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Simulation-based analysis of energy flexible factories in a regional energy supply system

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Abstract

In a decentralized and renewable energy system, reliable and economical solutions are necessary to adjust power demand to a volatile power supply by photovoltaic and wind energy plants. A high potential for the balancing of short and medium-term power supply fluctuations is seen in energy flexible factories. To leverage this potential, monetary incentives and technological enablers have to be developed. Apart from that, the ecological and social aspects of energy flexible factories have to be considered in transdisciplinary research, to achieve a broad public acceptance. To assess the complex interrelations between the technical, political, legal and social sector, a clear and accessible base for discussions is necessary. This paper presents an approach for a simulation based-analysis of energy flexible factories with focus on high applicability and comprehensibility for stakeholders from different disciplines. This paper presents the general structure of the simulation model including the operation module for the energy flexible region Augsburg.

Keywords: energy flexibility; production processes; energy oriented simulation; load profiles; model region; transdisciplinary research

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1. Introduction

The participants of the UN Climate Change Conference in Paris agreed on “holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels” [1]. Germany claimed to pursue efforts to incrementally reduce its greenhouse gas emissions by 80 % to 95 % until 2050 compared to 1990. Germany’s energy policy thus supports ambitious targets, such as the nuclear phase-out by the year 2022 [2] and the energy transition to renewable energy systems [3]. The largest share within the German renewable electricity generation constitute wind power systems and photovoltaics with around 13 % and 6 % share of gross electricity production, respectively [4]. This induces a big technical challenge in balancing electricity supply and demand, as solar radiation and wind conditions are uncontrollable and difficult to predict [5]. A promising solution to the problem with fluctuating generation is demand side management (DSM), which originally consists of several activities to influence customers’ use of electricity [6]. [7] provides an overview of flexibility measures both on electricity supply and demand side. [8] presents an economic analysis of spatial load migration as an alternative form of DSM. In the following, the activities time of use and demand response are summarized by the term energy flexibility. Energy flexibility describes the ability of a manufacturer to adapt the production to short-term changes in the provision of electrical energy with as little loss of time, effort, costs and performance as possible [9,10]. The industry sector is by far the largest electricity consumer with a share of 47 % of the total German net electricity consumption in 2016 [11].

To leverage the potential, research focuses on the technical possibilities to enable the adoption of production processes to the energy availability. To create economic incentives for this, suitable business models for existing national and international energy markets, but also innovative concepts for regional energy markets need to be developed. The changes in production planning and processes may lead to a postponement of production operations to an overnight shift, or to transferring their production to other industrial facilities [12]. As a result, energy flexibility can lead to interventions in employees’ life. It is likely that business models for energy flexibility will have an impact on energy prices for the society. Moreover, energy flexibility may reduce energy efficiency and therefore increase pollutant emissions of manufacturers. These points are exemplary for many scientific issues relating the individual requirements of the respective stakeholders [13].

The German federal research project SynErgie, funded by the German Federal Ministry of Education and research (BMBF), has the objective to conceptualize and improve the technical and economic requirements for the trading of industrial energy flexibility. In a subproject, a research team analyzes the so-called energy flexible model region Augsburg in the south of Germany to design and illustrate a transdisciplinary approach to utilize energy flexibility. Thus, stakeholders from different disciplines and backgrounds, like scientists, plant operators, plant employees and conservationists participate in a holistic discussion with respect to technological, ecological and social restrictions. The central prerequisite for applicable discussion results is common understanding of interdependencies in the energy system. This requires that the complex interrelations of energy flexibility are modelled transparently and that the impact on the energy supply scenarios are visualized clearly. The general requirements for a simulation model, regarding the regional use of industrial flexibility and the evaluation of regional stakeholders were described in preceding papers [14,13].

In this paper, the modular structure of the simulation model, which is based on the described requirements, is introduced in section 2. The optimization problem is presented in detail to build-up an executable simulation adapting the power demand to the power supply. A first setup in the discussion process and evaluation of the applicability is presented in section 3. Section 4 reflects the results and concludes with an outlook.

