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Monitoring long-term trends of spatial and temporal flexibility in electricity systems

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ABSTRACT

The long history of evolving energy systems is also the history of adding new forms of flexibility, from run-of-the-river hydropower with limited spatial and temporal flexibility to contemporary fossil-fuel based electricity systems allowing more flexibility due to storable and transportable fuel and controllable generation. The increasing shares of solar and wind energy, which are available everywhere, but not all the time, calls for new types of flexibility strategies. Monitoring changing patterns of flexibility strategies add to our understanding of the status and direction of long run energy system transformation. To capture such broad trends and allow for comparison across regions, this study develops two indicators: Gross spatial flexibility (GSF) and Gross temporal flexibility (GTF). The indicators are tested on a sample of countries including Australia, Germany-Luxembourg-Austria (GLA region), Sweden and the USA. By normalising storage and transmission capacity to average power demand these indicators are shown to enable comparisons across time and across regions of different sizes. At present, publicly available data in most countries remain insufficient for simple indicator construction and continuous updating. The German MaStR platform is an exception and could serve as inspiration for database construction in other countries.

Introduction

The current trend of adding new forms of flexibility builds on a long history of evolving energy systems. The emergence of large-scale coal use two centuries ago did not only imply access to larger energy resources, but also brought new types of flexibility, as compared to the preceding system of human labour and work animals, run-of-the-river hydropower, and wind-powered transport by sailing ships. Coal could be stored without degradation and was available when needed, and with coal came steam-powered railways and ships that not only used coal, but also moved it around the world [1]. One century ago, electricity, a versatile energy currency, added to the flexibility of energy systems by separating the direct link between the type of energy in demand and the type of energy resource available. Today, electricity is becoming the dominant energy carrier making electricity systems a central part of most energy conversion systems.

With increasing shares of solar and wind energy in current electricity systems, the flexibility pattern evolves again. Compared to fossil fuels and uranium, wind and in particular solar energy are more evenly spread across the globe, but instead unevenly distributed in time. In short, they are available everywhere, but not available all the time. As steam railways and ships added spatial flexibility in the coal-based system to complement its uneven distribution in space, solar and wind now need to be complemented with other flexibility technologies for its uneven distribution in time. In addition, even if solar and wind in principle are available everywhere, they are not evenly distributed, and, hence, could also benefit from increased spatial flexibility.

There are many flexibility strategies available including energy storage technologies, electric grid solutions and demand side management strategies [2–4]. According to the International Energy Agency, investment in electric grids has remained high in the recorded period 2015–2023, and investment in energy storage and end-use energy technologies have grown rapidly [5]. While the deployment of all these technologies is forecasted to grow in the coming years, the future balance between options is unknown. Even if many measures are complementary, heavy investment in one may reduce the need for another. Within the broad frame of a solar and wind-powered world there are many alternative pathways [6,7], with varying social, economic, geopolitical and environmental implications [8]. It is not only the speed of the energy transition that matters, but also its precise direction [9].

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Monitoring broad trends of flexibility strategies could improve the understanding of directionality in energy system transformation, improve actor adaptation strategies and allow for strategic path selection.

A range of different types of indicators are required to capture diffusion of flexibility strategies along the value chain from electricity supply to demand [10], in both temporal and spatial dimensions [11]. In addition, along these dimensions, attention needs to be paid to various kinds of scales, for example distinguishing between measures suitable to handle energy imbalances over the course of a second, some hours or a year [12], and between neighbouring houses, countries or continents [8,11]. The literature provides examples of studies developing indicators of supply-side flexibility [13–16], demand-side flexibility at different system levels [17,18], flexibility provided by energy storage technologies [3] and by extended electric grids [19–21], or combinations of storage and grid development [11,22–24].

Many of the proposed models and measures are both sophisticated and comprehensive [25,26], but as such, they also require sophisticated understanding and comprehensive data gathering. A complementary strategy is to develop simpler indicators that still give an overview of the development and enables comparisons across time and space.

