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Industrial demand-side flexibility: A key element of a just energy transition and industrial development

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HIGHLIGHTS

- Industrial demand-side flexibility holds unique potentials for system stability.
- Hereby, it may be an engine for sustainable and inclusive industrial development.
- We illustrate guidelines of a corresponding flexibility transition pathway.
- We develop a first monitoring approach for a country's flexibility transition.
- Our monitoring approach indicates mis-developments and needed countermeasures.

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ABSTRACT

In many countries, industry is one of the largest consumers of electricity. Given the special importance of electricity for industry, a reliable electricity supply is a basic prerequisite for further industrial development and associated economic growth. As countries worldwide transition to a low-carbon economy (in particular, by the development of renewable energy sources), the increasing fluctuation in renewable energy production requires new flexibility options within the electricity system in order to guarantee security of supply. It is advanced in this paper that such a flexibility transition with an active participation of industry in general has unique potential: It will not only promote green industrial development, but also become an engine for inclusive industrial development and growth as well as delivering a just transition to a low-carbon economy. Given the high potential of industrial demand-side flexibility, a first monitoring approach for such a flexibility transition is illustrated, which bases on a flexibility index. Our flexibility index allows for an indication of mis-developments and supports an appropriate implementation of countermeasures together with relevant stakeholders. Hence, it holds various insights for both policy-makers and practice with respect to how industrial demand-side flexibility can ensure advances towards an inclusive, just, and sustainable industrial development.

1. Introduction

Electricity is a key input for various production processes in all industrial sectors. In most developed countries, industry accounts for around 50 percent of total electricity consumption, which highlights the importance of electricity in general. With electricity being a crucial economic commodity, electricity systems with a stable and secure supply are a fundamental precondition for the proper and efficient functioning of the industrial sector – both in developed and in developing countries – and also to meet wider societal needs [1,2]. Being a driver for further industrial development and growth, appropriately designed electricity systems have therefore become a key success factor for industrialization and therefore also for the overall economic growth of a nation [3].

In the past, centralized electricity systems with a few large conventional power plants provided industry and society with its electricity where demand and supply were managed accordingly. Then, gradually more liberalized electricity systems evolved [4]. With the onset of the

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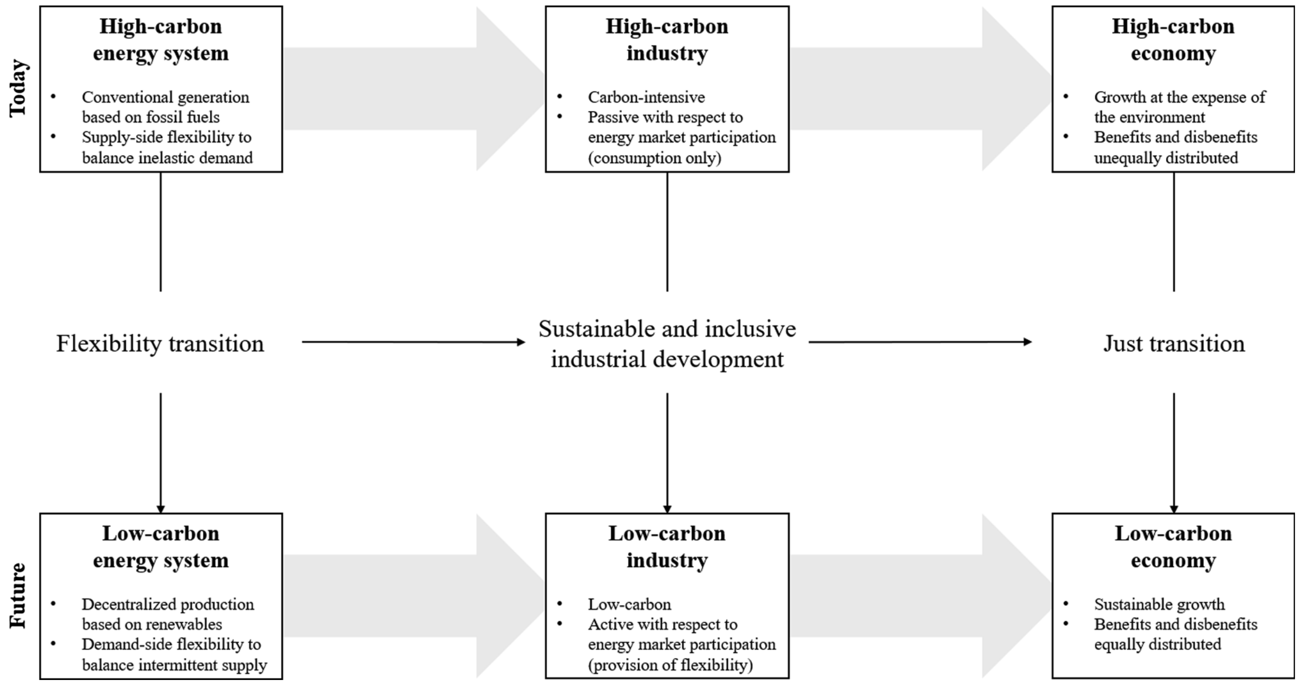


Fig. 1. Highlighting the relevance of a flexibility transition, a sustainable and inclusive industrial development, and a just transition towards a low-carbon economy. A joint transformation is needed in all three dimensions: within the energy system, within the industry, and within the economy itself.

growth of low-carbon electricity generating infrastructure, more production from renewable energy sources (RES) is currently observed. This development has been further supported with several global climate initiatives, such as the Paris Agreement 2015, where many countries have decided to speed up their energy transition towards a sustainable, low-carbon economy [5]. Complementary to the increase of RES, conventional plants are to be decommissioned step by step. This holds not only for Germany that decided to phase out its nuclear power plants by 2022 and plans to shut down its coal-fired power stations by 2038 at the latest, but also for many other countries around the world. However, an increasing share of RES will directly lead to a typically decentralized and highly intermittent electricity supply structure, as the sun does not always shine, and the wind does not always blow [6]. Ultimately, this calls for an incorporation of new and more cellular flexibility options to close the arising flexibility gap [7,8].

In this context, flexibility relates to the ability to address short-run and unexpected imbalances between demand and supply [9]. New flexibility may come from various sources that will have to be exploited over the next years, e.g., through new storage technologies, increased sectoral coupling, industrial demand-side management (DSM), or improvements in operational efficiency through technological development [7,10]. There is a growing literature around flexibility and it has focused, e.g., on renewable energy [11,12] or localized electricity grid options [13,14] – more is detailed on this in Sections 2 and 3.

While reliable and financeable electricity systems will form the basis for a successful industrialization in general, at the same time the ongoing energy transition has the unique potential to foster a *sustainable industrial development*. In this respect, energy resources may be used in a sustainable way without future generations being harmed by the excessive exploitation of the limited natural resources [15]. Thus, prosperity and growth associated with further industrialization can reduce associated negative impacts on our environment.

In order to develop such a sustainable industrial development, the energy transition pathways that are chosen need to ensure that flexibility becomes an option through which the different industrial sectors of a country can actively play their role in the electricity system [16]. Otherwise, due to insufficient flexibility, future energy systems may still have to rely on harmful conventional backup generation facilities as a source of stability and plannability. In this context, especially industrial demand-side management (DSM) may allow for a better adjustment of intermittent supply of renewables and demand [17,18]. Here, industrial demand-side flexibility relates to all measures that allow to shift demand over time and space in order to better address fluctuations in renewable energy production [19,20].