2. Structure of the simulation model

An intuitive user interface to comprehensively visualize a first estimation of the potential of industrial flexibilities and to encourage the dialog of the different stakeholders was developed. In this paper, the exemplary goal of reducing positive and negative residual load peaks by deploying flexibility measures is used. In the following, the residual load is defined as the difference between the sum of produced energy and consumed energy in the considered region. Reducing this measure is the principal target for the regional energy balance and therefore suitable for the development of business models. Great importance was attached to the tool's easy, quick, and comprehensive application for different user groups, which not necessarily have previous knowledge in the field of flexibility modelling and assessment. Thus, the required user input was reduced to a minimum. Therefore, the tool is not designed to give detailed and well-founded recommendations for action or to be used as a decision support system. The consideration of a monetary potential analysis would require detailed information on different flexibility marketing opportunities and flexibility measure specific additional cost components, such as additional personnel costs. Current and future regulations and legislations in the field of industrial power flexibility as well as inefficiencies which are caused by flexibility provision are excluded.

The simulation tool consists of three modules (Figure 1). The first module allows the definition of an energy supply scenario. This energy supply scenario is the basis of the residual load calculation. The second module allows the configuration of flexibility measures. After defining the input in the first two modules, which is described in the following two sections in more detail, the user can run the simulation of flexibility measure deployment for the requested time frame. As soon as the user starts the simulation, the tool aggregates the user input to a simulation scenario, determines a schedule for the flexibility measure deployment and illustrates how this impacts on the residual load.

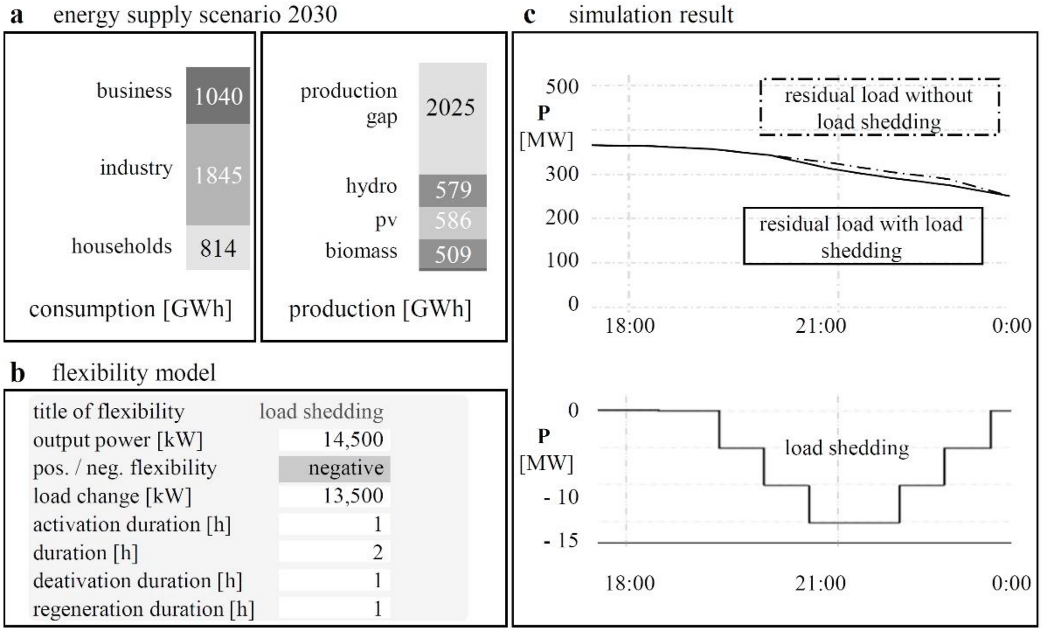


Figure 1: (a) energy supply scenario data, (b) flexibility model, and (c) simulation output example

Two exemplary use cases are: The detailed analysis of a short time frame with only one flexibility measure and the long-term analysis of a long time frame with multiple flexibility measures. In the first mentioned exemplary use case, the simulation tool allows the detailed analysis of a specific flexibility use and the resulting impact on the residual load. This use cases support a discussion on the consequences caused by the flexibility use in particular for the company providing a flexibility measure. The second mentioned use case rather puts the focus on the long-term potential of different flexibility measures. A possible point of discussion encouraged by this case is the varying applicability of different flexibility measures and their potential to reduce residual load peaks. [9] distinguishes 10 different types of industrial energy flexibility, such as adoption of shift starts, interruption of production processes and changing the machine utilization. The tool allows to model these flexibilities for use in the simulation.

The following describes how the tool collects and aggregates the required input and then explains, how it determines the schedule for deploying the defined flexibility measures.