The aim of this study, hence, is to develop simple indicators that measure the progress of flexibility strategies and capture broad trends in their diffusion, as tools for monitoring the long-term direction of energy system transformation. While acknowledging that flexibility problems in electricity systems are constraining the adoption of variable renewable generation and the connection of new demand, this study does not aim to identify specific present or future flexibility problems or to provide prescriptive solutions. Instead, it takes a descriptive perspective, providing a conceptual foundation for understanding how flexibility emerges and shifts over time and a measurement for monitoring and comparing development trajectories of flexibility strategies.

To this end, we first develop an overarching typology of flexibility strategies. Thereafter, we focus on spatial and temporal flexibility and develop two indicators: Gross spatial flexibility (GSF) and Gross temporal flexibility (GTF). While recognising the importance of supply- and demand-side flexibility, the scope of this study is limited to the grid-side, excluding pure supply and demand-side measures that start or end with other forms of energy besides electricity. The motivation for this choice is further discussed in Section 2.1. The study also aims at testing the availability of public data required for easy indicator construction and updating. The indicators are thus tested on a sample of countries. For different measures we use different temporal scopes with data series ending in 2022.

Theory

This section classifies flexibility measures in energy systems. It focuses on the distinction between technologies that shift energy in the two dimensions space and time. and on how these can be further subdivided based on their position in a value chain from original supply, via a grid to demand. Thereafter, two indicators are proposed, which in combination can be used to construct a two-dimensional flexibility space.

A typology of flexibilities

All energy systems provide flexibility in the transformation of primary energy resources found in nature to final use of energy services. This is the primary function of all energy systems. We here distinguish four fundamental types of flexibility, which in different ways disconnect the final use from the characteristics of the resource. First, *spatial flexibility* allows final demand to take place at a different place than where the primary resource is found in nature. Second, *temporal flexibility* allows final demand to take place at a different point in time than when the energy was extracted from nature. When a sailing ship catches the wind there is neither spatial, nor temporal, flexibility, but when early humans carried home wood from the forest to be used for cooking in the evening, or when coal was shipped from Britain to be used across the world in 19th century, a combination of spatial and temporal flexibility was employed. Coal shipping can also illustrate the third kind of flexibility, *quantitative flexibility*, which disconnects the required power of a discrete final demand and the power outlet of an energy resource, for example letting one coal mine supply millions of homes with fuel for domestic heating or several mines supplying one large industry with process energy. Finaly, energy systems that introduce intermediate energy carriers enable the fourth type of flexibility, *qualitative flexibility*. This means that energy resources of different forms are converted into a versatile energy carrier, a kind of energy currency, which is later exchanged into the various energy forms demanded in end use applications.

Electricity is the prime example of such an energy currency providing energy systems with qualitative flexibility. It can be produced from almost any type of energy resource and easily be converted into the light, heat, and motion we need, or used to mould and manipulate materials and information. Similarly, electricity systems are great at providing quantitative and spatial flexibility, combining, and transporting vast amounts of energy over long distances in electric grids, and then chopping it up in the exact parcel sizes costumers require. However, electricity is poor at providing temporal flexibility, and large amounts of energy cannot yet economically be stored as electricity in superconductors or capacitors. Temporal flexibility has thus historically been handled before other energy forms are turned into electricity, for example by storing chemical energy in coal piles or gravitational energy in hydro power water reservoirs.

This leads us to a second layer of flexibility types. Spatial and temporal flexibility in electricity systems can be further subdivided depending on position in the value chain [10]. Here we make a distinction between *Supply, Grid and Demand side* flexibility, as shown in Fig. 1. Processes occurring prior to or at the point of electricity generation are defined as Supply side flexibility while processes occurring when, or after, electricity is converted to another energy form never to be converted back to electricity again are defined as Demand side flexibility. To highlight the importance of this distinction and the scope of this study we use capital letters for these concepts.