In particular, the energy transition must in an inclusive way make sure that no one is left behind, i.e., that there is a 'just' transition to a low-carbon economy. In a world with growing cross-border energy supply chains (e.g., the continued EU efforts to develop the internal EU electricity market), such an inclusion does obviously also apply to countries. Hereby, this article – as well as expanding the literature on flexibility and energy – reflects and is in line with the concept of 'flexibility justice' as was stated recently in the journal *Nature Energy* [21]. Among others, flexibility justice aims to have a flexible and dynamic energy sector where the market-place is open to all stakeholders, and as a result a market can take advantage of the (flexibility) technologies that are available. Against this background, the goal is to also allow new players to enter the energy market including completely new flexibility suppliers. Ultimately, this may require a change of existing market and policy structures that must keep pace with the current worldwide developments.

In the case where the new system requirements described above associated with a further development of RES, individual flexibility potentials of industry, and an equitable distribution of future gains and costs are appropriately taken into account by energy policy, such an *inclusive and just flexibility transition* may ultimately serve as a powerful engine for inclusive industrial development without detrimental effects on economic growth; see Fig. 1. Thus, tackling climate change, both, sustainability and inclusiveness, must be addressed in order to ensure a development of the overall economy that drives long-term growth and prosperity for everyone – i.e., in essence meets the demands of the energy trilemma [22]. Here, this is developing a low-carbon economy, but achieveing this through a fair and equitable process, i.e., a just transition, and encouraging active participation with respect to the supply of flexibility of the industry is the key focus of this paper [23]. In Fig. 1 below, it is demonstrated how the flexibility transition will support society to move from today's energy system to one that is low-

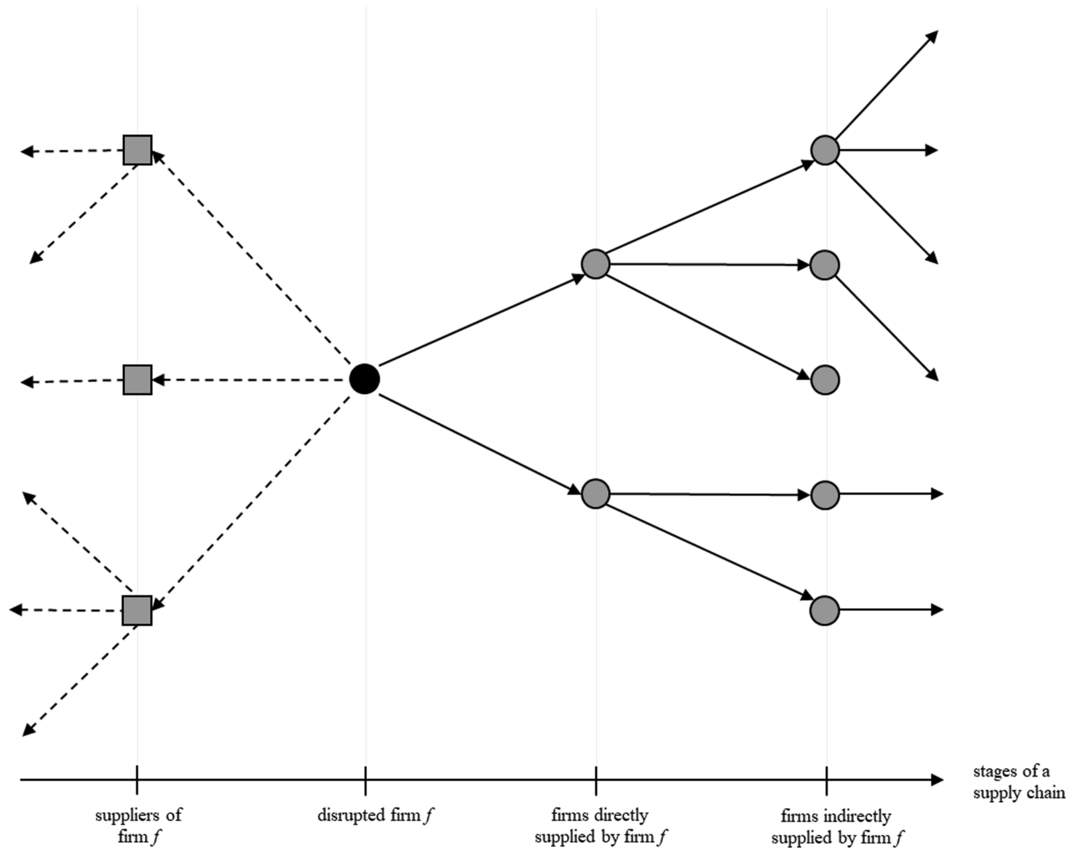


Fig. 2. Cascading effects of a local electricity supply shortage at a disrupted firm f (black circle). The forward propagation is indicated by grey circles and solid arrows, while the corresponding backward propagation is described by grey rectangles and dashed arrows.

carbon based and where key characteristics will be industrial flexibility and justice.

Our research proposes that a first approach supporting the design and especially the monitoring of the flexibility transition in the industry is utilized by countries. The latter approach may allow an indication of mis-developments and support an appropriate implementation of countermeasures together with the relevant stakeholders in order to keep moving forward on the path towards an inclusive and sustainable industrial development in times of green energy. There is significant literature on examining how concepts of justice (utilizing the term energy justice) can benefit the energy sector and therefore society [15]. Against this background, we advance a practical application of how industry can improve its performance in meeting energy and climate goals that would see a just transition to a low-carbon economy. As is noted in Section 4.3, governments begin to introduce new law and policy in this area and our focus on resolving flexibility in the electricity system for industry would have highly relevant real world research application on this issue as well as making an advance on just transition and energy justice literature. To the best of our knowledge, we are the first to highlight the important role of industrial demand-side flexibility as a key element of a just energy transition and industrial development.

This paper is organized as follows: Section 2 highlights the importance of a well-functioning electricity system for industrial development and growth, where particularly the high interdependence between the electricity sector and the other sectors of an economy are elaborated on; Section 3 focuses on the need for flexibility in modern electricity systems, while in Section 4 we highlight the potential of the 'industrial flexibility transition' to become an engine for sustainable and inclusive industrialization, and an overall just transition to a low-carbon economy. In the penultimate section (Section 5), the originality of the article is presented with a first approach for the challenging monitoring of such a flexibility transition of the industry; and finally, Section 6 concludes the paper.

2. Electricity, industrial development, and economic growth

Prevailing literature states a positive correlation of electricity consumption and economic growth all over the world in both, developed and developing countries [1,2,24]. Hereby, electricity empowers almost every process in the industry. For example, in 2016 in Germany industry accounted for around 47% percent of net electricity consumption [25]. Based on the United Nation's International Standard Industrial Classification of all Economic Activities [26], by 'industry' we refer not only to the manufacturing sector, but also to sectors such as agriculture, forestry, and fishing; transportation and storage; or information and communication. Given the high electricity dependency of industry, electricity supply security is a pre-condition for a smooth and well-functioning of industry processes in the short-run (and obviously for a well-functioning economy in the short-to-medium and even long-run). In particular, not only the availability of an absolute amount of energy, but rather a reliable, uninterrupted, and constant electricity supply is an important prerequisite for the successful operation of many industry processes [2]. Against this background, industries such as aluminum production even need 100% security of supply for their sensitive production processes that rely on electrolysis, which is not a given in many industrialized countries in Europe [27].