2.1. Energy supply scenario

The region which has to be analyzed needs to be modeled by load profiles. These are understood to be a set of electrical power data with timestamps. In the following, energy supply scenarios are defined as data models which depict the energy production and consumption of a specific region. In order to determine the residual load, all regional power consumers and producers have to be integrated. The data quality of the regional energy mix is an important prerequisite for representative simulation results. Relevant scenarios can be the current supply situation depicted by measured data but also future situations such as an expected energy mix in climate protection scenarios. Depending on the availability of data, the energy consumption can be distinguished between households, small businesses and industries. In addition, energy intensive factories in the region can be modeled separately. This is especially recommendable when energy flexibility measures are provided by these production sites. The generation side is usually distinguished in photovoltaic roof systems, freestanding photovoltaic systems, offshore and onshore wind power, and biogenic combined heat and power plants [5]. If these profiles do not exist, suitable profiles of transformer stations may be used instead. The simulation tool calculates the deviation of renewable energy production to energy consumption and thereby determines the positive or negative residual load which has to be minimized by the optimization algorithm.

2.2. Energy flexibility model

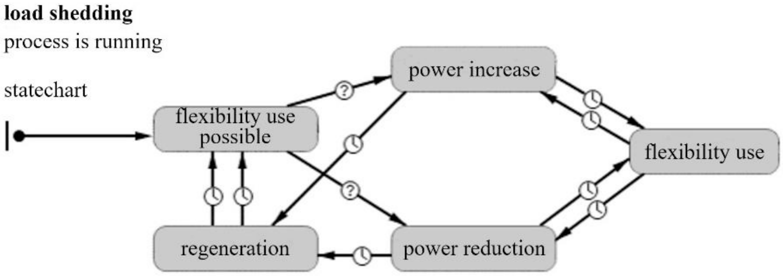


Figure 2: Flexibility statechart

In the tool a flexibility measure is modeled as a residual load increase mechanism (positive flexibility measure) or a residual load reduction mechanism (negative flexibility measure) that could be temporally shifted. An example for a temporally shiftable load increase mechanism is the start of an energy-intensive melting furnace which must run twice a day. An example for a temporally shiftable load reduction mechanism is the interruption of a cooling unit in a large-scale cold storage. In the following the information, which a user must enter to define a flexibility measure is described exemplarily. As an example, the above-mentioned melting process, which must run twice per day, is modelled. Thus, the process is a positive flexibility measure. The user has to enter the time frame, in which flexibility measures can be started. It is assumed, that the melting process can be started arbitrarily between 08:00 am and 03:00 pm. Moreover, the user has to define the duration of the activation phase, which is assumed to be 45 minutes. Next, the user has to define the peak demand, which is reached after the activation phase and the duration that this peak demand is held. In the example, a peak demand of 4 MW which is held for 45 minutes is assumed. The next required value is the duration of the deactivation phase. This duration is assumed to be 15 minutes. Afterwards, the furnace must regenerate for 75 minutes, before it can be used again. Accordingly, the user has to enter a regeneration duration of 75 minutes. The last two required values describe the maximum and minimum number of uses per day. Both values are two since the process must exactly be performed twice a day. After entering the required input for a flexibility measure, the user can either start the data aggregation or enter a further flexibility measure.

Every entered flexibility is visualized by a statechart, which can be used for an easier understanding in the stakeholder dialog (Figure 2).

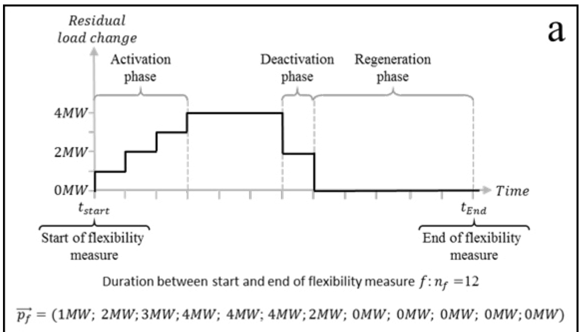
2.3. Data aggregation and optimization model

As soon as the user completes the data input, the tool aggregates the data to generate a simulation scenario which is required for the following optimization model. The simulation scenario is based on a planning horizon of 24 hours, starting at midnight. This planning horizon is discretized with 15-minute steps and denoted by $T = \{1, \dots, 96\}$. To analyze the potential of flexibility measures for more than one day, the tool automatically generates the individual simulation scenarios with the time frame of one day and iteratively executes the optimization model. Afterwards, the tool automatically aggregates the results of the individual days.

