Whitepaper

INDUSTRIAL FLEXIBILITY OPTIONS AND THEIR APPLICATIONS IN A FUTURE ENERGY SYSTEM

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Industrial Flexibility Options and their Applications in a Future Energy System

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Executive Summary

The ratification of the Paris Climate Agreement in 2015 and the resulting efforts to reduce emissions require a fundamental shift towards a system of Renewable Energy Sources. The increasing use of wind and solar power creates fluctuations in the electricity supply. However, in electricity systems, it is crucial to balance electricity supply and consumption at any point in time. Therefore, future electricity systems require flexibility on the demand side, to dynamically adjust electricity consumption to the availability of electricity from Renewable Energy Sources, as well as on the supply side, to adjust electricity output.

We structure this demand for flexibility into different flexibility applications (e.g., ancillary services or intra-day market). In turn, various flexibility options (e.g., industrial Demand-Side Management or battery storages) can meet these flexibility applications. The objective of this Whitepaper is to answer the question which flexibility options qualify to meet the requirements of specific flexibility applications to provide insights for the deployment of flexibility options in the German electricity system. This Whitepaper provides a comprehensive analysis of overall flexibility options based on literature. The focus of the Whitepaper lies on the flexibility option industrial Demand-Side Management and the underlying Energy Flexibility Measures like, e.g., the adaption of production start.

The evaluation of technical and regulatory aspects of flexibility options based on empirical data of participating companies within the Kopernikus-project SynErgie and the matching of flexibility options and their possible applications yields the following results: In the overall view, industrial Demand-Side Management can contribute to every flexibility application. As a part of industrial Demand-Side Management, there are Energy Flexibility Measures that only meet the requirements of specific flexibility applications, such as for energy-only markets or ancillary services (in the positive direction), but also single Energy Flexibility Measures that can be used for every flexibility application. Therefore, industrial Demand-Side Management must reach a competitive price level to prevail against competing flexibility options.

Overall, we derive five recommendations for policy makers:

- **First**, in the short to medium term, barriers should be lifted by policy makers for industrial companies to incentivize investments in industrial Demand-Side Management and to foster flexibility. So far, inhibited by existing regulations, we see a need for change, with regard to, e.g., grid charges, which today penalize the provision of flexibility for energy-intensive industrial companies. Also, the conflicting goals of energy flexibility and energy efficiency must be addressed by regulation.
- **Second**, there is a need for change in the medium to long term for (non-discriminatory) market access to flexibility applications with respect to industrial companies providing flexibility.
- **Third**, we recommend that the current levy and tax system must be reconsidered, which distort the electricity price signals in a way, that low and negative electricity market prices are hardly reflected in the effective electricity prices of most industrial companies.
- **Fourth**, a higher degree of harmonization of flexibility-providing market players such as utilities, industrial companies, and residential consumers, in the form of standardized communication must be created to avoid lock-in effects when deploying flexibility potentials and thus, effectively foster these flexibility potentials.

- **Fifth**, flexibility options and their corresponding Energy Flexibility Measures need to be explored further and the transfer of findings between research and practice needs to be strengthened.

Summarizing, regulatory barriers and financial disadvantages for flexibility provision by industrial companies must be lifted and incentives should be provided by policy makers to foster the flexibility potential of industrial Demand-Side Management.

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Acronyms

aFRR	automatic Frequency Restoration Reserves
CCGT	Combined Cycle Gas Turbines
CHP	Combined Heat and Power
DSM	Demand-Side Management
DSO	Distribution System Operator
EBGL	Electricity Balancing Guideline
EEG	Erneuerbare-Energien-Gesetz (Renewable Energy Sources Act)
EFM	Energy Flexibility Measures
EnWG	Energiewirtschaftsgesetz (Energy Industry Act)
FCR	Frequency Containment Reserve
GT	Gas Turbine
ICT	Information and Communications Technology
iDSM	Industrial Demand-Side Management
mFRR	Manual Frequency Restoration Reserve
NABEG	Netzausbaubeschleunigungsgesetz (Grid Development Acceleration Law)
PEM	Polymer Electrolyte Membrane
PSH	Pumped-Storage Hydroelectricity
PV	Photovoltaic
RES	Renewable Energy Sources
SO GL	System Operation Guideline
StromNEV	Stromnetzentgeltverordnung (Grid Charges Ordinance)

1 Introduction

One of the major global challenges of this decade and the decades to come is finding a sustainable and adequate answer to the challenges resulting from global warming and climate change. Despite how controversial the opinions, strategies, and discussions on this topic may be, the world community has at least collectively agreed on a joint goal by signing the 2015 Paris Agreement [1]. Beyond, there is also mutual consensus that for achieving this goal, a fundamental change of the current energy system largely based on fossil fuels is inevitable. While a significant number of countries such as the United Kingdom or France defined the generation of electricity by low-carbon nuclear power as their way to go, another significant number of countries, including Germany and Denmark, relies on a system of decentralized Renewable Energy Sources (RES) mainly founding on wind and solar power.

Energy systems resulting from this latter path face significant volatility on the supply side due to varying weather conditions during days and seasons. Electrical energy will be exceedingly and cheaply available in times of sunshine or breeze, but scarce in other periods. Nevertheless, the energy demand needs to be fulfilled, possibly without creating too many occasions of necessary demand restrictions. On top, grid stability needs to be ensured in a very narrow band, thus requiring a thorough balancing of electricity demand and fluctuating supply.

Yet, in such new energy systems, there will be a huge need for flexibility, i.e., the ability to manage imbalances in electricity supply and demand, of all actors involved [2]. Flexibility manifests itself in various (technical) flexibility options offered to the system [3]. Flexibility options consist of energy storage system options, like batteries, supply-side options, like temporary shutdowns of wind turbines, sector coupling options, like power-to-heat, or demand-side options, like industrial Demand-Side Management (iDSM) [2]. This Whitepaper focuses on one of these flexibility options, namely, iDSM. This term comprises a multitude of demand-side measures, which all offer flexibility within industrial manufacturing processes. These processes can be adapted to the prevailing electrical energy supply situation. In doing so, iDSM competes with all other flexibility options mentioned above. Beyond, single Energy Flexibility Measures (EFMs) as part of iDSM are also in competition to each other.

To answer the question which flexibility options, in particular, the underlying EFMs of the flexibility option iDSM are applicable for the given flexibility applications and to indicate to which alternative flexibility options iDSM must be compared to, a matching of flexibility options with current flexibility applications is required. Examples for flexibility applications are redispatch or day-ahead trade. Regarding the context outlined so far, this Whitepaper intends to discuss the question, how well-suited iDSM – and its different measures – is in comparison to competing flexibility options. In other words, which flexibility option is the most applicable for which flexibility application to adequately meet the system’s need for flexibility?

In order to address this question, the Whitepaper at hand is structured in seven sections: Following Section 2, which provides details on relevant flexibility applications available in the German electricity energy system, Section 3 elaborates on general flexibility options on a higher level, while Section 4 focusses on EFMs resulting from iDSM. In Section 5, the matching of flexibility options and flexibility applications is presented, with limitations and policy recommendations outlined in the subsequent Section 6. The Whitepaper concludes with a summary in Section 7.

2 Flexibility Applications

Flexibility applications outline the demand for flexibility to ensure electricity system stability and to balance electricity supply and demand at any point in time. The different flexibility applications are described in the following.[1]

2.1 Long-Term Storage (Integration of Excess Feed-In)

Excess feed-in refers to the situation of electric energy feed-in exceeding current consumption leading to an overlapping load coverage. Typically, excess feed-ins are balanced by flexible power plants or cross-country exchanges. However, it may occur that the feed-in exceeds the consumption to such an extent, that the fluctuations of the residual load cannot be compensated by the regulation of flexible power plants or the exchange of electric energy with foreign countries. In these cases, renewable energy plants are curtailed. Flexibility options commonly known as “long-term storage” can be used to avoid this curtailment of renewable generation plants [4]. It is important to note, that the storage of excess feed-in does not exclusively refer to seasonal storage, but also includes daily, or weakly storage. The term ‘excess’ does not mean, that the stored electrical energy is plentiful, but rather that this excess feed-in cannot be integrated without the use of flexibility options [4].

Already today, the need for this flexibility option is existent, as the occurrence of negative prices for electric energy on the spot market indicates [5]. In the future, this need will most likely continue to grow [4].

2.2 Participation in Energy-Only Markets

Participation in the Day-Ahead Market (Load-Smoothing Effect)

Day-ahead trading involves the trading of electric energy for the following day. The trading on the European electricity exchange EPEX SPOT SE (European Power Exchange) takes place in form of daily blind auctions, which are conducted at 12 pm on the previous day. In Germany, hourly or multiple hours day-ahead contracts with a minimum volume of 0.1 MW and a minimum price of 1 €/MWh are traded on the EPEX. Due to the high liquidity of the day-ahead market, the German day-ahead price evolved into one of the main European references. All markets of the EPEX, except Switzerland, are part of a multiregional interlinking [6]. A participation in the day-ahead market aims for an optimization of the portfolio and the generation of revenues according to the principle “buy low, sell high”. The participation in the day-ahead market leads to a load-smoothing effect for the grid because fluctuations of the residual load during the day are balanced.

[1] The content in this section stems from project work together with the Forschungsstelle für Energiewirtschaft e.V.