A key problem is the coincidence of several electricity supply interruptions together with a slow restoration of electricity supply through corresponding control options of the grid operator, which can be very costly and harmful for companies. During such an electricity-supply interruption, shortages of electricity may deteriorate product quality, increase waste, reduce or irreversibly destroy product output (e.g., if the temperature of the production process falls below a certain limit value due to an oven failure), and damage machines together with a possibly increased danger for workers; see [28,29]. However, production may not only be negatively affected during an electricity supply interruption, but also hours, days, and even weeks after such an event. In particular, during the company's transition phase to a normal operation of its production processes there may be severe economic losses in terms of additional maintenance work, missing production with possible short-time work, as well as existential forgone profits that can reach into the millions.

From a supply chain perspective, interruptions at individual suppliers may have a negative impact on companies that rely on the corresponding input in subsequent stages of the supply chain (forward propagation) as well as on suppliers of the interrupted company itself (backward propagation). Especially in times of increased (inter-) national interconnection with just-in-time production and reduced inventory levels, local electricity-supply interruptions may rapidly spread within supply chains and even yield supply bottlenecks for end products [30]. Fig. 2 below illustrates how such a disruption at a given company may (1) negatively affect subsequent companies in the supply chain that heavily rely on the disrupted company's input as well as (2) the corresponding backwards propagations to the disrupted company's own suppliers during the company's restoration phase as described above. Such spreads of local electricity supply shortages are commonly referred to as cascading effects [31].

A developed and reliable electricity infrastructure is therefore a major part of the long-term basis for strengthening a country's economic location through well-functioning production processes and competitive cost levels [3]. Valuable investment incentives in new factories or machines may be created by a reliable electricity system, which may then directly attract potential investors. In turn, newly invested production plants may yield new jobs. If the newly hired workers then spend their salaries on goods, new jobs in the industry will directly have further positive effects on overall economic growth and may create even more jobs in other sectors. On the opposite, insufficient electricity infrastructure may directly yield the long-term threat of a slowdown in further industrialization and reduced growth rates of a country. Table 1 below summarizes corresponding negative economic effects of an unreliable electricity supply.

Notwithstanding the high importance of electricity for the (manufacturing) industry, electricity does not only satisfy needs of large industrial consumers, but is also one of the foundations of modern life in both developed and developing countries. Reliable and financeable electricity systems, for instance, ensure the operation of hospitals, care facilities, and educational institutions (from kindergartens to universities). Electricity is also a key ingredient for the mobility sector and contributes to agricultural advances including, e.g., innovative irrigation systems. On an individual level, electricity therefore allows for the satisfaction of human and societal needs [32,33] – and for many across the world energy access is a significant problem which future electricity systems based on RES and corresponding flexibility would resolve to some degree (see also the following sections for more details). Ultimately, reliable electricity supply can raise everyone's standard of living and contribute to social participation, inclusion, and equality. For the sake of a better overview, Table 2 briefly illustrates the electricity dependency of selected sectors of an economy.

Again, from a macroeconomic point of view, a sufficient supply with electricity does not only allow for a satisfaction of social or economic needs. Rather, if sufficiently supplied with electricity, a very wide range of non-industrial sectors may have the potential to further contribute to economic growth: For instance, educational institutions may raise knowledge and skills of (future) workers and employees, hospitals may contribute to a higher general life expectancy, and increased social security may yield a positive investment climate for foreign investors. Thus, a secure electricity supply is not only important for social reasons, but it can also be another central pillar for economic growth in addition to the industry itself.

3. The need for flexibility in future energy systems

3.1. From conventional generation flexibility to new sources of flexibility

The sections above illustrate the high dependency of a country on electricity and underlying electricity systems. Historically grown, in the past electricity systems were designed to adapt the timing of electricity feed-in to the demand patterns of mainly inflexible consumers. This inelasticity of demand implied that consumers based their electricity demand exclusively on their needs and did not respond, e.g., to electricity prices and corresponding temporal changes in the supply of electricity. The supply side, on the other hand, was designed as to flexibly compensate for variations in demand by either starting-up or shutting down flexible power plants, often at short notice. Therefore, in conventional energy systems, the supply side provided the necessary flexibility to ensure system stability. In this context, the term flexibility describes the general ability to address short-run changes and imbalances between electricity supply and demand [19,34].

Any electricity system must be able to deal with both uncertainty and variability on the demand and supply side [35]. However, with a further development of weather-dependent, intermittent RES such as photovoltaics (PV) or wind and a corresponding replacement of conventional bulk generation like nuclear or coal, it will become increasingly challenging to flexibly adapt electricity supply to inelastic demand [8,36,37]: Whereas the generation of conventional power plants could be actively controlled in the traditional electricity system, due to their generation patterns, RES are hardly controllable by humans. Ultimately, the energy transition has fundamentally transformed traditional electricity systems.

In addition, as compared to centralized bulk power plants, RES are much more distributed across the countryside and smaller in terms of their generation capacity [6,38]. As a result, RES do not necessarily feed in electricity evenly across a country. For example, due to general meteorological differences between parts of Germany, the majority of

Table 1
Possible barriers to further industrialization and negative economic effects of an insufficient and unreliable electricity infrastructure. Effects on industrial companies and other players such as staff are highlighted.

	Effects on industrial companies directly affected by a supply interruption	Effects on other players such as staff or companies in the supply chain
Effects *during* an electricity supply interruption	• Loss of production • Reduced product quality • Increased waste • Damage to machines	• Increased danger for workers • Impact on safety in operations and associated wider effects
Effects *after* an electricity supply interruption	• Additional maintenance work • Missing production • Reduced profits • Loss of customers • General strain on company performance • Loss of reputation	• Bottlenecks in the supply chain • Reduced working hours for workers • Increasing prices for end customers • Negative impact on consumer welfare and therefore overall economic growth

Table 2
Relevance for economic growth and electricity dependency of selected sectors. The considered sectors are in line with the International Standard Industrial Classification of All Economic Activities of the United Nations [26].

Sector	Relevance for economic growth	Dependency on electricity
Agriculture, forestry and fishing	• Less famine and higher life expectancy	• Operation of innovative irrigation systems or cold storage houses
Manufacturing	• Employer and source of value creation	• Production processes
Water supply, sewerage, waste management and remediation activities	• Fewer diseases	• Water pumping • Waste shredding
Transportation and storage	• Availability of input materials and labor	• Electric mobility • Operation of airports, train stations, or car parks
Information and communication	• Availability of data and information • Processing of information	• Digital services • Operation of news offices

the country's PV systems (as well as the industrial centers) are located in the south, while most wind turbines are located in the north of Germany close to the sea or off-shore [39]. Similar differences can also be found in many other countries. In modern electricity systems, such a spatial separation puts enormous stress on a country's existing grid infrastructure, which was originally designed in and for a world in which power plants were located close to consumption centers [20,38].

As a consequence, what is needed in future energy systems are new sources of temporal and spatial flexibility [7,19]. While temporal flexibility aims at better adopting electricity demand to supply, e.g., shifting demand inter-temporally, spatial flexibility is needed to transport electricity from locations where energy is supplied to locations where energy is consumed, cf. for example, the ongoing discussion about the construction of several high-voltage DC transmission lines between Germany's wind-intensive north and the energy-demanding south [40].

Research knows several options to increase the flexibility of a system [7,8,41], for example: (1) supply-side flexibility; (2) storage flexibility; (3) transmission flexibility, i.e., grid expansion; (4) demand-side flexibility; and (5) inter-sectoral flexibility. The goal of all five flexibility options is to reduce the flexibility gap, i.e., the increasing imbalance between flexibility provided and flexibility needed [7]. Although an in-depth analysis of the different flexibility options is not the focus of this paper, the five options are briefly described in the following.