Solar and wind energy are flow resources and can neither be stored nor transported in any meaningful quantities. Solar and wind energy can in principle be transformed into for example heat, chemical energy or gravitational energy and stored or transported in that form before being converted to electricity. However, except for bioenergy plantations (as a storage of solar energy) this potential is largely untapped and most solar and wind energy used for energy purposes are directly converted into electricity in solar cells and wind power plants and thus do not allow for Supply-side flexibility measures. However, being available in most locations across the world, these resources, as compared to most other energy resources, are themselves spatially well-aligned with the geographical distribution of energy demand. Still, there are important geographical variations calling for spatial flexibility on the Grid and Demand side. Demand-side spatial flexibility could here mean moving industries to locations with abundant solar or wind resources as once industries grew up around waterfalls and coalpits. More than 150 years ago the Swedish inventor John Ericson envisioned that the textile industry of Manchester would move to Egypt once solar energy had replaced coal as the dominant source of energy [27]. Even more importantly, the inherent intermittent characteristic of solar and wind calls for new temporal flexibility solutions on the Grid and Demand side. Demand-side flexibility solutions are always linked to end user activities and therefore more diverse due to the wide range of end-use applications. For instance, water heaters may advance electricity demand in time by heating water beforehand, or the final use of the hot water may be shifted in time by adapting the time of a daily hot shower.

Grid-side flexibility is here defined as the intermediate step between supply and demand, including any process happening after energy being

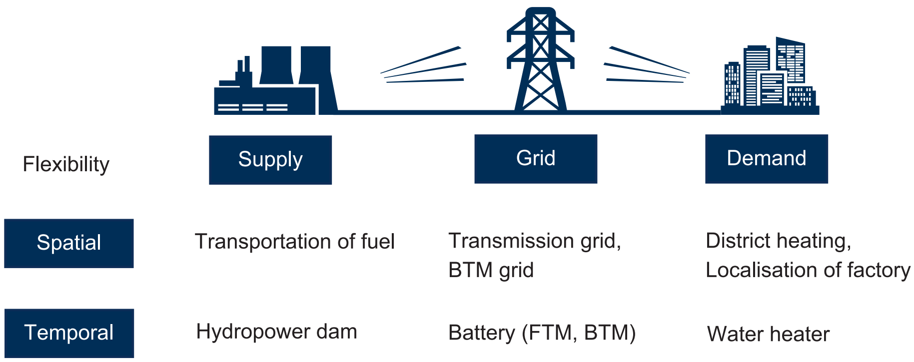


Fig. 1. Proposed typology of flexibility in electricity systems with exemplary technologies and actions.

converted into electricity and before electricity is converted into final target energy forms. In our terminology, Grid-side flexibility therefore includes conversions such as electricity-to-hydrogen-to-electricity in hydrogen energy storage and transport systems, and electricity-to-thermal-to-electricity in thermal energy storage systems. Other examples include batteries that shift electricity temporally and electricity lines shifting electricity spatially. Notably, this definition of "grid-side" extends beyond transmission and distribution networks to include electricity-to-electricity conversion at consumption sites, such as household cables and batteries. The Energy Storage Association of North America designates market applications on the utility side of the meter as Front-of-the-meter (FTM) and the appliances located on the customer side of the meter as Behind-the-meter (BTM) [28]. In this context, we adopt this nomenclature, referring to traditional transmission and distribution networks as *FTM grid,* while designating networks delivering electricity for self-consumption as *BTM grid*.

The electric vehicle (EV) is an example of a technology that can provide both spatial and temporal flexibility, and, in addition, at different places in the value chain. EVs can provide Demand-side spatial and temporal flexibility by charging at different places and at different times, and provide Grid-side flexibility if combined with Vehicle-to-grid (V2G) technology [29].

While acknowledging the importance of Supply- and Demand-side flexibility, this study focusses on the Grid-side only. This focus is motivated by the decreasing availability of Supply-side flexibility, which is attributed to the increasing share of solar and wind energy in an energy system. This decrease has transferred the pressure of flexibility to Grid- and Demand-side. Additionally, Demand-side flexibility solutions come in a myriad of forms and are hence difficult to track. Several studies have nevertheless provided insights into Supply- and Demand-side flexibility, including for example Kawajiri et al. [14], Lannoye et al. [15], and Yasuda et al. [16] on the Supply-side, and Söder et al. [17] and Zhou & Cao [18] on the Demand-side.

Indicators to measure flexibility

In this section two complementary indicators are suggested to measure spatial and temporal flexibility on the Grid side. They represent how long electricity use can be shifted in time or how far it can be redistributed in space, respectively. In this way, the two indicators are designed to capture the most fundamental features of spatial and temporal flexibility in electricity systems, which are the ability to shift electricity in space and time.