Participation in the Intra-Day Market (Balancing of Identified Forecast Errors)

Short-term electricity contracts are traded on the intra-day market. On the European electricity exchange EPEX SPOT SE it is distinguished between 15-minutes, 30-minutes and 1-hour contracts. In Germany, in the scope of continuous trading, 1-hour contracts are traded from 3 pm of the previous day, 30-minute contracts from 3:30 pm of the previous day and 15-minute contracts from 4 pm of the previous day. A contract must be concluded latest 5 minutes prior to delivery.

On the German market, additional to continuous trading, a daily blind auction takes place at 3 pm, where 15-minute contracts of the following day are traded. The results are published shortly after the blind auction and can be consulted as a price signal. Along the lines of day-ahead trading, contracts are traded in increments of at least 0.1 MW and 0.1 €/MWh [6]. Here, likewise to the day-ahead market, the aim remains the optimization of the portfolio and the generation of revenue according to the principle "buy low, sell high".

Forecast errors in the consumer loads and in electricity generation, particularly of PV and wind energy plants, are responsible for discrepancies in the actual accruing quantity of electricity and the amount from the previous day (cf. day-ahead market) [4]. Due to the participation in the intra-day market, flexibility options can contribute to the compensation of the identified forecast errors and therefore reduce the technical prerequisites on conventional power plants and avoid compensation payments for the settlement of forecast errors.

2.3 Provision of Ancillary Services

The operation of power plants resulting from trading on the wholesale electricity market does not always correspond to the physical balance of demand and supply. Therefore, balancing energy compensates for unforeseen power deviations in the electrical grid. The frequency of the grid acts as an indicator for the balance of electricity feed-in and consumption. The supply of balancing energy, the so-called ancillary services, is carried out by tenders on the balance capacity market. Balancing energy is differentiated into negative balance energy, due to an excess of power on the supply-side (increasing frequency), and positive balance energy, due to a power deficit on the supply-side (decreasing frequency) in the electrical grid. Because of the different requirements, balancing capacity is distinguished into Frequency Containment Reserves (FCR), automatic Frequency Restoration Reserves (aFRR), and manual Frequency Restoration Reserves (mFRR).

Frequency Containment Reserve (FCR)

In case of frequency deviation, Frequency Containment Reserve (FCR) is the first and therefore the short-term measurement for compensation. It is traded daily in 4-hour-blocks [7]. The offered capacity needs to be fully retrievable within 30 seconds and must be available for at least 15 minutes. To avoid time losses, the activation is executed by means of autonomous frequency measurements. If there is a deviation of at least 0.01 Hertz, the supplier is obligated to counteract this deviation. The activation occurs proportionally to the grid frequency, so that with defined deviation of 0.2 Hertz, the withdrawn capacity is fully activated. The compensation of FCR is solely made according to a capacity price [8].

Automatic Frequency Restoration Reserve (aFRR)

The automatic Frequency Restoration Reserve (aFRR) is used to balance out longer-term grid deviations, to replace FCR. This reserve is also traded daily, in 4-hour-blocks. The offered capacity must be fully available within 5 minutes and a first reaction must take place within 30 seconds. Hereby, the activation takes place through a retrieval of the respective transmission system operator. The compensation of aFRR composes of a capacity price and a commodity price component.

Manual Frequency Restoration Reserve (mFRR)

For even longer lasting deviations, the manual Frequency Restoration Reserve (mFRR) supersedes aFRR. Like FCR and aFRR, mFRR is traded daily in 4-hour-blocks, but the offered capacity needs to be fully available within 15 minutes. In analogy to aFRR, the activation is made through the retrieval of the respective transmission system operator and the compensation composes of a capacity price and a commodity price component [9].

2.4 Redispatch 2.0 (Redispatch & Feed-In Management)

Redispatch, as well as feed-in management, are measures of the congestion management for sustaining grid stability and mains fuse. Due to the feed-in prioritization of renewable energy and combined heat and power (CHP) plants, Redispatch exclusively focusses on conventional power plants. Network operators request a reduction or increase of the feed-in of generation plants to eliminate or prevent power overloading. This represents a shift of the feed-in, since the curtailed quantities in one place must be compensated physically and on balance sheet by simultaneous adjustments in another place [10].

Feed-in management, on the contrary, also includes the curtailment of renewable energy and CHP plants, demanded by network operators in case of congestions due to excess feed-in. However, this curtailment may only occur, if all other network security measures, like the regulation of conventional plants in the scope of Redispatch measurements, are already exhausted [11]. With feed-in management, a compensation on balance sheet is also necessary, like it is the case with Redispatch. Therefore, the curtailment of renewable generation in one place requires an increase of the replacement energy in another, grid compatible, place [10].

With the revision of the Netzausbaubeschleunigungsgesetz (NABEG), the regulations regarding feed-in management are abolished by October 01, 2021. Consequently, feed-in management will be integrated into a uniform Redispatch regime ("Redispatch 2.0"). Then, additional plants from 100 kW, as well as remote-controlled plants are included in the Redispatch [12]. The principle of prioritizing renewable energy and CHP plant will be maintained. So, they only can be curtailed, if the avoidance of this curtailment of renewable energy and CHP plants would lead to a scenario where a multitude of conventional generation would have to face a curtailment instead (minimum factor indicated by the imputed price) [10].

2.5 Increase of Self-Consumption

The increase of self-consumption is a flexibility application targeted at end consumers of electricity, which operate a unit for self-generation. The aim is to increase the self-consumption, referring to the amount of the local self-consumed electricity, in order to reduce the withdrawal from the grid and therefore profit from omitted taxes, fees, and levies. This is opposed by a lower grid feed-in of the unit, which results in a reduction of feed-in compensations [4].

With controllable units, like CHP units, an optimization of consumption and generation is already considered in the system planning and realized accordingly through the operation mode of the unit, whereas the use of volatile generating units, like PV units, yield in a further potential for the increase of self-consumption through the application of flexibility options [4]. The use of an energy management system can facilitate such flexibility options by the preparation of forecasts [13].

From a legal perspective, self-consumption is defined as electricity, which a person consumes in a direct spatial link. Thus, the electricity did not pass the grid and the electricity generation unit is operated by the person him- or herself [14]. A significant restriction of self-consumption is the personal identity of generation and final consumption. Moreover, industrial companies need to pay levies and fees, which diminishes the incentive for self-consumption. Due to beneficial regulatory conditions, the optimization of self-consumption in private households, especially in single-family homes with PV-units, had a particular importance in the past [4].

It must be considered, that in contrast to the prior flexibility applications, the increase of self-consumption does not represent a typical flexibility application for electrical grid stabilization from a system perspective [4].

2.6 Further Flexibility Applications (Watchlist)

Table 1 provides an overview over potential flexibility applications, that may serve as a basis for further research.

Table 1: Further flexibility applications.

Further flexibility applications	Description
Peak load management	Operational peak load management does not focus on the grid stability. However, this flexibility application can contribute to ease the strain on the distribution grid.
Flexible grid usage	Within the scope of flexible grid usage, flexibility options can be deployed to conform to the requirements of special forms of grid usage according to § 19 Stromnetzentgeltverordnung (StromNEV). This flexibility application thereby can contribute to the electrical stability (e.g., in case of atypical grid usage). However, the focus of this flexibility application is on the reduction of grid fees (by up to 80 %) for cost savings from a stakeholder perspective.
Interruptible loads	In the context of interruptible loads, the consumer may be instructed to reduce their electricity consumption to eliminate grid congestions or reduce a generation deficit. However, the importance of interruptible loads is significantly decreasing. In 2019, the total breaking capacity was reduced by 50 % to 750 MW, because the former capacity of 1.5 GW was never exhausted.

3 Flexibility Options within the Energy System

To meet the flexibility applications described in the previous section, various flexibility options within the energy system are presented in the following.[2] These options meet the needs of flexibility from the electricity system and respond to the different forms of flexibility available in the different parts of the electrical grid. They can be separated into the following four categories [15–17]:

- **Demand-side flexibility** refers to the management of the electricity demand, to match the electricity supply through increasing, reducing or shifting electricity demand. Therefore, it represents the energy system's ability to adjust demand rapidly to match changes in the supply. Demand-side flexibility includes consumer reaction to price incentives, as well as dispatchable flexibility, on which flexibility capacities are offered and harnessed on demand by grid operators. An example of demand-side flexibility is iDSM, which will be addressed in Section 3.1.1. Due to the number of participants, their different capacities, and availabilities the need for structured coordination of loads of various sizes is a major challenge.
- **Sector coupling** is the interconnection of the different energy demand sectors via the transformation of energy carriers and has been identified to hold a large flexibility potential. There are multiple ways of converting electricity to other forms of energy required by recipients, like the conversion of energy using heat pumps and resistive heating, thereby electrifying heat. Another form of sector coupling is done through Power-to-X technologies, like methanation or electrolysis which will be explained in Sections 3.2.1 and 3.2.2 respectively. Even though it is not always economically viable, the implementation of sector coupling as an energy flexibility option promises significant advantages to the energy system.
- **Energy storage systems** are a key component to overcoming the issue of energy system stability with the increasing use of renewable energies. Due to the intermittency of RES, the value of the generated power can vary strongly throughout an observable timeframe. This volatility can be seen during a small period, i.e., a day but also long term in the form of seasonal storage. Through the use of energy storage systems, such as batteries (Section 3.3.1) or pumped storage hydroelectricity (Section 3.3.2) energy can be stored in times of surplus production and supplied in times of energy scarcity.
- **Supply-side flexibility** is the ability of electricity suppliers to adjust the generated power as a response to changes in the electricity demand. This can be achieved through retrofitting current power generation units with more flexible systems, like adjustable generators or through the coupling of variable RES. Thermal flexibility for example is becoming increasingly important in the transformation of the energy sector, due to decarbonization efforts and the resulting limitation of fuel choices. While supply-side flexibility is mainly concerned with the economically viable usage of investment to current production capabilities, future legislative changes and technological developments should be considered.