Flexibility option 1: Supply-side flexibility. This flexibility option refers to the modification of the electricity output of power plants to align power supply with demand. Due to their inherent start-up or ramping characteristics, peaking or load-following power generation units such as gas and hydro power plants allow system operators to quickly respond to changes in demand within seconds to minutes. RES may also provide supply-side flexibility, e.g., through curtailment [35]. The most significant benefit of supply-side flexibility is that the costs for providing flexibility are comparatively low as the flexibility that is already inherent in existing assets can be exploited. A major challenge with this flexibility option is, however, that as conventional power plants are increasingly replaced by RES, the flexibility provided by the supply-side will decrease. Curtailment of RES may not be able to compensate for this decrease, as it is only a one-sided measure that also involves losing some of the generated electricity, which in turn is costly [35].

Flexibility option 2: Storage flexibility. This flexibility option allows to shift the supply of power through time, thereby balancing temporal mismatches between supply and demand [42]. In particular, batteries charge power in times where supply from power plants is abundant and discharge power in times where power supply is scarce [35,43]. A major benefit of storage flexibility is that it also allows for seasonal shifting of electricity. However, an exemplary challenge with this flexibility option relates to the fact that energy storage technologies are still relatively costly.

Flexibility option 3: Transmission flexibility. This flexibility option allows to balance local mismatches between supply and demand [38]. Since electricity is not always produced and consumed at the same location, sufficient transmission capacity is needed to transport the power from generation units to consumers. Accordingly, one major benefit with this flexibility option is that it is the only option that allows inter-regional shifting of electricity. Challenges with transmission flexibility include the relatively high investment costs as well as possible transmission losses, especially over very long distances; see also [44].

Flexibility option 4: Demand-side flexibility. This flexibility option reflects a variety of measures to provide flexibility on the energy demand side [10,18,19]. Among others, DSM, and in particular, its subcategory of demand response, includes, first, temporal flexibility, i.e., rescheduling energy demand, and second, spatial flexibility, e.g., by enabling spatially distributed, redundant consumers like data centres [18–20,45]. Hereby, the main benefits are obvious: with a flexible demand-side being able to adopt to intermittent RES generation, consumers may significantly contribute to grid stability [10]. However, a core challenge of demand-side flexibility is that the demand-side must be (technically) enabled to increase or decrease its energy consumption at short notice; see also Section 3.2 for a more detailed discussion of this flexibility option.

Flexibility option 5: Inter-sectoral flexibility. This flexibility option relies on an interconnection of different sectors, e.g., gas, heat, and mobility, with energy generation [46]. Considering power-to-X technologies as an enabler of such interconnection [47], their main benefit is to contribute to grid stability similar to options 2 and 4 [48]. However, an implementation of inter-sectoral flexibility is currently challengend by high costs for this flexibility option.

Until recently, energy systems have relied mostly on flexibility options 1 and 3 to balance supply and demand. However, with RES increasingly reducing the profitability of conventional and load-following power plants by pushing them out of the merit order [49,50], the importance of flexibility option 1 will inevitably decrease in the coming years. For this reason, in addition to increasing transmission flexibility (option 3), which currently lacks acceptance among the population in some countries, it is particularly necessary to develop completely new flexibility options such as 2, 4, and 5. While the costs of option 2 are still (prohibitively) high and progress on option 5 is still very slow, demand-side flexibility appears to be a very promising flexibility option at present [51]. By developing option 4, as well as the other four flexibility options, countries will be able to integrate large numbers of RES and maintain security of supply in future electricity systems. Undoubtedly, developing the five different flexibility options supports a paradigm shift from a world with mainly plannable conventional supply that follows demand towards a world with mainly intermittent renewable supply that must be embedded within different flexibility options. Despite this change in thinking, the electricity system must still deliver now on three core issues: (1) reliability; (2) less greenhouse gas (GHG) emissions; and (3) ensure justice in its outcomes (i.e., fairness, equity, and equality). While reliability has always been a focus of electricity systems, the Paris COP21 Agreement in 2015 has accelerated

Table 3
Exemplary benefits, risks, and challenges associated with (industrial) DSM.
Sources: [10,53]

Benefits of (industrial) DSM	Risks and challenges of (industrial) DSM
• Increased use of RES production with less curtailment • Utlization of synergies with existing production infrastructure • Low emissions during operation including pollutants or noise • Fast response time: industrial loads can be switched off within seconds and react even faster than, e.g., gas power plants • Decentralized flexibility option	• Increased mechanical wearing and maintenance efforts due to a flexible plant operation • Complex system with high dependencies within the production process may be error-prone • Possibly negative effects on underlying production processes, product quality etc. • Information asymmetries and complex opportunity costs may yield severe economic gaming problems on markets

society's perspective that increased action on reducing GHG emissions and ensuring that the development of low-carbon economies happens in a 'just' way is needed [52].

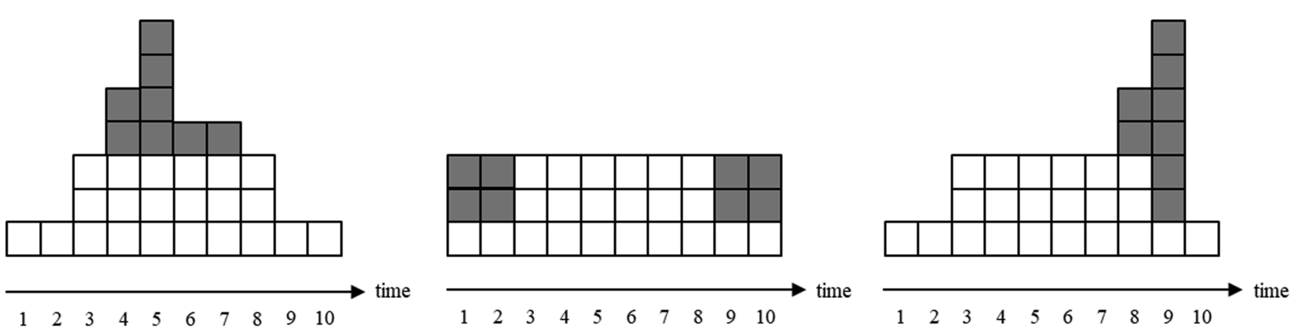
3.2. Industry's new role in providing flexibility

In shaping future electricity systems, demand-side flexibility may play a crucial role as highlighted above. Here, the main reasoning is simple: With supply being increasingly less flexible, the demand side must somehow increase its flexibility to ensure a balance of demand and supply at all locations and times [19]; see Table 3 for exemplary benefits, risks, and challenges associated with (industrial) DSM [10,53]. In most industrialized countries, industry promises the biggest potential for providing demand-side flexibility. For example, Paulus and Borggrefe [18] find that an overall industrial DSM potential of 2.660 MW will be available in Germany by 2020, which could provide up to 50% of positive tertiary capacity reserve. Similar potentials can also be found in other countries. In general, such a flexibility provision implies that consumers, e.g., industry or households, must reduce their demand in periods where electricity is scarce, and increase their demand when flexibility is abundant.

Fig. 3 illustrates a simple ten-period example with three different demand profiles of a company – depending on how its production processes are operated. In particular, given constraints relating to the technical characteristics and the inter-temporal dependencies of a company's underlying energy-consuming production processes, by altering its production, the company is able to temporally shift electricity demand between the ten periods and thus helps to balance the variable supply from RES. Starting with the original, ex-ante planned electricity-demand profile in Fig. 3a, the company could increase production in periods 1, 2, 9, and 10, and reduce its production in periods 4 to 7, respectively. This would lead to a constant demand profile as illustrated in Fig. 3b. Similarly, if high electricity supply of RES in periods 8 and 9 is anticipated by the company, it could shift its production to these two periods according to Fig. 3c. Adopting this temporal shift of electricity demand, a company may not only contribute to grid balancing, but may also benefit from financial advantages, e.g., lower electricity prices.