Gross spatial flexibility, GSF

The indicator Gross spatial flexibility (GSF) theoretically represents how far electricity can be shifted in space (across land and sea) after energy being converted into electricity and before electricity is converted into final target energy forms, i.e., on the Gird-side. The unit of the indicator is a capacity normalised meter, which should not be confused with a distance in reality. The prefix "Gross" is deliberately adopted to indicate the aggregate and system-level nature of these indicators, analogous to Gross Domestic Product (GDP). Just like GDP provides a broad statistical measure of national economic development, this indicator is constructed for offering a high-level quantitative view of flexibility progress.

The calculation of the indicator is presented in equation 2.1. Firstly, the carrying capacity of electricity of a flexibility solution $P_{i,t}$ (GW) is multiplied by the distance it can move electricity $L_{i,t}$ (m) to represent its capability to shift electricity in space. Then, these products are summed up over all available flexibility solutions m_t to represent the energy-carrying ability of the entire network in country j in the year t. Finally, the sum is divided by the average power demand.

$$GSF_{j,t} = \frac{1}{P_{j,t}} \sum_{i=1}^{m_t} P_{i,t} \bullet L_{i,t} \ \ (\mathrm{m}) \qquad 2.1$$

$P_{j,t}$ (GW) is calculated as the annual electricity consumption (GWh/yr) of country j in the year t divided by 8760 h/yr.

Theoretically, any facilities or activities that can shift electricity in space can be seen as a source of spatial flexibility in electricity systems and therefore can be included in m_t. Currently, moving electricity in space mostly rely on electricity cables, both FTM and BTM, but in the future spatial shifts can also be catered for by moving hydrogen, other electrofuels, or even batteries. For electricity lines, the carrying capacity of electricity is the power capacity of each line and the distance of moving electricity is the length of each line. For electrofuels, one can reinterpret this into the length and power capacity of pipelines or truck and boat routes.

By constructing the indicator in this way, a theoretical ability of shifting electricity in space is assessed. A higher value of GSF represents a better capability to shift electricity spatially. Low carrying capacity or short distance can both lead to a low value of GSF. The spatial flexibility provided by transmission lines with long distance but very low power capacity, or with high power capacity but very short distance, is limited. Since GSF is normalised to electricity demand, a high electricity demand also leads to a low value of GSF. If an electricity system, despite being equipped with long transmission lines of large capacity, cannot shift large shares of the electricity consumption in space, the spatial flexibility could be seen as limited.

An alternative, or complementary, indicator (GSF*) would use electricity production, and not electricity consumption as denominator. For countries with little import and export the difference is small, but for countries with large export it could make sense to measure the capacity to distribute produced electricity, not only to domestic consumption, but also across borders.

Gross temporal flexibility, GTF

The indicator gross temporal flexibility (GTF) measures flexibility in a manner analogous to that of GSF and theoretically represents how far electricity can be shifted in time after energy being converted into electricity and before electricity is converted into final target energy forms. The unit of the indicator is a capacity normalised hour, which again should not be viewed as some time duration in reality.

The calculation of the GTF is presented in equation 2.2. Shifting electricity in time is indeed storing energy for a certain period and using it when needed. Therefore, GTF is constructed based on energy storage capacity. By dividing the energy capacity $E_{i,t}$ (GWh) of all energy storage technologies, n_t, with the annual average power demand $P_{j,t}$ (GW) of country j, a given year t, this indicator theoretically represents for how long national electricity consumption can be postponed if all energy storage facilities are fully charged and connected as a massive energy pool in the country.

$$GTF_{j,t} = \frac{1}{P_{j,t}} \sum_{i=1}^{n_t} E_{i,t} \quad \text{(h)} \qquad 2.2$$

All kinds of energy storage technologies that shift electricity in time can be included in n_t. By limiting n_t to a certain type of technology, temporal flexibility provided by this technology can be studied. A larger value indicates a higher temporal flexibility of the system. Similarly to the GSF* indicator, a GTF* indicator that use electricity production instead of electricity consumption as denominator can be constructed.

The concept of GSF can be extended to the Supply- and Demand-side. When applied to the Supply-side, it assesses the ability to delay electricity generation. Exemplary technologies include hydropower or biomass combustion, both of which store energy for a certain period before it is converted to electricity. When applied to the Demand-side, it assesses the ability to postpone or advance electricity consumption. For instance, a water heater advances a certain amount of electricity consumption for a couple of hours.