[2] The content in this section stems from project work together with the Forschungsstelle für Energiewirtschaft e.V.

While there is a multitude of flexibility options available, they are not always financially or technically viable to address the different flexibility applications. A detailed description of the flexibility options is presented in the following sections, structured by the aforementioned categories.

3.1 Demand-Side Flexibility

3.1.1 Industrial Demand-Side Management

The aim of demand-side management (DSM) is to align the electricity consumption with the electricity generation. Due to the increasing number of predominantly volatile RES and the high share of the industrial sector in electricity consumption, iDSM is gaining in importance [18, 19]. Energy-intensive industries (metal production, chemicals, paper, cement, glass and ceramics) are particularly qualified, since they are responsible for approximately 2/3 of the industrial electricity consumption in Germany [20]. Considering a relatively small number of plants with a relatively high flexible load (several hundred kW up to several hundred MW), these processes represent a strong and controllable lever for flexibility options within the energy system [21].

In numerous studies on load flexibility potential in energy-intensive processes, the aluminum electrolysis, among others, was detected as suitable for a flexible operating mode [22]. Hence, in the following sections of the Whitepaper, this process will be used as an application example of iDSM.

3.2 Sector Coupling

3.2.1 Methanation (Power-to-CH_4)

Methane is an important energy carrier in the industrial sector and energy sector. In recent years, research increased its focus on catalytic and biological methane production as an alternative to fossil natural gas resources. With this technology, efficiency rates of about 83 % for the transformation of electrical energy can be achieved [23]. During the catalytic methanation, hydrogen is reacting with carbon dioxide or monoxide to form water and methane. The used CO_2 for methanation accumulates mostly as a by-product, e.g., in biogas plants. Conventionally, nickel is utilized as catalyst. The process temperature is approximately 200-500 °C [21, 24]. Next to the chemical methanation, the biological methanation represents another variant. In this process, carbon dioxide reacts with hydrogen with the aid of microorganisms, at process temperatures from 35-60 °C, to form methane [25].

The produced methane can be transported and stored in the natural gas infrastructure. Thereby, a high flexibility is given, and existing storage facilities can be accessed in vast capacities [25]. The feed-in is feasible without restrictions, and only a processing of the methane might be necessary [21]. The produced methane is regulatorily treated like biogas, if the used electricity for the electrolysis and the CO_2 for the methanation stem from predominantly renewable energies (Energiewirtschafts-gesetz (EnWG) § 3, Nr. 10c).

3.2.2 Electrolysis (Power-to-H_2)

During hydrogen electrolysis, water is decomposed into hydrogen and oxygen gas using electric energy. The electrolysis consists of two partial reactions. While hydrogen evolves at the cathode, oxygen will appear at the anode. A membrane at the inside of the electrolysis cell ensures a segregation of the hydrogen and oxygen. An electrolyte is responsible for the necessary charge equalization. Dependent on the used electrolyte, different electrolysis processes can be distinguished. Today, the alkaline water electrolysis and the polymer electrolyte membrane (PEM) electrolysis are the most widespread processes, since they already passed the development stage [26, 27].

The produced hydrogen can be stored in gas storages or can be fed into the existing natural gas infrastructure. Contrary to methane, the amount of hydrogen, that can be fed into the natural gas infrastructure, is limited [21]. At present, it is possible to mix up to 10 vol.-% hydrogen into the natural gas infrastructure, depending on the conditioning factors. The future goal is to achieve an admixture of up to 20 vol.-% [28]. Furthermore, hydrogen in its direct form can be used as fuel or raw material for industrial processes [21].

Hydrogen, which was predominantly generated via electricity from renewable energies, is, according to the EnWG, defined as biogas (EnWG § 3, Nr. 10c). Electricity used in this process, which stems from at least 80 % renewable energies, will be exempt from grid fees for 20 years as well as from feed-in fees into the gas infrastructure. Moreover, reduced grid connection costs for feeders (25 %, max. 250,000 €/year), as well as avoided utilization fees of 0.7 ct/kWh injected gas for 10 years can be claimed. On request, electricity used for electrolysis can further be exempt from electricity taxes [21].

Alkaline Water Electrolysis

The alkaline water electrolysis is the oldest electrolysis method and represents the most widespread technology, which achieves efficiency rates of about 73 % during transformation [29]. This technology is already in commercial operation [26] and uses an electrolyte, which consists of 20-40 % potassium hydroxide. The thereby existent alkaline condition increases the conductivity [21].

Polymer Electrolyte Membrane Electrolysis

Polymer Electrolyte Membrane (PEM) Electrolysis is in the early stages of industrial implementation and currently reaches efficiency rates of about 66 % [29]. Plants for demonstration projects are already in place. A proton-conductive membrane is employed as an electrolyte [26, 27]. In comparison with the alkaline water electrolysis, PEM is more compact. Furthermore, a higher current density and hence, a higher power density is achieved, due to the lower electrical resistance [21].

3.2.3 Power-to-Mobility

Controlled Charging

Controlled charging is defined as the charging of electrical vehicles dependent on the available renewable energy as well as the structural framework conditions [30]. This approach reaches efficiency rates of up to 90 % [31]. Network operators publish load forecasts to the power suppliers, so the suppliers can operate the charging stations accordingly [32]. Hence, electric vehicles can only be charged right after the plug-in, if for instance sufficient power of volatile renewables is available.

With the decline of peak loads, expensive oversizing of cables and transformers can be avoided, like a study regarding Germany by Agora Verkehrswende, Agora Energiewende and the Regulatory Assistance Project confirms [32]. Consequently, controlled charging leads to an optimized utilization of renewable energies and simultaneously contributes to a grid stabilization [30].

Bidirectional Charging Management

Bidirectional charging management of electrical vehicles describes the flow of electrical power in both directions [33]. This means that by using a bidirectional wallbox[3], an electrical vehicle, which supports directional charging, can draw electricity in off-peak periods via charging, whereas in periods of peak load provides electricity via discharging. On the contrary to the already established and common unidirectional charging, energy is fed from the battery of the vehicle into the grid in periods of peak demand but low offer from renewable sources. The execution of this bidirectional charging management is currently under research and can reach efficiency rates of about 81 % [31]. The aim of vehicles with energy recovery capability is to optimize the intake of regenerative energies and simultaneously increase the grid stabilization and security of supply.

3.2.4 Power-to-Heat

Power-to-Heat defines the utilization of electrical energy for heat supply. This is possible via various technologies, e.g., electrical heat pumps or electrode boilers. Through Power-to-Heat, the curtailment of renewable energy plants can be avoided by utilizing surplus electricity for heat generation. The produced heat can be used for the heat supply of individual buildings, as well as for district heating [34].

Large-Scale Heat Pumps

Large-scale heat pumps are used for industrial and commercial purposes. The system performance ranges between 2,000 and 50,000 kW. The heat drawn from heat sources, like waste heat or surrounding air, is brought to a higher temperature level by the heat pump. The resulting heat can for example be used as process heat or for the heating of buildings. This technology reaches a thermal efficiency rate of up to 352 % [29]. In contrast to other countries, like the USA or Great Britain, only relatively few large-scale pumps are used in Germany, due to higher electricity prices [35]. Thus, for simultaneous heat and cooling demand, large-scale heat pumps are already economically exploitable. Furthermore, a high temperature of heat sources or a low temperature level of the heat grid facilitates economic operations [36].

[3] A charging station for electrical vehicles, which is intended to be placed on a wall. It functions as an interface between the vehicle and the energy grid.

Electrode Boilers

Electrode boilers produce hot water or steam via several electrodes. They are predominantly utilized for process heat in production as well as district heating in the field of public supplies. Due to a performance capacity in the range of megawatts, a participation in the balancing capacity market is possible without pooling. However, an integration into a pool occurs frequently in practice since operators of electrode boilers already offer balancing capacity [37]. This technology has a thermal efficiency rate of about 99 % [29].

Heat Pumps in Private Households

In private households, heat pumps are particularly used for the heating of warm water, which in return is used for heating or as service water. Heat pumps in private households can reach thermal efficiency rates of up to 299 % [29]. Air-based heat pumps exist in form of air-to-water heat pumps as well as air-to-air heat pumps. The latter does not possess a water tank, which is why they are not further considered as a flexibility option in this context. In contrast to water-to-water heat pumps, the temperature difference with this type is large, which leads to a smaller coefficient of performance [21]. In the context of this Whitepaper, the flexibilization of existing heat pumps is analyzed.

3.3 Energy Storage Systems

3.3.1 Lithium-Ion Battery

A (secondary) lithium-ion battery, also called lithium-ion accumulator, is an electrochemical voltage source based on lithium. It differentiates from the primary lithium-ion battery by being rechargeable [38]. In this Whitepaper, with respect to flexibility options, the focus exclusively lays on the rechargeable secondary version.

Secondary lithium-ion batteries are used in many applications. Photovoltaic (PV), electromobility or even laptops, mobile phones, and tooling equipment. Especially its high energy density (high cell voltage and capacity), barely recognizable self-discharge at room temperature, as well as the non-existing memory-effect[4] are beneficial [38]. In comparison with conventional lead-storage batteries, lithium-ion batteries have a considerably higher durability of up to 20 years. In the following, a distinction is made between small-scale battery storages for private households and large-scale battery storages for commercial purposes. Small-scale battery storages cannot participate on the day-ahead market on their own, whereas with large-scale storages this is possible. However, large-scale storages do not support an increase of self-consumption. Every accumulator with a performance / capacity of max. 30 kW / 30 kWh is generally considered as small-scale storage, whereas accumulators with a higher performance rank among large-scale storages [39].