Energy-intensive industrial sectors such as glass, paper, chemicals, and metals are among the most promising sectors when it comes to exploiting demand flexibility. Other sectors are at a first glance less promising, for the simple reason that they do not consume as much energy as the sectors mentioned before. Nevertheless, as Table 4 illustrates, almost every industrial sector has at least some demand-side flexibility potential and may therefore possibly add value to the system by supplying its flexibility. For example, the agriculture, forestry and fishing sector, or the food industry, may use demand flexible cold storage where the cooling process is managed in such a way that it starts not at a fixed point in time, but rather within a specified time interval, depending on the respective supply situation of RES. Moreover, the transportation and storage sector is able to provide demand flexibility given the electrification of road traffic that is currently on the rise [54]: The digitally controlled charging of electric truck fleets, which is geared to the renewable energy supply and is time-shiftable, offers enormous potential for balancing demand and supply over time. In addition, also the information and communication sector may play its part in the flexibility transition: Spatial load shifting of, for instance, data centers, may enable the flexibilization of their energy demand [20].

With respect to specific industrial processes that can be flexibilized, it is typically the supporting processes like cooling or heating that have the highest flexibility potential. The main reason is that there must not be any negative effects on the production of the end product, e.g., reduced product quality or increased waste, when a company changes its production pattern to provide flexibility. In addition to thermal supporting processes, flexible main processes might be the graphitization of graphite electrodes, the paper production from wood chips, or the melting down of steel crap in blast furnaces. Ultimately, the actual flexibility potential depends on many different factors – which can, in turn, not only change from sector to sector, but also from one company to another within a given sector.



a) Original Demand Profile b) Constant Demand Profile c) Demand Profile with Delayed Peak

Fig. 3. Demand flexibility: Demand pattern for a ten-period example with two possible inter-temporal demand shifts.

Table 4
Exemplary flexibility potential of selected sectors. The considered sectors are in line with the International Standard Industrial Classification of All Economic Activities of the United Nations [26].

Sector	Flexibility potential
Agriculture, forestry and fishing [55]	• Demand-driven biogas production • Demand-side flexibility of cold storage houses
Manufacturing [25]	• Flexible production processes • Smart factories
Water supply, sewerage, waste management and remediation activities [9]	• Demand-side flexibility of waste processing plants
Transportation and storage [56]	• Vehicle-to-grid technologies • Smart mobility • Intelligent operation of cold storage houses
Information and communication [20,57]	• Spatial flexibility of data centers

4. The flexibility transition as an engine for sustainable and inclusive industrial development

4.1. Inclusive industrial development: Active participation of industry in future energy markets

In traditional energy systems, industry merely behaved as a consumer of electricity. As described, this implied that most companies based their demand for electricity exclusively on their production processes. Their primary (and sometimes their only) touch point with electricity markets therefore was electrical energy procurement [51]. In future energy systems, however, this rather passive role of industry with respect to electricity market participation must change towards a much more 'active' one. In consequence, companies must no longer only behave as 'passive' energy consumers, but actively participate in different electricity markets as flexibility suppliers and in this way contribute to the balancing of variable supply and demand in energy systems with large shares of RES [58–60].

To activate industry, companies must change their perspective on electricity as a sole production factor. In particular, electricity must no longer be only a cost factor, but it must offer the possibility for additional revenues via an electricity-system stabilizing flexibility supply [45,61]. Against this background, companies must develop sophisticated business models and DSM strategies. In addition, companies need to identify, which production processes are actually available for a flexible operation or may be flexibilized via adequate investments [9]. Along with this, companies must analyze how they can implement demand-side flexibility both technically and economically [45,51].

For policy-makers it is necessary to provide the appropriate financial incentives so that companies actually make their flexibility available for the system [62]. In this context, for instance, new flexibility and balancing markets - as well as adapted regulatory rules - need to be created that set as few barriers as possible for companies to market their flexibility [10,63]. In particular, there is a need to appropriately compensate companies for the costs of supplying a certain amount of flexibility [9]. Such flexibility costs may result from ex-ante unplanned shutdowns and subsequent start-up of processes as well as from unexpected downtimes of machines. If these costs are not appropriately compensated for, the technically possible flexibility potential of the industry may not be activated und remain unused. By activating the industry and incentivizing the industry to supply their demand flexibility on electricity markets, countries will thus achieve a more inclusive industrial development in the sense that the supply side of flexibility includes new active players.

However, industrial development will not only be inclusive in the sense that industry will participate more actively in electricity markets, but especially in the sense that the flexibility transition can generate significant economic added value and growth from which in turn all members of society can profit. Such economic value may be provided through various channels.

First and probably most obvious, industry's flexibility will help to ensure a reliable electricity system in the future. Since reliability of energy supply is the basis for most economic activities, the companies themselves thus contribute to ensuring that the different sectors of an economy can continue to produce without harmful supply interruptions in the future. In addition, also societal needs may be better satisfied through a reliable energy system, which is for instance obvious with respect to modern ways of communication.

Second, for many companies, selling their flexibility will be a potential new revenue stream as highlighted above [39,53,58]. When companies use, for example, their additional earnings to hire new staff, not only investors and shareholders will benefit, but also the companies' employees through the mechanisms described in Section 2. In this way, the additional economic value gained may ultimately lead to new economic growth.

Third, further additional value may be created along the whole DSM value-chain. For instance, supplying demand flexibility, companies have to invest into sophisticated information and communication technologies, or, e.g., automation, to adapt their production processes to an intermittent power generation structure [45]; additionally, employees need to be trained accordingly to be able to implement the new DSM strategies. Such a stronger integration of industry into the overall economy may also lead to a generally increased collaboration along the value-chain, which in turn could have further positive effects, e.g., on innovation and value creation [39]. Finally, if countries develop new DSM technologies and strategies, they may export their knowledge to other countries – developing countries in particular – that are also transforming their energy systems. This clearly highlights the high international relevance of industrial DSM as a key element of inclusive industrial development.

4.2. Sustainable industrial development: Low-carbon production and resource efficiency in future economies

As described in Section 3, industrial demand-side flexibility may be a key element for balancing intermittent supply and demand in energy systems with a large share of RES. If future industrial demand is sufficiently flexibilized, consumers – including industry itself – can be supplied with green energy from low-carbon RES. Thus, the industry can power its production processes with renewable energy and therefore lower its carbon footprint significantly [64,65]. In contrast, today large amounts of renewably produced electricity have to be down-regulated in order to avoid overloading of transmission lines. More specifically, the responsible grid operator may temporarily suspend the feed-in from RES if the grid capacities are not sufficient to transport the total electricity generated. Being an example for many other countries, in Germany alone, the corresponding feed-in management ("Einspeisemanagement") involved volumes of 5.403 GWh and monetary compensation payments of 635,4 million Euro in 2018 [66]. What makes such downregulations even worse is the fact that conventional power plants are often switched on instead, which then emit additional and unnecessary GHG.

In addition, by incentivizing the industry to supply its flexibility, countries exploit inherent technical flexibility potentials and thereby save large financial and natural resources (including for instance land or raw materials) that would have to be used to install completely new flexibility options [53]. For example, instead of having to build new gas-fired power plants (flexibility option 1) or instead of extending the electricity grid to a much larger extent (flexibility option 3), industrialized countries could draw on the industrial DSM potential that already exists in many production systems; the use of already inherent flexibility in the industry may therefore generally support the transition towards low-carbon economies [67]. With respect to developing countries that are currently in the process of industrialization, they could design their energy and industrial policies in a way such that the ability to supply flexibility is already considered during the planning and construction of new factories without additional and costly ex-post investments.