Flexibility space

These two indicators describe two ideal situations: on the one hand a massive energy storage pool, and in the other a perfect transmission grid without congestion. However, they are still meaningful as they provide an assessment of the relative availability of flexibility resources in electricity systems and thus offer a way to compare countries or regions regardless of their sizes as well as monitoring change over time. If combined, the two measures form two axes of a two-dimensional *flexibility space*, or *flexibility map*, in which countries and regions are placed in different positions and move in different directions.

To get an idea of the maximum size of this flexibility space one can estimate the extreme endpoints on both axes with a thought experiment. First imagine a society localised on the North or South Pole, reliant only on solar energy. It has no access to any gridlines extending beyond the community; in other words, it has no spatial flexibility. It is an extreme off-grid scenario [7]. If one assumes an even energy demand over the year, half of the produced electricity then needs to be stored half a year, implying that on average the electricity consumed has been stored a quarter of a year giving a GTF of 2190 h. If the energy demand is higher in the dark winter the required GTF would increase above 2190 h towards a final theoretical maximum of 4380 h when all energy is shifted from summer to winter.

Imagine now that societies on the North Pole and South Pole exist in parallel, but without any energy storage, i.e., no temporal flexibility, and that they instead are connected by a large transmission cable. If the consumption is even around the year, they both need to supply half of their needs from a distance amounting to half the circumference of the Earth, implying that on average the electricity consumed has been travelling a quarter of the circumference of the Earth giving an GSF of about 10 000 km. As above, if each community demand more electricity in the dark winter, the required GSF moves above 10 000 km towards the theoretical maximum of 20 000 km when production and consumption patterns are completely swapped. Another thought experiment also reproduces the 10 000 km. Consider a global grid where all electricity is produced in one place, say a desolate location with a massive amount of large nuclear reactors once fantasised by nuclear proponents in the 1970 s. In this idealised global ‘super grid’ demand would on average be localised about one quarter of the Earth’s circumference, or 10 000 km from the powerplant if the demand is not too unevenly distributed across the globe.

While these extreme examples of GTFs and GSFs are very far from what would be required in most places, they are not totally absurd in today’s global energy economy. However, many of today’s large spatial and temporal shifts take place at the Supply side. Large spatial shifts occur when massive amounts of coal, petroleum oil and gas are shipped across the globe before turned into other energy carriers. In 2023, for example, the coal shipped from Indonesia, accounting for almost 70 % of world coal export, was on averaged transported 5200 km [30]. The Nordic countries provide an example of a substantial temporal shift. Sweden (a country not so far from the north pole) has a hydropower resource with the capacity to store energy from the spring flood and use it when needed, which is mostly in the winter. If this gigantic battery was used only for Swedish consumption, its maximum capacity corresponds to a GTF of about 2200 h. On average, 60 % of this is used providing Sweden with 1300 h of Supply side temporal flexibility every year [31].

In this study, it is claimed that the two indicators can be used to monitor change and compare regions. However, no normative claims are made about ideal or better and worse positions on the flexibility map. For each region this will depend on available technologies, patterns of demand and specific demographic and geophysical circumstances.

Method

This section identifies key flexibility technologies monitored in this study, followed by a description of methodological choices for collecting data.

Flexibility technologies included in this study

Focusing on the Grid side, this study monitors a subset of technologies that move electricity in space and time, as shown in Table 1. For temporal flexibility, both non-battery and battery energy storage technologies are evaluated. Non-battery storage technologies include mainly pumped storage hydro (PSH) and, to a lesser extent, compressed air energy storage. For battery technologies, FTM and BTM batteries are considered separately. They are essentially grid-connected large-scale batteries and household-connected small-scale batteries, respectively. There are also some large-scale BTM batteries at factory sites.

Mobile batteries in electric vehicles (EVs), including both battery electric vehicles (BEVs) and plug-in hybrid electrified vehicles (PHEVs),

Table 1
Flexibility technologies studied in this study.