To build the simulation scenario, the tool combines the input of the energy supply scenario and assigns to every quarter hour $t \in T$ an aggregated residual load r_t. Based on the entered flexibility measures, the tool defines a set of flexibility measures F. For every flexibility measure $f \in F$, the tool determines a subset of time periods $T_f \subseteq T$ at which f can be started. This subset is based on the entered validity of the respective flexibility measure. Moreover, the activation duration, the holding duration, the power state, the deactivation duration, and the regeneration duration characterize the load profile of every flexibility f. This load profile is based on the user input and describes the load of the flexibility measure. The load profile is defined as the vector $\overrightarrow{p_f} = (p_{f,1}, \dots, p_{f,n_f})$. The number of elements of this vector (denoted by n_f) is equal to the duration between the start and end of flexibility measure f (including activation, deactivation, and regeneration phase). The elements of the vector describe the load of the flexibility measure f in each time period. Thus, $p_{f,1}$ represents the load of flexibility measure f at the time period in which f is started, $p_{f,2}$ describes the load of f at the second time period and so on. Positive values of $p_{f,i}$ represent a load increase and negative values represent a load decrease caused by the flexibility measure use. During the activation and the deactivation phase of a flexibility measure f, a gradually adaption of the load of flexibility measure f whereby the delta between the time periods is equal is assumed.

In the above mentioned example (melting furnace) the peak load of flexibility measure f *is* $4\ MW$. Accordingly, for this example, the first element of $\overrightarrow{p_f}$ is equal to $p_{f,1} = 1\ MW$, the second value to $p_{f,1} = 2\ MW$ and so on (Figure 3). Based on the input regarding the minimum and maximum number of uses per day, the tool defines a lower bound $\underline{b_f}$ and an upper bound $\overline{b_f}$ for the number of uses.

Based on the simulation scenario, the tool performs an optimization model. The objective of the optimization model is to minimize the squared sum of the residual load and the flexibility measures. In the best possible case, the model strives for achieving a sum of zero via a perfect match between residual load and flexibility measures in every time



b

Symbol	Description
T	Set of all time periods with $T = \{1, \dots, 96\}$
F	Set of all flexibility measures
$T_f \subseteq T$	Set of all time periods, where f can be started
n_f	Duration between start and end of flexibility measure
$\overrightarrow{p_f}$	Load profile of f with $\overrightarrow{p_f} = (p_{f,1}, \dots, p_{f,n_f})$
r_t	Residual load at t
$\overline{b_f}$	Maximum number of uses of f in time horizon T
$\underline{b_f}$	Minimum number of uses of f in time horizon T
$x_{f,t}$	Binary variable: $x_{f,t} = 1$ if f starts at t, 0 otherwise

c

$$\min \sum_{t \in T} \left(r_t + \sum_{f \in F} \sum_{i=0}^{\min(n_f - 1, t-1)} p_{f,i+1} \cdot x_{f,t-i} \right)^2 \tag{1}$$

$$x_{f,t} = 0 \qquad \text{for all } f \in F \text{ and } t \notin T_f \tag{2}$$

$$\sum_{i=0}^{\min(n_f - 1, t-1)} x_{f,t-i} \leq 1 \qquad \text{for all } f \in F \text{ and } t \in T_f \tag{3}$$

$$\sum_{t \in T_f} x_{f,t} \leq \overline{b_f} \qquad \text{for all } f \in F \tag{4}$$

$$\sum_{t \in T_f} x_{f,t} \geq \underline{b_f} \qquad \text{for all } f \in F \tag{5}$$

Figure 3: (a) Flexibility load profile, (b) simulation scenario, and (c) optimization model

period $t \in T$. A perfect match means that the residual load r_t and the load of all flexibility measure in time period t have the same amount but an opposite sign.

To model this objective, a binary decision variable $x_{f,t}$ with $x_{f,t} = 1$ if flexibility measure f starts at t (Figure 3-b) is introduced. The objective function (1) over all time periods $t \in T$ is the squared sum of the residual load r_t and the load of all flexibility measures $f \in F$ at t. By considering the squared sum, higher deviations from a residual load are punished more heavily. The optimization model thus preferably schedules the given flexibility measures during positive and negative peak phases of the residual load in order to optimally cut them. The load of a flexibility measures $f \in F$ at t is calculated based on the binary decision variable $x_{f,t}$ and the respective element of the load profile of flexibility measure f. If the above defined flexibility measure f (melting furnace) exemplarily starts at t_3, the load of f in time period t_4 corresponds to $p_{f,1} \cdot x_{f,4} + p_{f,2} \cdot x_{f,3} + p_{f,3} \cdot x_{f,2} + p_{f,4} \cdot x_{f,1} = 1\ MW \cdot 0 + 2\ MW \cdot 1 + 3\ MW \cdot 0 + 4\ MW \cdot 0 = 2\ MW$. At t_5, the load of flexibility measure f would correspond to $3\ MW$ and so on.