Furthermore, industrial DSM is typically more efficient than many other flexibility options like power to gas technologies (flexibility option 5), as it does not require the conversion of energy, but rather shifts the timing of a specific production process [60]. Companies that supply their flexibility could in this way also contribute to a reduction in overall investments in RES capacities that would be necessary to account for the described conversion inefficiencies. In this way, an overall reduction of the costs of future energy provision may be the result [39].

Finally, by providing flexibility, companies are able to develop and deepen their internal knowledge about electricity systems in general [39]. In turn, this could put companies into a better position when it comes to the implementation of other energy-related measures, e.g., energy efficiency measures. Thus, energy flexibility may serve as a catalyst for other attempts towards a reduction of GHG emissions. To sum up, as industrial demand-side flexibility may enable the reliable supply of green energy, the flexibility transition may not only lead to more inclusive but also to more sustainable industrial development.

4.3. The just transition to a low-carbon economy

So far, we have seen that the different electricity-consuming industrial sectors must take on an active flexibility role to help mitigate climate change by fostering an inclusive and sustainable energy system transformation as well as industrial development. While many agree that climate change is among the world's central issues [68], the specific solutions to climate change are often discussed either from a socio-technical or from an ethical perspective - integrated solutions are rarely proposed [69,70]. However, a large transition such as the flexibility transition will inevitably bring with it benefits and disbenefits that have to be discussed with all the relevant stakeholders. As we will also see below, an overall solution can only be determined in a corresponding stakeholder dialogue that brings the different hopes and fears together, rather than ignoring them.

Whether it is possible to actively involve industry in a successful flexibility transition and in balancing markets obviously depends not only on purely economic or technical details, but especially on whether the benefits and disbenefits of the flexibility transition are distributed through a fair and equitable process among all members of society. Moving towards a low-carbon society, this idea forms the basis of the concept of the 'just transition' [23,52]. It seeks to promote justice by developing "principles, tools and agreements that ensure both a fair and equitable transition for all individuals and communities" [23]. Prime examples of energy problems for which such a consideration appears important for ethical reasons include involuntary resettlement due to energy projects, fossil fuel pollution by power plants, or the disposal of nuclear waste [69].

As the example of the German EEG levy illustrates, a single energy problem can give rise to several different ethical concerns [53]. Through the EEG, the producers of electricity from RES receive a fixed remuneration for every kWh they feed into the grid. This remuneration is financed by the EEG levy, which final consumers in Germany contribute to and which is part of the electricity price. The state subsidy for RES is thus financed jointly by all citizens – which can be seen as the *partial implementation* of distributional justice. At the same time, however, the German industry was able to secure considerable exemptions from the EEG levy by expressing concerns about maintaining its international competitiveness [71]. Thus, the costs of the new green energy supply are predominantly borne by regular households, while the industry profits from it with a low level of (financial) participation – which is a *partial violation* of the principle of distributional justice [53].

This example demonstrates that it is therefore not only important to financially incentivize the industry to supply its demand-side flexibility, but also to bear in mind the non-industry stakeholders when it comes to allocating both the costs and benefits of the industrial flexibility transition. In contrast to a unilateral financing through non-industry stakeholders, active participation and acceptance also requires an active, inclusive, and 'tangible' involvement in the distribution of benefits as well as confronting risk preceptions of the public. Even though the overall monetary burden of the industry should clearly be reasonable in order to avoid international competitive disadvantages due to prohibitively high energy costs, inclusiveness must imply that transformation costs are not passed on to the non-industry stakeholders with some kind of industry excuse accepted by the government. It is here that the discussion on energy justice is relevant. In achieving justice, a government will have to ensure that different stakeholders engage to make sure that the electricity sector itself and the wider economy deliver just economic outcomes.

In different countries, governments themselves are looking already to take the first steps towards action here. A recent development that encapsulates a new movement by government is the development of a Just Transition Commission (JTC). The aim of this JTC is to ensure for everyone in society that there is a just transition to a low-carbon economy. The development of a JTC is the first legislative step to achieve it; and there are currently nine forms of such an emerging commission in the following jurisdictions: Australia, Canada, the EU, Germany, Ireland, New Zealand, Scotland, South Africa, and the US. Such a commission will have different functions from country to country but in essence and at the very least it will provide expert advice on the ways to achieve a just transition and also will monitor the effects of existing laws and policies to ensure they contribute to the delivery of a just transition.

In legal terms these JTCs would be a form of a new public administrative unit (i.e., attached to a ministerial department such as energy, labor, etc. or spanning a few departments). Overall, however, the aim of a JTC is to accelerate the societal shift to a just transition to a low-carbon economy. Such a development is designed to address also societal inequality, clean energy development, and climate action. Some countries are even considering the establishment of a Just Transition Fund which would support financially more acute needs, for example of a selected industry, to transform itself.

Early research into JTCs indicates that countries are going for a number of options but there are two emerging solutions which can be identified as an external JTC and an internal JTC. An external JTC is now in evidence in Germany (2018) and in Scotland (2019) and this is where the majority of the membership of the JTC consists of external appointments – i.e., they represent different stakeholders in society in terms of the development of the just transition to a low-carbon economy. The internal JTC (New Zealand – 2019) in contrast consists of civil servants who then engage with stakeholders.

While the issue of the powers of a JTC remains undefined, there is research needed into exploring which type of JTC, the internal or externally oriented one, will have more power. As of yet, the powers of the JTC are slowly beginning to emerge and this is in essence an international 'live' research issue. Indications are that this is an area that governments are approaching with caution, as it is politically sensitive and also requires cooperation from multiple government ministries.

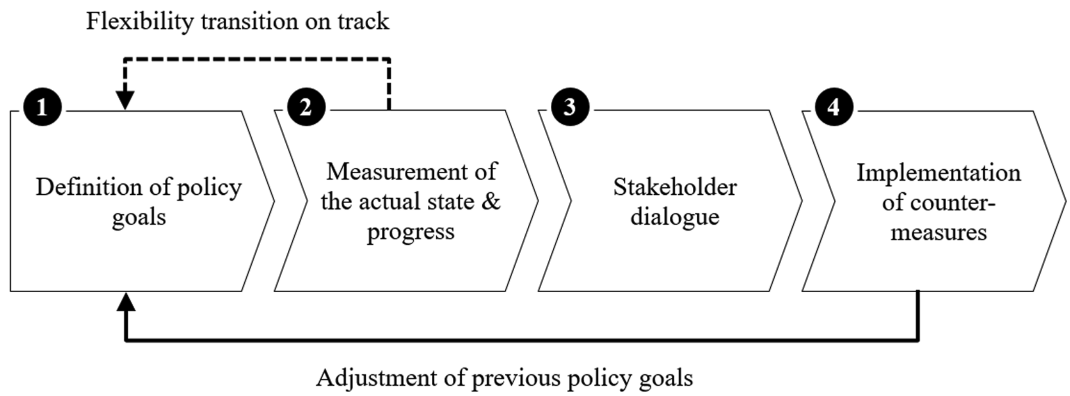


Fig. 4. Four-step monitoring approach for the flexibility transition. Monitoring consists of (1) the definition of policy goals based on a flexibility index, (2) the measurement of the actual state and progress, (3) a stakeholder dialogue, and (4) the implementation of needed countermeasures.

However, if there is success, a JTC could have a transformative effect in the development of low-carbon economies worldwide.