Flexibility	Temporal flexibility	Spatial flexibility
Technology	Non-battery energy storage technologies: Pumped storage hydro* Compressed air energy storage Thermal energy storage Battery energy storage technologies: Front-of-the-meter battery Behind-the-meter battery Passenger electrified vehicles (BEVs, PHEVs)	Transmission grid (AC with voltage above 220 kW and HVDC)

*For pumped storage hydro, only storage capacity is accounted for; generation capacity is not included.

are included as a separate category considering the current great expansion of the EV market worldwide. Although it is still debatable whether PHEVs will play an important role in future V2G applications, we include them to examine the maximum spatial flexibility potentials in electricity systems. The average capacity of a household battery is in fact similar with that of a PHEV, both of which are around 10 kWh.

Electricity networks remain the main source of spatial flexibility in electricity systems. Among electricity networks, FTM grids delivers electricity to remote locations, extending the distances between generation and consumption. The FTM grids are subdivided into transmission and distribution grids. Considering the amount of flexibility obtained and data availability, this study focuses on the transmission grid, which provides for the long-distance travel of electricity.

Data preparation

Table 2 presents the geographical scope and data sources of this study. Theoretically GSF and GTF can be calculated at different scales, such as a city, region, nation, continent or the world by limiting geographical boundaries of data collection. However, this study focuses on the national scale aiming at testing the ability of the two indicators to make comparisons across time and geographies of different size. Overall, four regions are considered: Australia, Germany-Luxembourg-Austria region (referred as the GLA in the following), Sweden and the USA. Germany, Luxemburg and Austria are considered as one region since the electricity systems of Germany, Luxemburg and Austria are closely interconnected and data are available for the region as a whole. For example, the Vianden pumped hydro plant built mainly for the German electricity system is located in Luxemburg [32]. This region is of course also connected to the larger European system, as is Sweden. Hence, we make a separate analysis at the European level of the GSF added to the European system by cross boarder connections.

Data on operational energy storage facilities was collected from a wide range of sources, including databases, such as EU Database, U.S. Department of Energy (DOE), Marktstammdatenregister (MaStR) and supplementary information from websites, reports and newspaper articles.

Transmission network data were more difficult to obtain. There are a few projects attempting to map the contemporary transmission networks of European countries across different years, such as the SciGrid, GridKit, and PyPSA projects [33–35]. However, these projects are all based on a secondary processing of the ENTSO-E Grid map and produce inconsistent results. Therefore, data from these projects were not used. Instead, first-hand data from transmission network operators or governmental agencies were collected. Due to limited access to historical data, a long-term trend of GSF was only constructed for Sweden. For comparison, shorter time series were collected for some European countries, while an indicator value for the four regions in focus was only constructed for 2022.

Power capacity data for individual transmission line is unavailable for the USA, Australia and Sweden. Therefore, for these countries we assume a power capacity of 250 GW for lines with voltage between 220 kV and 380 kV, 962 GW for lines with voltage between 380 kV and 750 kV and 1500 GW for lines with voltage above 750 kV. This assumption is based on the average of maximum current of transmission lines in JAO Static Grid Model which records real operation performance [36]. By considering the maximum operational current, we aim to investigate the maximum potential of an electricity system to shift electricity in space.

Table 2
Data sources.

	Temporal flexibility (Energy storage facilities)	Spatial flexibility (Transmission network)
Germany-Luxembourg-Austria region (GLA)	Marktstammdatenregister [45], Database of the European energy storage technologies and facilities [46], DOE Global Energy Database [47], Kraftfahrt-Bundesamt [48]	Joint Allocation Office [36]
United States	Annual Electric Power Industry Report, Form EIA-860 [49], Annual Electric Power Industry Report, Form EIA 861 [49], Alternative Fuels Data Centre [50]	Homeland Infrastructure Foundation-Level Data [51]
Australia	Australian Renewable Energy Agency [52], Australian Bureau of Statistics [53], Bureau of Infrastructure and Transport Research Economics [54], Database of the European energy storage technologies and facilities [46], DOE Global Energy Database [47]	Geoscience Australia [55,56]
Sweden	Database of the European energy storage technologies and facilities [46], DOE Global Energy Database [47,57–59]	60

Results

This chapter presents the Grid-side GTF and GSF for Sweden, Australia, the GLA and the USA (Section 4.1 and 4.2) as well as the position of these regions in flexibility space (Section 4.3).