Due to the considered squared sums of binary variables, the model contains a binary non-convex objective function that is subject to four linear constraints. The subset T_f defines for every flexibility measure $f \in F$ all time periods at which the flexibility measure f can be started. Constraint (2) assures that in all other time periods ($t \notin T_f$) flexibility measure f is not allowed to be started (i.e. $x_{f,t} = 0$). Moreover, a flexibility measure can only be started if the previous use of the same flexibility measure already ended. Therefore, constraint (3) assures that the flexibility measure is not started again while it is already in use. The last two constraints limit for every flexibility measure the number of uses to the given upper (4) and lower (5) bound. To reduce complexity of the given optimization model, we can substituted the squared term in the objective function by an additional continuous decision variable $y = r_t + \sum_{f \in F} \sum_{i=0}^{\min(n_f - 1, t-1)} p_{f,i+1} \cdot x_{f,t-i}$. Thus, we can reformulate the given optimization problem as a mixed-integer quadratic problem with the objective function $\min \sum_{t \in T} (y)^2$ and linear constraints.

3. Setup and evaluation in the energy flexible model region

The aim of the described assessment of the energy flexible model region is not a precise forecast of future energy supply situations and statistical results for flexibility use, but rather an analysis of the potential and impact of energy flexible factories. The simulation approach therefore accompanies the discussion of the stakeholders by delivering realistic energy flexibility use-cases which encourage a structured and purposeful dialog. As Figure 4 shows, the impact assessment is preceded by the described simulations, which need energy supply data of a clearly delimited and representative region.

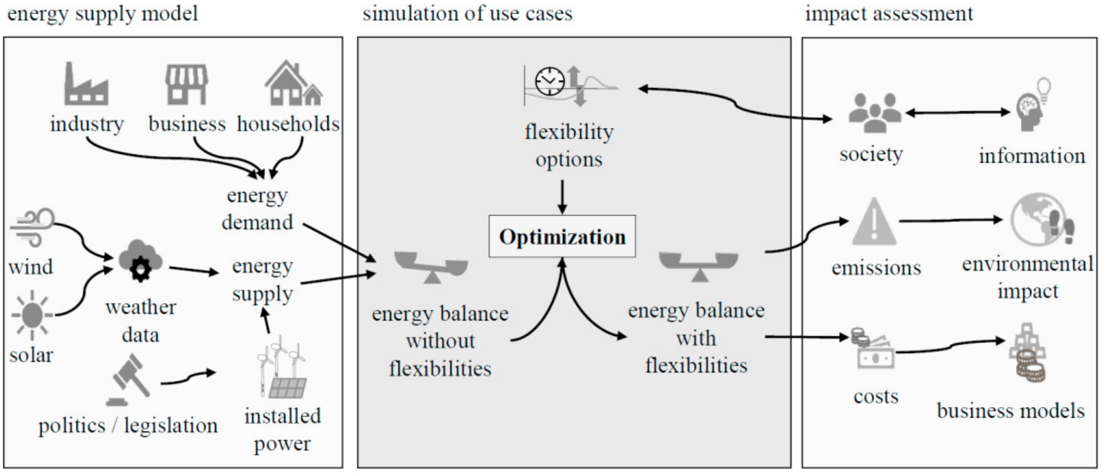


Figure 4: Interrelationship model

The model region of Augsburg has been selected since it offers an adaptable and scalable image of a regional power supply scenario and a suitable cross section about the industrial energy use. It includes the city of Augsburg with its nearly 300,000 citizens, the district of Augsburg, and the district Aichach-Friedberg. In the past decades, small, medium and large companies from the sectors machinery and equipment, rubber and plastic production, chemistry, paper and paper products have settled in the model region [15]. The annual electricity demand in the region is around 5,400 GWh. Nearly 80 % of this demand is caused by industrial customers, partly due to the large number of energy-intensive companies [14]. The share of renewable energy supply compared to the total electricity demand in 2016 was around 28 % (national average 30 %). In particular photovoltaic with an installed capacity of about 500 MW is causing volatility in the distribution grid of the model region. With an output of about 3 GW electrical power, the nearby plant of Gundremmingen used to be the most powerful nuclear power plant in Germany [16].