Alongside other scholars worldwide we hope to answer the questions highlighted above as these issues continue to develop in future research. However, we aim in the next section to propose a method of practically identifying a solution to flexibility problems in terms of flexibility use by industry. Against this background, we are among the first to advance a practical application of how industry can improve its performance in meeting energy and climate goals that would see a just transition to a low-carbon economy. As various governments are beginning to introduce new policy in this area, resolving flexibility challenges in the electricity system would therefore have important international real-world research application.

5. A four-step monitoring approach for the industrial flexibility transition

With an ambitious project such as the flexibility transition, there is always a risk that the set goals on the path towards a more energy-flexible industry will be delayed or not achieved at all. One of the most prominent examples for this phenomenon is probably the community of states' effort to reduce GHG emissions under the Paris COP21 Agreement in 2015. Currently, only six members (China, India, Indonesia, Japan, Russia, and Turkey) of the G20 are on track to achieving their nationally determined contributions to this goal – with Argentina and the EU28 requiring low, Australia, Canada, South Africa, the Republic of Korea, and the United States requiring high additional effort [72].

One reason why the enthusiasm and commitment for self-imposed policy measures and goals typically fade quickly is the complexity of the projects to be tackled. Complexity can come from various sources. For example, the more sectors of an economy and the more societal domains are affected by a project such as, e.g., the reduction of GHG emissions, the more difficult it is for policy-makers to keep track and predict the diverse consequences of their decisions and policies. In addition, if the various stakeholders pursue different goals and each wants to benefit as much as possible from a specific policy, the complexity of the overall system increases even more. As a consequence of this complexity, the measures and goals that were initially set by policymakers may not be appropriate anymore or be simply not achievable at a later point in time.

Practically implementing the industrial flexibility transition in a way that everyone can benefit from it and no one is left behind requires the joint effort of all stakeholders as well as appropriate policies and clearly defined goals. In particular, the process of making the industry more flexible will necessitate numerous policy measures which touch not only on the realm of energy and industrial policy – but also on that of, e.g., environmental and social policy. In concrete terms, this often means for countries all around the world that several political groups across several different ministries would have to work together to coordinate these policies. This increases the coordination effort on the political side, which must be taken into account when planning and implementing a project such as the flexibility transition, both, complexity and coordination effort are increased by the peculiarities of the electricity sector itself. In particular, electricity markets are generally highly regulated, and regulation has traditionally been geared towards flexibility provision of conventional power plants. However, existing regulation makes access to electricity markets considerably hard or even impossible for the new flexibility options described in Section 3. As a consequence, when regulatory authorities try to adapt the regulatory system accordingly, they must not only take into account the goals that they want to achieve with this specific matter (i.e., simplify the industrial flexibility provision), but also how new rules affect the existing regulatory system with its complex interaction of markets, regulated monopolies, technologies, and the various stakeholders.

As has been described, updating and establishing the policy and regulatory framework such that it enables industrial flexibility is a 'Herculean' task – especially in a complex policy area such as electricity, with the many side-effects on other policy areas beyond the energy and climate change boundary. While respective policy initiatives have faced severe challenges in the last decades, we propose a holistic and transparent approach (i.e., a continuous monitoring) to ensure that an industrial flexibility transition is to be achieved. Against this background, we develop a first monitoring approach that may ensure that the flexibility transition is and keeps on track by appropriately monitoring the status quo and the progress made on the path towards a more energy-flexible industry, as well as by regularly involving every relevant stakeholder. Our approach can be applied in both developed and developing countries.

In particular, in this section we present a general four-step monitoring that will allow to continuously measure the progress made on the flexibility transition pathway as highlighted in Fig. 4. This approach may either assist the JTC in its work or even be an integral part of it. In the first step of this approach, we use a composite index to capture the flexibility targets as well as to set appropriate and measurable policy goals. The second step is there to track how this index develops over time and to introduce first 'triggers' that may indicate when something goes wrong with respect to the implemented policies and the targeted goal achievement. In the third step, we propose a stakeholder dialogue to make sure that everyone can actively take part in the process of rethinking and reshaping currently misdesigned policy that hinders the supply of flexibility in the just transition. Here, directly concepts of energy justice that for instance relate to an active involvement of the different stakeholders as well as the consideration of their risk perceptions are important. Finally, the last step implements countermeasures based on the previous stakeholder dialogue whenever the

Table 5
Possible targets for the industrial flexibility transition. The different criteria may be used in a corresponding flexibility index.

Possible industrial flexibility transition targets
• Extend industrial demand flexibility to *x* MW. • Increase investments in new demand flexibility to *x Euro*. • Introduce necessary flexibility markets and trading products. • Install necessary sensors and meters in the electricity system. • Increase the number of flexible consumers in rather inflexible regions. • Ensure an appropriate spatial distribution of flexibility. • Increase the absolute number of companies that provide flexibility. • Increase the number of new industrial projects where future flexibility already plays a role in planning. • Support innovation and enhance scientific research with respect to industrial DSM. • Increase access to information and communications technology that allow for demand-side flexibility.

index signals that policy is not on track.

- **Step 1: Definition of policy goals**

Fighting globally against climate change, national actions and corresponding policy goals towards the flexibility transition should always be aligned with the overarching Sustainable Development Goals (SDGs) and other international climate agreements. Similar to the SDGs themselves, concrete targets must be set to commit industry and all other relevant stakeholders. Here, composite indices are a well-known concept that is commonly applied in many policy areas and also by organizations like the UN or the OECD; see [73]. On the one hand, composite indices allow targets to be set, either in the form of concrete target values, minimum targets, or target corridors. On the other hand, indices offer the possibility of informing the parties involved about both the actual status and the target situation (see also Step 2). As can be seen in Table 5, there are different possible targets that may be set by policy-makers with respect to the flexibility transition.

Table 6 exemplarily highlights which of the overarching SDGs 7 (Affordable and Clean Energy) and 9 (Industry, Innovation and Infrastructure) targets could be positively influenced by reaching the industry flexibility targets above.

- **Step 2: Measurement of actual state and progress**

A continuous 'success' measurement builds on the comparison of the determined target index ϕ_{target} value of Step 1 with the currently realized index value $\phi(t)$ in a period *t*. There are several triggers that may indicate that the index develops in a somehow 'wrong' direction; see also [74]. A natural lower limit for such a trigger may be the ex-ante index value ϕ_0; see Fig. 5(i). An early warning may also be triggered if the index value $\phi(t)$ at time *t* is less than the index value $\phi(t-1)$ at time *t-1*; see Fig. 5(ii). The latter case indicates a slowdown in the policy progress. Another trigger may monitor whether the policy is making a steady and targeted progress in the area of flexibility supply: If the index falls below a certain benchmark, this may also indicate a general slowdown in policy progress; see Fig. 5(iii).

- **Step 3: Carrying out a stakeholder dialogue**

If a corresponding comparison of the actual and target index value indicates that targets are missed, reasons for the mis-development must be found out by involving the relevant stakeholders (stakeholder dialogue). In this way, current barriers to a further flexibility supply are discussed and uncovered. In addition, adjustments to the existing policy framework may be jointly decided on. This may include the replacement of outdated regulations that currently hamper an appropriate flexibility supply of the industry. Concrete examples of such complex regulations that may have to be updated in the course of the flexibility transition may be the present 'sanctioning' of flexibility via grid charges, e.g., in Germany, and the (statutory) conflict of objectives between energy flexibility and energy efficiency. Obviously, in this context issues from energy justice play a crucial role. In particular, society should not have to undergo a major rise in activism [75] and climate strikes [76]. Instead, more collaborative work needs to be completed [52].

