is included, the activation only takes place twice a year. Using the ventilation system to decrease the load EFM2 is the most frequently activated EFM (more than 4500 activations). This is due to the low activation costs. The only constraint here is the maximum active time and the necessary regeneration time. The EV charging stations are always activated as defined. In this problem formulation, they only exploit the negative prices in the DAM but not the minimum DAM during the day, since the schedule does not consider future power consumption. Thus, the current decision model does not fully optimize the timing for vehicle charging. This would require the



	FIX	AN FIX	PS FIX	FIX-FM	AN FIX-FM	PS FIX-FM	DAM	AN DAM	PS DAM	FM-DAM	AN FM-DAM	PS FM-DAM
Comparison with respective RS	-2,25%	-2,51%	-2,64%	-3,10%	-3,38%	-3,52%	-2,23%	-2,50%	-2,65%	-2,35%	-2,64%	-2,79%
Comparison with RS2	7,94%	7,66%	7,52%	-3,10%	-3,38%	-3,52%	-0,68%	-0,96%	-1,11%	-5,18%	-5,46%	-5,60%
Activation costs over the total	0,04%	1,44%	0,61%	0,04%	1,60%	0,68%	0,04%	1,57%	0,66%	0,04%	1,64%	0,69%

Figure 3: Simulation results for each scenario with EFM activation. The total costs are compared to the respective reference scenario (RS) and to the reference scenario based on the forward market and fixed price (RS2). Total EFM activation costs as a percentage of the total costs are shown.

optimization run to consider a longer optimization time period, as for an entire day in the DAM scenarios.

6 Conclusion

This paper presents a decision model for optimizing EFM activation to reduce energy costs in multiple markets. The system complexity results from the multiplicity of market options and the EFM imposing constraints on the maximum load at a facility´s connection point and on the EFM activation. Costs for energy purchase and EFM activation are optimized for a corresponding load profile. The results are compared to reference scenarios neglecting the activation of EFM. The results show that the utilization of energy flexibility allows for an energy cost reduction of up to 3.5% in every scenario, assessing the positive effect of demand response for industrial companies. Alternative market options further reduce overall facility energy costs by up to 5% when purchasing energy on FM and DAM and reducing network charges through PS or AN.

This decision model provides an initial evaluation of the benefits of EFM implementation for different market options. A single time step optimization assesses the best possible cost reduction through flexibility activation and demand response. Further research should investigate optimization over a longer period of time, such as one day, to allow scheduling EV charging in line with minimum DAM prices. A more realistic representation of the decision model in real-time should be pursued. The current method assumes prices to be known, which is not the case for a real-life market bidding phase. A risk-evaluation strategy could reduce the risk of price volatility on the DAM and lead to safer purchase and flexibility activation solutions for industrial consumers [26]. Forecast strategies for prices and loads could be included to investigate the effect of forecasts on EFM profitability [19]. Further investigations on the EFM's long-term profitability can be carried out considering future price scenarios instead of past price profiles.

This work is funded by the German Federal Ministry of Education and Research (BMBF) within the project „SynErgie (Synchronisierte und energieadaptive Produktionstechnik zur flexiblen Ausrichtung von Industrieprozessen auf eine fluktuierende Energieversorgung)“ as part of the Research Program „Kopernikus projects“ managed by the Projektträger Jülich. The authors would like to thank the BMBF and Projektträger Jülich for supporting the partners of the Institute for Energy Efficiency in the Production (EEP) of the Stuttgart University and the Fraunhofer Institute for Manufacturing Engineering and Automation (IPA) within this project (fund number for EEP: 03SFK3K1-2; fund number for Fraunhofer IPA: 03SFK3Q2-2)

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