[4] The memory-effect is observed when an accumulator memorizes the status of the amount of energy after repeated partial discharging and therefore only provides the remembered amount. This leads to the decline of the storage capacity.

Small-Scale Battery Storages (Private Households)

Small-scale battery storages for private households on lithium-ion basis are typically used in PV systems. They are charged with the electric energy from the PV system and can be discharged as needed at any time. The aim is to increase the share of self-consumed energy in the self-generated energy as well as the share of self-generated energy in the self-consumed energy (self-sufficiency) [21].

Even though small-scale battery storages on lithium-ion bases are currently still more expensive than the established lead-accumulators, they enable an evidently more frequent charging or discharging (up to 7,000 times), a clearly deeper discharge (up to almost 100 %) and reach an efficiency rate of up to 95 %. Hence nowadays, the market of PV-storage systems based on lithium-ion technology encompasses numerous producers [40].

Large-Scale Battery Storages

Large-scale battery storages are used for commercial purposes, e.g., for the delivery of (primary) balancing capacity or peak loads. The storages consist of numerous modules, where each is built from a certain number of individual lithium-ion batteries.

3.3.2 Pumped-Storage Hydroelectricity

Pumped-storage hydroelectricity (PSH) is an established and well-engineered technology for the storage of energy. With the aid of electric energy, water is pumped from a lower reservoir into a more highly situated upper reservoir to transform electric energy into potential energy [21, 41].

The electric energy used to deploy the pump is sourced at low prices at times of excess feed-in. In periods with peak demand, this stored water can be converted into electrical energy via turbines and generators. The sale of this peak-load power can be realized at higher prices. Even if the losses in the pumps, turbines and water pipelines are not neglectable, PSH is regarded as the only well-engineered large-scale technology for storing electrical energy cheap as well as efficient over an extended period of time (efficiency near 90 %). An essential advantage of PSH is the fast actuation and the significant load following rate, if needed [42].

Next to 31 PSH facilities and an installed power of 6.4 GW in Germany, there are nine PSH facilities in Luxembourg and Austria, which feed an installed power of 3.4 GW in the German power grid. Altogether, an installed electrical power of 9.8 GW is available [10].

In general, it is differentiated between PSH, which generate electricity solely during pump operation, and PSH, which additionally use the energy of natural inflow. In respect of storage potential, the usage of PSH heavily depends on geographical, ecological, and legal conditions. Hence, the capacity of plants in Germany can only be extended marginally, due to lack of eligible locations [21].

3.4 Supply-Side Flexibility

3.4.1 Flexibilization of Renewable Energies

Due to amended terms of tender in 2017, wind turbines and PV systems were able to participate in the balancing energy market. Hence, tender for aFRR and mFRR now occur on a daily instead of a weekly basis. Furthermore, aFRR must be kept available for only four hours instead of twelve and the required minimum quantity was reduced from five to one megawatt. As a result, operators of renewable generating plants can now participate in tenders in the balancing energy market [43].

Prognoses expect wind turbines and PV systems to be able to hold 14 to 34 % of the negative balancing energy in Germany in 2035, especially due to onshore wind turbines. For positive balancing energy, the prognosis of the relevance of fluctuating energy sources is low [44].

To harness the flexibilization of renewable energies, it is crucial to interlink the individual plants with an information and communications technology (ICT) system. The requirements towards the ICT system depend on the requirements concerning each form of marketing. For example, it is considered that the technical requirements (pre-qualification requirements) for a participation in the Frequency Containment Reserve (FCR) market are higher than for participating in the aFRR market.

3.4.2 Flexibilization of Combined Heat and Power Generation Plants

Combined heat and power (CHP) generation comprises the thermodynamic process of simultaneous conversion of used energy into heat as well as mechanical and electric energy [10]. This technology reaches an efficiency rate of about 95 % [21]. The deployment of CHP plants enables a higher flexibility when combined with thermal energy storages, particularly in form of hot water reservoirs. Due to the thermal energy storage, a decoupling of electricity generation and heat supply is possible. This, on the other hand, enables a timewise decoupling of the supply and demand of heat. This flexibility can be used to achieve higher electricity prices [21].

3.4.3 Gas Turbines Natural Gas

Gas Turbines (GT) are heat engines, consisting of a compressor, a combustion chamber, and a turbine. Initially, air is drawn in and compressed by the compressor. Inside the combusting chamber, air is mixed with a fuel (usually natural gas). Due to combustion of the gas in the chamber, the air is heated up to 1.500 °C, which causes its expansion. The expanded air, together with the combustion gases, strikes the runner of the turbine and actuates it. Therefore, thermal energy is converted into kinetic energy. Out of that, a connected generator generates electrical energy [45].

The high exhaust gas temperatures that develop in the combustion chamber require a continuous cooling of the turbine. Together with the energy losses of the compressor, this means a substantial energy loss. Therefore, only efficiency rates of about 42 % are achieved. Advantages of gas turbines are particularly their rapid commissioning and their quick-start ability [46]. On basis of the low greenhouse gas emissions in comparison to coal-fired power plants, gas power plants are seen as an addition to the electricity generation from renewable sources and therefore as a bridging technology in the course of transformation of the energy system to a renewable one [47]. Start-up and rundown processes with this flexibility option can be performed whenever needed.

3.4.4 Combined Cycle Gas Turbines Natural Gas

In combined cycle power plants, or also referred to as combined cycle gas turbines (CCGT), the waste heat of a gas turbine power plant (above 500 °C), which is produced during the combustion, is used as a heat source for the steam generation of a downstream steam turbine power plant. With the combination of gas and steam turbines, the achieved efficiency is higher than 60 % and thus considerably higher than the efficiency of sole gas turbines [46, 48]. Due to the efficient fuel deployment, gas and steam power plants are used at times of middle load and base load [49]. At times of peak load, the usually more rapidly adaptable and cheaper sole gas turbine power plants, as described in Section 3.4.3, are used, because of the inertia of the steam turbines [48, 50]. With this flexibility option, start-up and rundown processes can be performed when needed.

3.5 Further Flexibility Options (Watchlist)

Table 2 provides an overview over potential flexibility options, that may serve as a basis for further research.

Table 2: Further flexibility options.

Further flexibility options	Description
DSM in private households	A smart meter is a prerequisite for the flexibilization of domestic appliances. Furthermore, the domestic appliances must be able to be connected to the smart grid. Estimations assume, that in 2020, roughly 15 % of all home appliances had the ability to be connected to the smart grid and the number may rise to approximately 60 % in 2030. Next to the technical prerequisites, the development potential is dependent on regulatory parameters, the consumer acceptance and economic aspects [4].
Compressed air reservoir	The obtainable efficiency and energy density of conventional compressed air reservoirs are currently low, so that they only play a minor role. In the future, an increasing importance is possible due to adiabatic concepts [51].
Flywheel generator	Flywheel generators are mechanical energy storages, in which electrical energy is converted into kinetic energy by rotation. Depending on the speed of rotation, electrical energy can be extracted or fed in for short-term storage [52]. Due to their withdraw rate and capacity, they are not suitable for a (very) short-term storage and not for a larger amount of energy and therefore are not analyzed any further [53].
Solid oxide electrolysis (Power-to-H_2)	The solid oxide electrolysis offers the possibility to use process heat for energy supply, so that the use of electrical energy can be

	reduced. However, this technology is still in an early research phase. Current obstacles are the high costs, limited lifetime due to degradation processes, as well as material problems, which result from high operating temperatures [26].
Electrical grid expansion	The electrical grid expansion is, next to flexible producers, consumers and storages, another flexibility option, which enables the balancing of supra-regional fluctuations in supply and demand [54]. Due to the lack of data, this flexibility is not analyzed any further.
Electricity-based fuels (Power-to-Liquid)	Power-to-Liquid describes the generation of fuels with the aid of electrical energy. So far, the underlying technologies are still in an early development phase with limited testing. In the future, power-to-liquid could become more important, if a reduction of costs can be achieved [55].
Lean-acid battery	The share of new-installed lean-acid batteries for small-scale battery storages decreased in favor of lithium-ion batteries over the last years. In 2018, the share of lithium-ion batteries was at almost 100 %. Even when it comes to large-scale battery storages, lean-acid batteries, in contrast to lithium-ion batteries, only possess a minor share, regarding the cumulative battery storage capacity [56].
Redox flow battery	In contrast to conventional batteries, redox flow batteries can scale the storage capacity regardless of the performance. However, they are still in the development phase. Their low energy density, the handling of high volumes of acids combined with high costs remain, however, significant obstacles for a wider spread [57].
CCGT hard coal	On July 3rd, 2020, Germany passed the law for the coal phase-out [58]. In 2038, the capacity of coal-fired power plants is planned to be at 0 % [59]. Therefore, this flexibility option is not considered any further.
GT mineral oil	Most gas turbines are fueled with natural gas [58]. Therefore, GT natural gas is analyzed as a flexibility option, while GT based on mineral oils is not considered any further.