With the termination of the nuclear energy supply, a gap in electricity supply must be covered by wind power from the north of Germany, pump storage power from Austria or the expansion of gas fired power stations. Hence, the available renewable sources must be integrated to the regional supply system in the most effective way. [17] describe the need for a strong increase of flexibility measures both on electricity supply and demand side. The present discussion shows that energy flexible factories can be able to reduce the reserve capacity of controllable fossil power plants by adapting the industrial energy consumption with regards to production of renewable energy [18]. Furthermore, by decreasing peaks in the residual load, the need of positive and negative residual power can be decreased. Therefore, energy flexible factories are considered to reduce both fossil energy supply and the need of cost-intensive grid expansions [19]. Different approaches provide a framework for the use of energy flexibility on a regional level, such as the flexibility tendering in decentralized markets in case of local grid congestions [20]. Furthermore, studies outline energy cells, which are characterized by energy consumption structures that cope with fluctuations by energy flexible factories [21,22].

With the objective to evaluate the simulation-based approach, an example of an energy flexible factory was simulated for one week in an energy supply scenario of the year 2030. The current supply situation [16] was scaled to a renewable energy development path according to the climate concept of the model region [23]. The chosen flexibility was the movement of work shift start taking into account the hours of high power supply in the model region. The optimization determined the available energy periods in the specific week and therefore the shift starts of several factories have been postponed e.g. from 7:45 to 8:15 on Tuesday. In addition, the shift start on Wednesday was one and a half hours earlier than usual. The shift movements led to the desired improvement of the regional balance, according to the mentioned studies of decentralized markets and energy cells. This simplified case was demonstrated to the transdisciplinary group of manufacturers, distribution grid operators, representatives of politics and economical researchers. By the structured visualization with statecharts and energy scenario loads, it is possible to lead a structured and focused discussion about impacts of flexibility use on employees and society. The subsequent discussion thereby led to valuable assessment points, like the way and timing of the notification of the employees and the reduction of energy efficiency by the impact on production processes.

4. Discussion and Outlook

The implementation of some specific use-cases with certain flexibility measures shows that our simulation model can deliver the information to encourage and enhance a transdisciplinary discussion process. Next to insights on technical impacts of flexibility measures, the described bipartite approach in the simulation operator’s perspective of analysis and demonstration facilitates the dialogue process with the different stakeholder groups, as they are encouraged to use the tool themselves for a better understanding of the energy system. The user of the simulation model receives direct feedback on parameter changes when utilizing the tool with the user interface and is empowered to better retrace the complex interdependencies in the energy system. This is one fundamental issue to create acceptance for the usage of flexibility in the different relevant stakeholder groups. From a technological perspective, the simulation model serves as an important tool to assess the balancing potentials of energy flexibility for the local electricity grid. Still, further research must be undertaken to complement the impacts of industrial flexibility measures in the economical, the environmental and the societal dimension. For an analysis of economic impacts, it is necessary to analyze potential business models and the availability of these business models in specific countries. In general, utilities and distribution system operators (DSOs) should increasingly enable the energy-intensive industry to exploit their flexibility potentials and to use it for local balancing purposes. Ecological impacts can be measured according to the change of emissions of certain pollutants like carbon dioxide, methane, but also noise. For this purpose, it is necessary to define the relevant pollutants and to weigh their emissions in accordance to their environmental impact. The shown grid-levelling effect of industrial flexibility measures enables an increased deployment of renewable energy sources and can therefore contribute to reduce pollutants from fossil power plants. Nevertheless, possible emission increases caused by industrial flexibility measures, e.g. by efficiency losses, have also be taken into account. Finally, it is necessary to measure the impact on societal stakeholders in order to find a holistic solution path towards energy transition with acceptance of all relevant stakeholder groups. For the implementation in the simulation model, further research must first determine the relevant indicators for societal impacts and provide methods for measurement. Extending the simulation model with these three dimensions enables a holistic assessment of industrial flexibility measure’s impact and can therefore serve as an important tool to create acceptance in the relevant stakeholder groups.

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