- **Step 4: Implementation of countermeasures**

The previous steps of the proposed monitoring approach allow for detecting possible policy challenges via early warnings and associated triggers. Therefore, a country has a range of signals for a stakeholder dialogue and for the introduction of updated policy and law instruments. These new regulations may regularly be brought into the legislative process by the government so that a country remains on course to deliver a just transition to a low-carbon economy with an efficient functioning and inclusive industry sector.

6. Conclusions

Tackling the devastating effects of climate change that can already be felt in many countries is a worldwide problem and recent global cooperation is on the rise in the last few years, notably via the Paris COP21 Agreement in 2015. National energy transitions across the world are associated with an increased need of new flexibility options to ensure energy and climate goals are realized via the development and efficient utilization of RES. Our paper focusses on industrial demand-side flexibility that is considered to hold unique potential. In this

Table 6
Selected targets of SDGs 7 and 9 that industrial demand-side flexibility directly contributes to achieving.

Sustainable Development Goal	Target
Goal 7: Affordable and Clean Energy	7.1 By 2030, ensure universal access to affordable, reliable and modern energy services. 7.2 By 2030, increase substantially the share of renewable energy in the global energy mix. 7.B By 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular least developed countries, small island developing States, and land-locked developing countries, in accordance with their respective programs of support.
Goal 9: Industry, Innovation and Infrastructure	9.1 Develop quality, reliable, sustainable and resilient infrastructure, including regional and transborder infrastructure, to support economic development and human well-being, with a focus on affordable and equitable access to all. 9.2 Promote inclusive and sustainable industrialization and, by 2030, significantly raise industry's share of employment and gross domestic product, in line with national circumstances, and double its share in least developed countries. 9.4 By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities. 9.A Facilitate sustainable and resilient infrastructure development in developing countries through enhanced financial, technological and technical support to African countries, least developed countries, landlocked developing countries, and small island developing States.

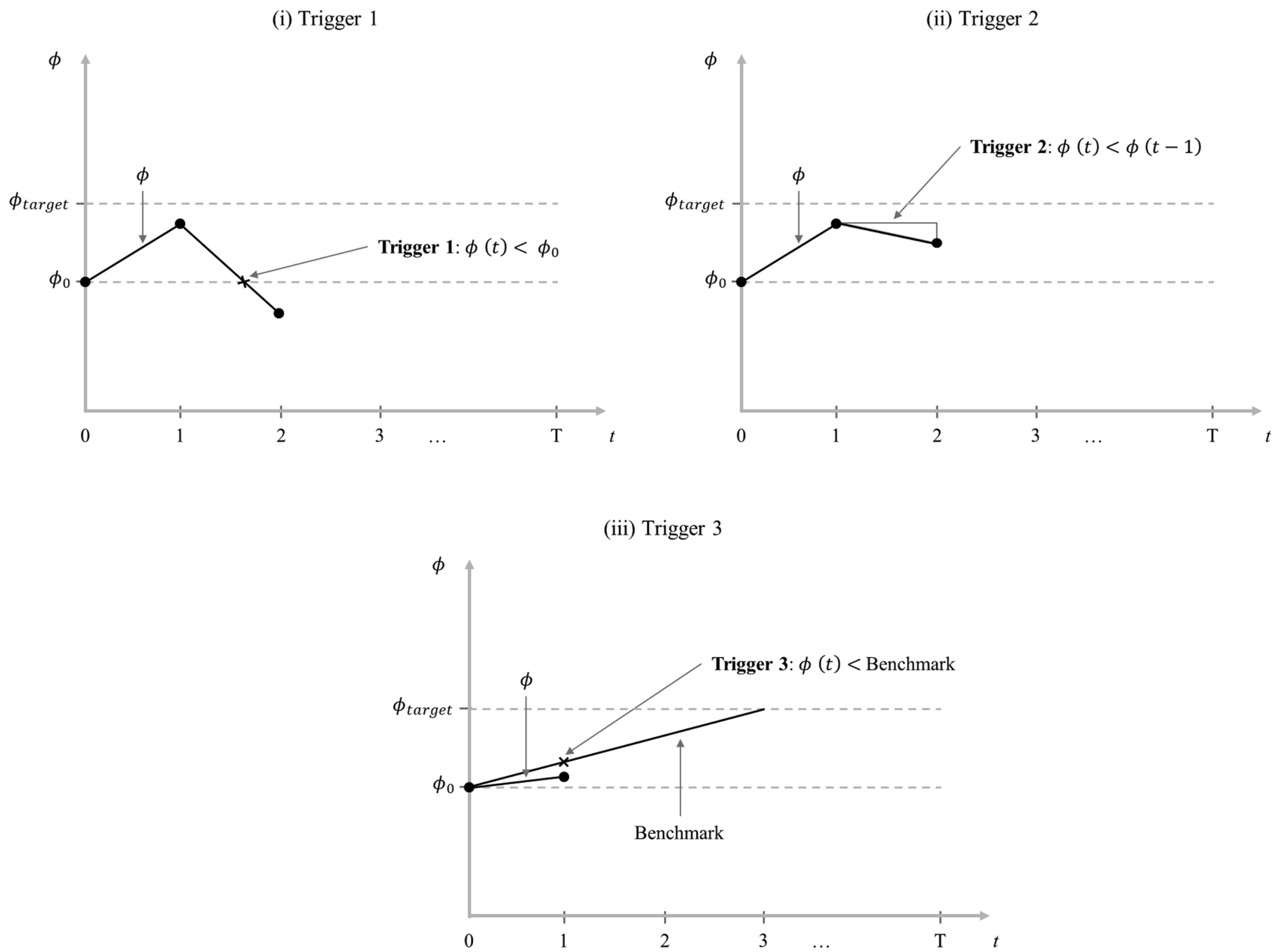


Fig. 5. Three different triggers that may indicate mis-developments of the flexibility index. Source: Created by authors inspired by [74].

context, flexibility refers to the ability to balance demand and intermittent supply that increasingly comes from RES. Inherently, the latter are influenced by uncertain weather conditions that determine their actual production volumes. As this paper advances, a corresponding flexibility transition has the unique potential of fostering sustainable industrialization and growth, that – given the influence of industry over the rest of the economy – can be transformational as nations all over the world aim to ensure a just transition to a low-carbon economy.

However, no industry sector must be excluded both in terms of the exploitation of its flexibility potential and in terms of the distribution of the future benefits of a successful energy system transformation. Therefore, a sustainable and inclusive flexibility transition is needed as an engine for further industrialization and growth. While many policy initiatives faced severe challenges in the past, we propose a holistic and transparent approach (i.e., a continuous monitoring) to ensure that this global and important goal is to be achieved. In particular, to ensure that the flexibility transition is and keeps on track, we develop a first monitoring approach that builds on a composite flexibility index that is embedded within a four-step approach. These four steps proposed here are: (1) utilizing a composite index to capture the flexibility supply by the industry and then setting measurable policy goals; (2) track how this index develops over time with 'triggers' indicating when policy reform is needed; (3) an (industry) stakeholder dialogue process begins to rethink and reshape new reform to increase the supply of flexibility in the just transition; and (4) implementation of countermeasures based on the previous industry stakeholder dialogue whenever the index signals that policy is not on track. We underline that such a flexibility index may support the concept of flexibility justice by increasing transparency in the energy system.

CRediT authorship contribution statement

Raphael Heffron: Conceptualization, Supervision, Writing - review & editing. **Marc-Fabian Körner:** Investigation, Writing - original draft, Writing - review & editing. **Jonathan Wagner:** Conceptualization, Investigation, Resources, Writing - original draft, Visualization. **Martin Weibelzahl:** Investigation, Visualization, Writing - original draft. **Gilbert Fridgen:** Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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