4 Detailed Analysis of Industrial Demand-Side Management Measures

This section takes a closer look at the flexibility option iDSM and the underlying EFMs. In doing so, the key concept of EFMs is introduced in Section 4.1. Section 4.2 provides a categorization of organizational and technical EFMs of iDSM and introduces 15 different EFMs underlying iDSM according to recent literature contributions [60–62]. Section 4.3 describes each of the organizational and technical EFMs, whereas Section 4.4 characterizes 8 out of these 15 EFMs in more depth, which were empirically identified at industrial companies within the Kopernikus-project SynErgie. The characterization is based on empirical data, obtained by a structured survey, on four key technical indicators for EFMs of industrial companies: (1) type of energy flexibility, (2) activation duration, (3) active duration, and (4) flexible power (see Section 4.4). Although there may be additional technical indicators important to consider when matching EFMs with flexibility applications, flexible power, activation duration, and active duration to reflect the most essential technical characteristics and boundary conditions for the provision of flexibility [63]. Finally, we briefly address the regulatory and social aspects of the considered EFMs in Section 4.5.

4.1 Energy Flexibility Measures

An EFM is a conscious and quantifiable action of a flexibility option to adjust its operative state to, e.g., price signals [62] Changes in the operative state refer to changes in its electricity consumption. Through the activation of an EFM, the flexibility option is thus able to adapt its electricity consumption. With regard to industrial companies, we refer to EFMs of industrial companies as iDSM measures. iDSM measures can be implemented at different levels within the industrial companies, which might be represented by a specific machine, a series of machines that execute a similar task, or even the complete energy infrastructure of a factory.

4.2 Differentiation of Industrial Demand-Side Management into Organizational and Technical Measures

iDSM measures can be generally differentiated into organizational and technical measures [62, 64]. Both, organizational and technical iDSM measures can either shift the energy demand of industrial systems (load shifting), where the overall energy demand does not change, or alter the energy demand of industrial systems (load shedding, load increase or decrease). Organizational iDSM measures represent production planning adaptions that affect the electrical energy consumption of a process. Such organizational iDSM measures mostly lead to a shift of the energy demand. In contrast, technical iDSM measures directly influence the machine-product-specific electrical load profile due to changes, e.g., in efficiency of the industrial system in use or in the energy sources in use. Table 3 provides an overview of technical and organizational iDSM measures identified by relevant literature [60–62].

Table 3: Classification of organizational and technical iDSM measures [62].

Classification	iDSM measure
Organizational	Adaptation of staff break times
	Adaptation of working shifts
	Adaptation of order execution sequence
	Capacity planning adjustment
	Adaptation of production start
	Manufacturing order interruption
	Adaptation of order production sequence
	Adaptation of resource allocation
Technical	Adaptation of operation parameters
	Operation interruption
	Adjustment of the operational sequence
	Inherent energy storage
	Bivalent operation
	Energy carrier exchange
	Dedicated energy storage

4.3 Detailed Description of Industrial Demand-Side Management Measures

In the following Section, we provide detailed descriptions for organizational and technical iDSM measures.

4.3.1 Organizational Measures

Adaptation of Staff Break Times

The iDSM measure adaptation of staff break times relates to shifting employees' break times in the short-term. This measure can be applied when employees' work-related activities have an immediate effect on the electricity consumption of a production facility. A production facility may comprise a series of industrial systems, e.g., production lines or cells. Each industrial system, in turn, may include different components, e.g., machines, executing intended production processes that yield a specific good [62, 65]. An example for this iDSM measure may be shifting the lunch break by half an hour in response to electricity price signals, leading to a short-term shift in energy consumption. However, this iDSM measure is only suited for production processes in which the staff break times do not have to follow a strict schedule, e.g., due to externalities of a production process.

Adaptation of Working Shifts

The *adaptation of working shifts* relates to aligning the employees' working shifts with an intended electricity consumption profile. Exemplary applications refer to effectively moving working shifts to periods with excess electricity supply from RES, and therefore low electricity prices (e.g., during public holidays and weekends). This iDSM measure can only be implemented if shift plans provide sufficient degrees of freedom. For example, this does not apply to production processes operating in 24 hour / 7 days a week shift operation.

Adaptation of Order Execution Sequence

The *adaptation of order execution sequence* refers to changing the chronological sequence in which different manufacturing orders are processed. The underlying idea behind this measure builds on the fact that processing different manufacturing orders may feature different electricity consumption profiles. For example, the electricity consumption of a component (i.e., a machine or workstation) may vary for different goods (i.e., manufacturing orders) that are processed. Hence, adapting the order execution sequence of manufacturing orders leads to a change in the electricity consumption of affected components and the industrial system at large. An example for applying this iDSM measure would be processing manufacturing order A instead of manufacturing order B to induce a change in electricity consumption.

Capacity Planning Adjustment

Changing the production schedule with respect to which component is used to produce a specific good, relates to the iDSM measure *capacity planning adjustment*. Individual components of an industrial system may feature different electricity consumption profiles, depending on the technology used, age, model, and customized designs of the component. Consequently, the assignment of a good to a component determines the electricity consumption required to process the respective good. For example, a good may be processed by either one of two different components A or B. Component A may feature a longer processing time at lower load as compared to component B. Although the total electricity consumption of both components may be equal, changing the assignment of the good to component A or B will change the electricity consumption profile and therefore provides flexibility.

Adaptation of Production Start

The iDSM measure *adaptation of production start* relates to an early or delayed start of production. For example, available production capacities or seasonal sales fluctuations may constitute the foundation for adapted production starts. In the short term, inherent buffers allow to adapt production starts. In the long term, excess production capacities allow to accept and process additional orders.

Manufacturing Order Interruption

The *manufacturing order interruption* induces a short-term interruption of the manufacturing order and leads to an abrupt, but temporary change in electricity consumption at those components of an industrial system that are engaged with processing this manufacturing order. Opportunity costs that stem from potential damages to machines and quality losses are important to consider when deciding on whether a *manufacturing order interruption* may be applied or not. Processes that are indirectly associated with adding value to a good, such as test facilities, are particularly suitable for the application of this measure.

Adaptation of Order Production Sequence

Changing the production sequence in which one specific order is being processed relates to the iDSM measure *adaptation of order production sequence*. This measure builds on the idea that one order may involve different production steps conducted at different components and featuring different electricity consumption profiles. For example, changing the sequence in which one specific order is processed at components A and B may induce a change in the electricity consumption profile. While the iDSM measure *adaptation of order execution sequence* refers to the chronological sequence in which different manufacturing orders are processed, the iDSM measure *adaptation of order production sequence* refers to a sequence in which one specific order is processed by different components.

Adaptation of Resource Allocation

The iDSM measure *adaptation of resource allocation* relates to a targeted selection of distinct components of an industrial system (e.g., individual machines) for a production process based on their resource consumption. While the iDSM measure *capacity planning adjustment* refers to the assignment of a good to a component, an adaption of resource allocation refers to the selection of a component to optimize resource consumption irrespective which good is processed by the component. For example, an industrial system may comprise two components that perform the same task but rely on different energy carriers, e.g., gas or electricity. Therefore, for an adaptation of resource allocation, different components featuring different demands for energy carriers are required. A targeted utilization of those components, in turn, changes the electricity consumption profile of the industrial system. In this regard, it is important to consider that an optimal resource allocation complies with quality and efficiency requirements and does not interfere with up- or downstream processes. An *adaption of resource allocation* differs from a bivalent operation in the sense that for a bivalent operation, the same component may dynamically switch between different energy carriers.

4.3.2 Technical Measures

Adaptation of Operation Parameters

The *adaptation of operation parameters* describes changing production process parameters, e.g., heat supply, as compared to a standard process to fit different electricity consumption profiles. However, process parameters must comply with respective tolerances. This, in turn, leads to an adjusted operation of an industrial system, which consequently affects the electricity consumption and/or the efficiency of the production.

Operation Interruption

An *operation interruption* induces a temporary suspension of the operation of an industrial system in the short term. Hence, this measure intermits the electricity consumption of the system. While a *manufacturing order interruption* refers to interrupting all components used to process a specific manufacturing order, an *operation interruption* affects specific components irrespective of which manufacturing orders they process.

Adaptation of the Operational Sequence

The iDSM measure *adaption of the operational sequence* relates to a change in the sequence of one specific component conducting different production tasks. Specifically, this measure refers to changing the chronological production sequence of a specific component. For example, one component may perform production tasks 1, 2, and 3 where each task exhibits a different electricity consumption pattern. Changing the sequence of production task, therefore, changes the electricity consumption profile at this component.

Inherent Energy Storage

The concept of *inherent energy storage* relies on the operative inertia of an industrial system. For example, technical processing parameters of industrial systems may feature specific tolerances (e.g., temperature ranges). These tolerances provide a possibility to adjust the electricity consumption. Response time and storage capacity of inherent energy storages determine the extent to which industrial systems can utilize iDSM measures.

Bivalent Operation

A *bivalent operation* of an industrial system describes switching between two different energy carriers to execute production. Consequently, bivalent industrial systems rely on the integrated use of more than one energy carrier. Switching dynamically and seamlessly between energy carriers is the prerequisite for industrial systems to qualify for this iDSM measure. For example, metal can be melted by resistance heating elements or gas torch, and thus by electrical or chemical energy. This, however, has significant effects on the production process (e.g., on processing time). While a *bivalent operation* of an industrial system leads to a change in the production process, the iDSM measure *energy carrier exchange*, that refers to switching the energy carrier entirely, has no effect on the production process.

Energy Carrier Exchange

The iDSM measure *energy carrier exchange* refers to switching the energy carrier that is used to cover the energy demand of production. For example, temporarily substituting electricity with an alternative energy carrier such as gas may lead to a change in the overall electricity consumption related to the production process. In contrast to the iDSM measure *bivalent operation*, specific production processes remain unaffected by an energy carrier exchange. For example, thermal energy demand of production may be covered by either a CHP unit or an electricity-operated steam generator.

Dedicated Energy Storage

The concept of *dedicated energy storage* relates to the deliberate storage of energy by means of a suitable storage medium. An energy storage system enables to either withdraw and store additional energy from the industrial system or to provide production processes with energy from the storage medium, which ultimately results in temporarily withdrawing less energy from the public energy system. This measure can be applied within a single component or even multiple industrial systems (factory-level).

4.4 Characterization of Selected Industrial Demand-Side Management Measures

In this Section, we consider empirical data from the Kopernikus-project SynErgie to characterize the iDSM measures. Considered data stems from medium- to large-scale industrial companies and comprises the following key technical characteristics for iDSM measures [60]:

- **Flexibility type:** describes the changes in the operative state of the industrial system through the iDSM measure activation. There are four possible directions available – load increase, load decrease, bidirectional and load shift. They indicate the direction of the change in electricity consumption induced by the iDSM measures. The types of flexibility indicate how the industrial system will adapt to changes in the energy markets.
- **Flexible power:** is the power delta that describes the maximum difference between the iDSM measure induced and original operative state of the industrial system, which results in a shift in electricity consumption.
- **Activation duration:** constitutes the timespan between the enactment of an iDSM measure to the resulting modification of the operative state of the industrial system.
- **Active duration:** is the minimum and maximum period for which an iDSM measure can be activated.

Four technical and four organizational iDSM measures, i.e., 8 out of 15 measures, could be empirically derived and quantified within the Kopernikus-project SynErgie. On this basis, multiple and different response data sets of various industrial companies for the same flexibility measure are presented in the form of ranges. No empirical data could be identified for four organizational and three technical iDSM measures. However, these measures are listed as further potential options for energy flexibility in

Section 4.2 as they are important to consider for industrial companies when identifying flexibility potentials. Table 4 provides a characterization of considered iDSM measures.

Regarding organizational measures, the *adaptation of staff free time* and the *adaptation of working shifts* exhibit similar characteristics with an activation duration of 480 minutes, whereas the latter allows a 16 times higher active duration with up to 5 times higher flexible power. Compared to this, *defer of production start* and *adaptation of resource allocation* offer similar values in active duration and flexible power or exceed them, especially in the availability of flexible power.

Regarding technical measures, especially with respect to flexible power, the *adaptation of operation parameters* and *operation interruption* represent a significantly higher flexible power available with up to 9,000 kW as compared to organizational measures. It is also evident that the activation times for *dedicated energy storage* and *energy carrier exchange* are extremely short with 1 to 60 minutes. No data could be retrieved from participating industrial companies for *Adjustment of the operational sequence*, *inherent energy storage* and *bivalent operation*.

Table 4: Characterization of iDSM measures.

iDSM measure	Type	Activation duration (min.)	Active duration (min.)	Flexible power (kW)
Organizational measures				
Adaptation of staff break times	Load Shift	480	< 30	14 – 20
Adaptation of working shifts	Load Shift	480	> 480	13 – 100
Adaptation of order execution sequence				
Capacity planning Adjustment				
Adaptation of production start	Load Shift	480 – 1080	60 – 900	20 – 400
Manufacturing order Interruption				
Adaptation of order production sequence				
Adaptation of resource allocation	Bidirectional		12 – 480	43 – 498
Technical measures				
Adaptation of operation parameters	Bidirectional		15 – 2880	10 – 90000
Operation interruption	Load Shift		60 – 1440	194 – 9000
Adjustment of the operational sequence				
Inherent energy storage				
Bivalent operation				
Energy carrier exchange	Load Shedding	60	480 – 1440	180 – 500
Dedicated energy storage	Load Shift	1 – 15	60 – 774	42 – 280

4.5 Regulatory Framework and Societal Challenges for Industrial Demand-side Management Measures

While technical indicators are particularly useful to define and characterize individual iDSM measures, the regulatory framework of iDSM as well as societal preconditions determine how, and under which circumstances industrial companies may effectively provide and market their flexibility [66]. This Section provides a brief overview on the key regulatory aspects that are important to consider for a successful implementation of iDSM measures. Specifically, current challenges for iDSM that result from the regulatory framework in Germany include (1) fees and charges that penalize the provision of flexibility [67], (2) a lack of market-based incentives to provide flexibility [66, 68], and (3) complex and elaborate prequalification requirements [69]. Further, this Section outlines societal challenges associated with the implementation of iDSM measures.

Fees and Charges

In Germany, energy-intensive industrial companies incur individually agreed and thus potentially lower grid fees based on a constant load profile. In contrast, variable load profiles with high peak loads result in considerably higher grid fees. Hence, the risk of being penalized for deviating from a constant load profile may keep energy-intensive industrial companies from implementing iDSM measures [67]. In addition, industrial companies may risk eligibility for reduced charges, levies, and taxes for electricity when they engage in iDSM measures. For example, above a certain electricity consumption level, energy-intensive industrial companies have to pay a reduced levy set by the Erneuerbare-Energien-Gesetz (EEG), which is a levy introduced by the German government to finance renewable energies. When industrial companies implement iDSM measures, however, they might reduce their overall energy consumption – thereby risking staying below the electricity consumption level that would make them eligible for the reduced EEG levy. As a result, iDSM measures may lead to increased electricity costs for energy-intensive industrial companies, which is an obstacle to the provision of DSM.

Lack of Market-Based Incentives

The economic viability of iDSM measures is highly related to the availability of financial incentives. In this respect, a suitable market design should induce financial incentives, e.g., in terms of market-based pricing signals that reflect a system's need for flexibility. A lack of incentives represents a fundamental obstacle for the implementation of industrial demand-side measures [70].

Complex and Elaborate Prequalification Requirements

Depending on the intended application for an iDSM measure, industrial companies are required to pass a formal prequalification process, that a specific flexibility measure fulfils various prerequisites (e.g., the availability of an adequate metering and control infrastructure). Although it is important to assure that industrial demand-side flexibility measures meet the high-quality standards of flexibility applications, the associated prequalification processes are often complex, time consuming and require specific legal expertise. Such prequalification processes confront industrial companies with a major operational challenge, as in many cases, industrial companies simply cannot access the required expertise internally [71]. Overall, current regulatory challenges increase the complexity of administrative efforts associated with the implementation of iDSM measures and may even hinder an economically viable marketing of flexibility.

Societal Challenges

Besides regulatory aspects associated with the provision of iDSM measures, societal challenges are important to ensure a considerate implementation of the presented iDSM measures based on public acceptance and support. Therefore, employees should play a central role in the design and implementation of iDSM measures. For example, it is imperative to comply with labor legislation when introducing flexibility measures related to adjusting employees' break times or shift scheduling [72]. To that end, the social impact of iDSM measures must not result in adverse or inequitable effects for employees. Instead iDSM measures must be brought into line with adequate working conditions. Overall, however, iDSM measures feature a high social acceptance [71] as they represent an important cornerstone of the energy transition towards sustainability. Nevertheless, it is imperative to holistically address technical, regulatory, and societal aspects associated with iDSM measures.

5 Matching of Flexibility Options and Industrial Demand-Side Management Measures with Flexibility Applications

While this Whitepaper takes a detailed look at flexibility options in Section 3 and iDSM measures in Section 4, we now evaluate their fit with flexibility applications, described in Section 2. To that end, we match flexibility options and particularly iDSM measures with flexibility applications based on technical and regulatory aspects. Specifically, we compare the technical and regulatory requirements of flexibility applications with characteristics of flexibility options and iDSM measures. Section 5.1 outlines the matching objective. Section 5.2 comprises a brief description of the matching process. Matching results are presented in Section 5.3 and Section 5.4 summarizes respective findings and concluding remarks.[5]

5.1 Matching Objective

The objective of the described matching approach is twofold: First, the matching results reveal insights on which flexibility options and iDSM measures may be suitable for each flexibility application. Such information induces significant implications for the targeted development of flexibility options for a future energy system. Second, matching results indicate for which flexibility applications iDSM measures compete against other flexibility options (e.g., incumbent flexibility options such as natural gas-powered turbines). A standalone comparison of technical characteristics of discussed flexibility options and iDSM measures neglecting flexibility options' requirements would lack such information. This integrated perspective, in turn, may serve as a starting point for a detailed assessment and comparison of flexibility options and iDSM measures with respect to their flexibility potential and associated costs on a system level as well as the economic feasibility for providers of such flexibility.

5.2 Description of the Matching Process

For the matching process, technical parameters were used to determine which flexibility options meet the requirements of which flexibility application. Therefore, the criteria shown in Table 5 were selected as relevant conditions. In the case, that for a flexibility option only data on the activation time was available, it was checked whether the activation time was less than or equal to the sum of the planning duration and the power gradient. In addition, compliance with regulatory requirements was reviewed and a plausibility check was performed. Only if all conditions are fully met, a flexibility option matches with a flexibility application.

[5] The content in this section stems from project work together with the Forschungsstelle für Energiewirtschaft e.V.

Table 5: Matching conditions based on technical parameters.

Flexibility application characteristics	Required condition	Flexibility option characteristics
planning duration	≧	planning duration
power gradient	≧	ramp-up time
derivative action time	≦	storage duration
active duration	≦	active duration

5.3 Matching Results per Flexibility Application

Table 6 provides the matching results and indicates whether a flexibility option fulfils the requirements of a flexibility application based on specified technical parameters in Table 5. The results discussed in the following are split into flexibility applications stemming from excess feed-in, energy-only markets or ancillary services.

5.3.1 Long-Term Storage (Integration of Excess Feed-In)

For the integration of excess feed-in, most of the flexibility options based on sector coupling applications (i.e., electrolysis, methanation, power-to-heat) fulfill all requirements and, thus, consistently match with the integration of excess feed-in. This can be attributed to the fact that sector coupling flexibility options predominantly feature relatively long active durations required for the integration of excess feed-in. However, one exemption among sector coupling flexibility options are power-to-mobility flexibility options. Here, a utilization for the integration of excess feed-in is not feasible due to a short active duration of around 5.5 hours, while we assumed active durations of at least 48 hours for the integration of excess feed-in.

Regarding storage-based flexibility options, only Large-scale heat storage systems allow for an integration of excess feed-in whereas small- and large-scale lithium-ion batteries as well as PSH fail to fully comply with the minimum required active duration of 10 hours. Based on the current usage of PSH, this flexibility option exhibits an active duration of 10 hours. Thermal power units, such as combined heat power generation, natural gas-based turbines, and combined cycle power plants, can be consistently applied since the integration of excess feed-in requires a relatively low activation duration but a long active duration.

Turning to organizational iDSM measures, our results reveal that an *adaptation of the staff break time* as well as the order execution sequence fails to integrate excess feed-in. Although the activation duration would be sufficient for the integration of excess feed-in, the active duration represents the limiting factor for both DSM measures that hinders a utilization for this flexibility application. In contrast, remaining organizational iDSM measures (adaptation of production start and manufacturing order interruption) feature longer active durations and, thus, match with the integration of excess feed-in.

Regarding the operational applicability of technical iDSM measures to the integration of excess feed-in, our results indicate that an adaptation of operation parameters as well as an energy carrier exchange are feasible. However, technical iDSM measures that rely on inherent or dedicated energy storage fail to fully comply with the technical requirements stated by the flexibility option integration of excess feed-in. Specifically, the underlying reason is that some of the considered inherent or dedicated energy storage measures fail to fulfill technical requirements in terms of activation duration, while others do so in terms of active duration. Overall, none of the considered measures complies with both requirements, activation duration and active duration.

5.3.2 Energy-Only Markets

Regarding flexibility applications that are based on energy-only-markets, i.e., the day-ahead and intraday market, matching results provide a mixed picture for the applicability of flexibility options that build on the concept of sector coupling, such as electrolysis as well as methanation, power-to-mobility, and power-to-heat. While alkaline water and PEM electrolysis provide viable flexibility option for the day-ahead and intraday market, methanation, power-to-mobility, and power-to-heat, fail to fulfil the technical criteria required by energy-only-markets. This is since activation duration of the flexibility options methanation is too long for the requirements of the energy-only markets. The flexibility options power-to-mobility, and power-to-heat are excluded because of their flexible power, as the minimal requirement for flexible power on energy-only markets is 0.1 MW.

Flexibility options based on large-scale storage technologies, such as large-scale lithium-ion batteries, heat storages, or PSH, fully comply with the requirement for marketing flexibility on the day-ahead and intraday market. However, small-scale lithium-ion batteries form an exception due to low flexible power, which prevents the provision of flexibility to these markets.

Flexibility options that rely on thermal power units, i.e., combined heat power generation, natural gas-based turbines, and combined cycle power plants, consistently match both, the day-ahead and intraday market.

For organizational iDSM measures, matching results reveal that an *adaptation of staff free time* yields a flexibility potential that qualifies for the day-ahead market only. This is due to long activation durations of some organizational measures that require planning processes up to several hours before activation. This ultimately contradicts with a short-term activation required by the intraday market. The activation duration associated with an *adaptation of the order execution sequence* allows to market flexibility on both, the day-ahead and intraday market. However, an active duration shorter that one hour qualifies only for the intraday market. The remaining organizational DSM measures, i.e., *adaptation of production start* or *manufacturing order interruption*, feature characteristics that allow an application to both, the day-ahead and intraday market.

Regarding technical iDSM measures, the *adaptation of operation parameters* as well as the *energy carrier exchange* fulfill all substantial technical and regulatory requirements to utilize respective flexibility potentials at the day-ahead and intraday market. In contrast, iDSM measures that rely *on inherent or dedicated energy storage* allow a utilization solely on the intraday market due to short active durations.

5.3.3 Ancillary Services

Regarding the flexibility applications known as ancillary services, i.e., frequency containment reserve, aFRR (positive and negative), and mFRR (positive and negative), the matching predominantly identifies electrolysis and thermal power units as applicable flexibility options. Further, large-scale battery storages, large-scale heat storages and PSH fulfill the technical requirements for providing ancillary services. However, methanation, power-to-heat units as well as small-scale battery storages do not match these flexibility applications. The flexible power of single small-scale batteries and heat pumps is not sufficient to fulfill the requirements for ancillary services as the minimum power requirement ranges from 1 to 5 MW, depending on the type of service.

In contrast to pumped hydro storage, the large-scale heat and battery storages feature an activation duration short enough to market frequency containment reserve. For automatic and manual frequency restoration reserve, all the analyzed energy storages can be marketed. Regarding thermal power units, only the CHP plants can deliver frequency containment reserve, due to the low activation duration. For positive and negative frequency restoration – automatic or manual – also natural gas-fired turbines fulfill the technical requirements. Combined-cycle gas power plants can only be marketed for manual frequency restoration.

Looking at the iDSM measures, the *adaptation of operation parameters* as well as the *energy carrier exchange* are applicable for every single application within the ancillary services, as they offer a variety in possible realizations regarding activation and active duration. The iDSM measures *adaption of production start* and *manufacturing order interruption* are only applicable for positive frequency reserve, meaning that those flexibility measures can only induce a temporarily reduced electrical load of the industrial system. Depending on the definition of the iDSM measure, an *adaptation of production start* or *manufacturing order interruption* can also be interpreted as an increase in electrical load. As we define flexibility as a deviation from a baseline load profile – in this case without flexibility provision e.g., the production would start – the adaptation of production start or manufacturing order interruption can be considered as load shedding. Furthermore, the considered *inherent or dedicated energy storages* within the SynErgie project also fulfill the technical requirements to market frequency containment reserve.

Table 6: Aggregated results for matching flexibility options with flexibility applications.

	Energy-only markets		Ancillary Services					Long-term storage
Flexibility Option	**Day-ahead market**	**Intraday market**	**Frequency Containment Reserve**	**Automatic Frequency Restoration Reserve - negative**	**Automatic Frequency Restoration Reserve - positive**	**Manual Frequency Restoration Reserve - negative**	**Manual Frequency Restoration Reserve - positive**	**Integration of excess feed-in**
Electrolysis - alkaline water electrolysis	+	+	+	+	+	+	+	+
Electrolysis - polymer electrolyte membrane electrolysis	+	+	+	+	+	+	+	+
Methanation	-	-	-	-	-	-	-	+
Power-to-Mobility	-	-	-	-	-	-	-	-
Power-to-Heat - heat pumps household	-	-	-	-	-	-	-	-
Lithium-ion battery - small-scale (households)	-	-	-	-	-	-	-	-
Lithium-ion battery - large-scale	+	+	+	+	+	+	+	-
Large-scale heat storage	+	+	+	+	+	+	+	+
Pumped-storage hydroelectricity	+	+	-	+	+	+	+	-
Combined heat power generation	+	+	+	+	+	+	+	-
Gas turbine natural gas	+	+	-	+	+	+	+	+
Combined cycle power plants	+	+	-	-	-	+	+	+
iDSM Measures								
Adaptation of Break Times (o)	+	-	-	-	-	-	-	-
Adaptation of order execution sequence (o)	-	+	-	-	-	-	-	-
Adaptation of production start (o)	+	+	-	-	+	-	+	+
Manufacturing order interruption (o)	+	+	-	-	+	-	+	+
Adaptation of operation parameters (t)	+	+	+	+	+	+	+	+
Energy carrier Exchange (t)	+	+	+	+	+	+	+	+
Inherent or dedicated Energy Storage (t)	-	+	+	-	-	-	-	-

+ flexibility option matches flexibility application; - flexibility option does not match flexibility application
(o): organizational iDSM measures; (t): technical iDSM measures

5.4 Summary and Conclusion

Our results illustrate that there are iDSM measures that meet the requirements of all identified flexibility applications. The adaptation of operation parameters and the energy carrier exchange are iDSM measures that exhibit the highest applicability and can therefore be characterized as the most flexible iDSM measure, with regard to the possible flexibility applications. The *adaptation of production start* as well as the *manufacturing order interruption* meet the requirements for most of the flexibility applications and can be used for the same flexibility applications. In contrast, the *adaption of break times* and the *adaption of order sequence* are only applicable for selected flexibility applications. Looking at flexibility options beyond iDSM, this also applies to energy storages. Furthermore, most of the iDSM measures comply with the requirements of the applications for energy-only markets, i.e., the day-ahead and intraday-market. For ancillary services that require an increase in electricity consumption, iDSM measures can only provide a limited contribution to the needed flexibility. In comparison to ancillary services that require a reduction of electricity consumption, iDSM provides several flexibility measures, that meet these requirements. These iDSM measures compete against electrolysis, large-scale batteries, large-scale heat storages, pumped hydro storages, and thermal power plants like CHP plants. Also, for the integration of excess feed-in, iDSM provides a contribution to the needed flexibility (see Table 6). Looking at all flexibility options, iDSM competes with further flexibility options. Therefore, iDSM must reach a competitive price level in order to be able to assert itself on the market.

6 Limitations and Policy Recommendations

6.1 Limitations of the Whitepaper

We see three potential limitations of the current Whitepaper:

First, the flexibility options, in particular iDSM, are characterized and matched by means of activation duration as well as active duration and whether a flexibility option allows to temporarily increase or decrease load (or both). Even though the considered characteristics represent highly relevant aspects for determining the applicability of a specific flexibility option for flexibility applications, there may be further characteristics that need to be considered. For example, economic requirements that relate to the profitability of a flexibility option as well as technical requirements in terms of an advanced metering infrastructure are disregarded. Therefore, we encourage further research to extend the scope of this Whitepaper by extending the characteristics considered for the matching process of flexibility options and flexibility applications.

Second, this Whitepaper is bound to the inherent limitations of empirical research. On the one hand, the Whitepaper offers new and highly relevant insights into the applicability of flexibility options in Germany as it builds on extant research and empirical data on flexibility applications, flexibility options, and iDSM measures. On the other hand, the empirical results of this Whitepaper are subject to uncertainty, respectively do not constitute factual evidence. Therefore, further research should investigate the generalizability of our results. For example, the results of this Whitepaper do neither reflect the potential of flexibility options that are not yet presented in existing literature nor contain practical implementations of a low maturity level. With regard to these flexibility options, which are not part of this Whitepaper, no conclusion can be drawn about the applicability of these flexibility options to the considered flexibility applications. However, Sections 2.6 and 3.5 include watchlists that characterize potential future flexibility applications and flexibility options, that may serve as a basis for further research.

Third, the characterization of iDSM measures is subject to limited data availability. Specifically, the dataset comprises a limited number of industrial companies participating in the Kopernikus-project SynErgie. Further, the involved industrial companies were only able to determine a limited number of parameters that allowed for a characterization of individual iDSM measures. For example, not all considered industrial companies could explicitly specify costs associated with the provision of an iDSM measure.

Still, this Whitepaper provides first and highly needed insights to evaluate the applicability of iDSM measures for different flexibility applications based on a set of real-world industrial companies. Thus, this Whitepaper represents a starting point for subsequent analyses building on larger datasets and more variables to comprehensively characterize iDSM measures and their applicability to flexibility applications.

6.2 Policy Recommendations

Based on the previous sections of this Whitepaper and in line with the SynErgie position paper [67], we derive various policy implications.

First, policy makers should, in the short and medium term, create incentives for industrial companies to invest in iDSM measures and to provide more flexibility, respectively. In Germany, existing regulation currently inhibits investments in iDSM measures and the use of flexibility. There is a need for change in this regard, particularly with respect to grid charges, and the conflicting existence of energy flexibility and energy efficiency. Regarding grid charges, the current design of the Grid Charges Ordinance (StromNEV) may penalize the provision of grid- and system-serving demand-side flexibility, as industrial companies are threatened with the loss of their individual (lower) grid charges due to possible load peaks as a result of the provision of flexibility. Therefore, this Whitepaper also recommends that regulators amend the StromNEV with the aim of ensuring that the provision of grid- and system-serving flexibility potentials does not have a detrimental effect on granting individual grid charges. With regard to possible conflicts between energy flexibility and energy efficiency, current regulations punish industrial companies in some cases, e.g., through the loss of the existential reduction of the EEG levy in the event that the industrial companies cannot meet certain efficiency targets due to the use of flexibility. Policy makers should adapt legislation to ensure that industrial companies do not suffer from any disadvantage if their energy efficiency deteriorates as a result of providing flexibility. With regard to the grid connection capacity of industrial companies, i.e., the contractually agreed maximum electricity consumption between the grid operator and the industrial company, further barriers need to be lifted. In terms of electricity demand and provision of flexibility, that serves the grid, the system, or the market can lead to these industrial companies exceeding the grid connection capacity. This leads to an increase in this grid connection capacity for which a penalty charge is due. Policy makers should eliminate this additional cost risk for industrial companies. Specifically, Distribution System Operators (DSOs) should deviate from the statically defined maximum grid connection capacity and take free grid capacities into account by dynamically considering the actual load flows.

Second, with respect to creating investment incentives, there are also mid- to long-term needs for change, especially with regard to flexibility product design as well as the (non-discriminatory) access of industrial companies to flexibility applications (i.e., market access). Especially at the distribution grid level, there are no standardized options for using grid-serving flexibility to counteract local grid congestion. Policy makers should therefore aim to ensure that the products on the power exchanges and for ancillary services are continuously developed. Bidding formats as well as pricing and allocation rules should be examined and, if necessary, adapted, especially for the short-term markets, e.g., intraday trading. Better consideration of the technical characteristics of market players in product development, bidding formats, pricing and allocation rules would simplify market access and increase liquidity. With regard to non-discriminatory access, the flexibility applications in the area of ancillary services, for example, are not accessible to all participants due to a prequalification process defined by the Electricity Transmission System Operation Guideline (SO GL) and the Electricity Balancing Guideline (EBGL) System and the needed technical requirements.

Third, policy makers should rethink the current charges and levies regarding electricity prices as well as the electricity tax, as the current system distorts such electricity price signals. In other words, low and negative electricity prices on power exchanges are hardly reflected in the effective electricity prices of most industrial companies. Moreover, policy makers should adapt charges and levies in a way that creates incentives to use electricity in other sectors as well. For instance, the electricity price – including charges, levies, and electricity tax – should better reflect the actual grid situation, i.e., the current infeed of RES as well as the grid's utilization, so that more consumers are incentivized to consume electricity in a grid-serving manner. In this context, especially the possibility of dynamizing certain charges and levies to accurately reflect price signals should be examined.

Fourth, in addition to removing the above-mentioned barriers to create incentives for investments, policy makers and regulators should increase the harmonization and standardization, in terms of communication, of flexibility providing market players such as utility companies, industrial companies, and residential consumers. To effectively harness all sources of flexibility, the digital communication between the different market players should be standardized in order to avoid both, barriers, and lock-in effects. Information flows (e.g., via the exchange of data) between different market players are currently mainly unidirectional; they do not exhibit the required dynamics to effectively harness the required flexibility. With respect to the standardized communication of information and data, e.g., using corresponding platforms, it will be essential to ensure the strict preservation of both, privacy, and security.

Ultimately, policy makers should further promote the testing of flexibility options, in particular, iDSM measures, and their transfer into practice. For example, there is a need for continuing research on the future demand for industrial flexibility and on the question of which (new) flexibility options are best suited for which (new) flexibility applications. The Kopernikus-project SynErgie is a successful example of how policy makers can promote cooperation between research and practice – such a commitment should be continued and expanded.

7 Conclusion

The fundamental threat of climate change requires drastic action today. For electricity systems the resulting integration of renewable electricity generation induces significant challenges, such as a fluctuating electricity feed-in that puts grid stability at risk. Consequently, electricity systems require flexibility options to compensate unforeseen flexibility needs due to imbalances between electricity supply and demand in the short term as well as predictable flexibility needs in the long term, e.g., due to doldrums affecting feed-in by wind power or periods of low solar activity affecting the feed-in of PV systems. Those different needs for flexibility required by electricity systems can be covered by different flexibility applications (e.g., ancillary services or day-ahead market).

This Whitepaper sets out to determine which flexibility options can be effectively utilized for different applications to keep electricity systems with high shares of renewable electricity generation in balance. Against that background, this Whitepaper provides a characterization of the most relevant flexibility applications. Further, a characterization of the most relevant flexibility options that can be utilized to meet the flexibility demand of different flexibility applications is provided. This Whitepaper specifically focusses on industrial demand-side management, being one specific flexibility option. Different industrial demand-side management measures, that were classified into organizational and technical measures, were described in detail, and characterized by means of key technical characteristics drawing on real world data from participating industrial companies in the Kopernikus-project SynErgie.

Following an approach that takes technical and regulatory characteristics of flexibility applications into account, the results of this Whitepaper reveal most relevant insights on which flexibility options and industrial demand-side management measures may be applicable for which flexibility application. Most important, our Whitepaper illustrates that the requirements of the flexibility applications are met by at least one industrial demand-side management measure. However, some industrial demand-side management measures can be applied only to specific flexibility applications. Hence, our results reveal a high applicability and therefore importance of industrial demand-side management measures to meet the various needs for flexibility of a sustainable electricity system. In light of the increasing demand for flexibility in more renewable electricity systems, it is imperative to unlock untapped flexibility potentials related to industrial demand-side management measures wherever feasible. Moreover, the results indicate for which flexibility applications (and respective markets), industrial demand-side management measures compete against other flexibility options, but also for which flexibility applications there are only limited flexibility options available. Especially, since there is no “one fits all option” regarding the characteristics and availability of flexibility options in general and for industrial demand-side management measures in particular, our results highlight the imperative to cover flexibility needs by means of a multitude of different complementary flexibility options.

In summary, while there might be several important challenges for the transition process towards sustainable electricity systems, our analyses highlight that industrial demand-side management measures will play a key role to meet current and future needs for flexibility in electricity systems. Industrial demand-side management can therefore make an important contribution to the needed flexibility in the electricity system. However, the necessary regulatory and economic framework must be created for industrial companies to invest in industrial demand-side management and completely exploit the existing potential. The matching, developed in the course of this Whitepaper, serves as a basis to contribute to this purpose.

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