Gross spatial flexibility

Fig. 2 illustrates the gross spatial flexibility of the four studied regions. Up to 2022, based on this indicator, Sweden had most spatial flexibility, while GLA had the least. The value of Sweden is approximately 5.6 times of the GLA. By contrast, the GSF of Australia and the USA are 3.4 times and 1.6 times that of the GLA, respectively.

Case study of Sweden from 1930 s

To put these numbers into a historical perspective, a retrospective study on the historical GSF of Sweden's national grid from 1930 to 2022 is conducted (Fig. 3a). A notable increase of Swedish GSF can be observed between the mid-1940 s and 1960, followed by a decrease from early 1960 s to about 1990, and a more stable situation over the last 30 years.

This pattern can be explained by the asynchrony between the expansion of the transmission network and the following and slightly lagging boost of electricity consumption. As shown in Fig. 3b

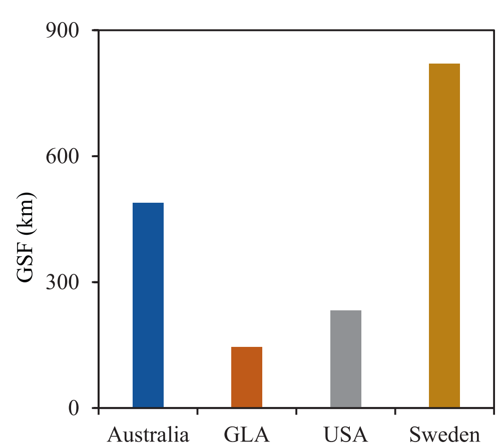


Fig. 2. Gross spatial flexibility of the four regions in 2022.

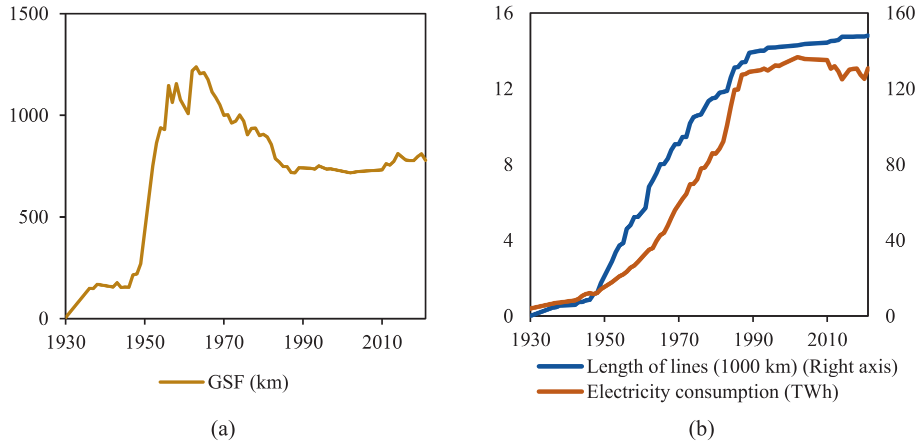


Fig. 3. Gross spatial flexibility of Sweden from 1930 to 2021.

transmission networks experienced rapid growth from the late 1940 s; the total length of transmission lines dramatically started to increase. The extended networks significantly enhanced the availability of electricity, which in turn stimulated electricity consumption and innovation in electricity utilisation appliances. Industries were electrified and the habits of citizens and norms of society changed deepening the demand for electricity. The growth of electricity consumption gradually outpaced the expansion of transmission networks, leading to a decline in the spatial flexibility from the mid-1960 s. From about 1990, the decoupling between electricity use and economic growth as well as a much slower transmission network growth jointly contributed to a stable spatial flexibility.

A similar stability of the GSF from around 1990 over the recent decades can be observed in many other European countries as well. As presented in Fig. 4, with the exception of Portugal, the countries in this sample have shown a stable GSF over the last two decades. At the same time, the GSF based on European cross-border transmission lines has increased 40 % from 2008 to 2022, representing a reinforced interconnection between European countries. This GSF is achieved by applying equation 2.2 to cross-border transmission lines (only the cross-border part of the network, not including purely domestic lines) and normalised to the electricity consumption of the EU. The results indicate that electricity generation and demand are increasingly balanced between countries through cross-border lines instead of within borders, and, in other words, that the increase in spatial flexibility to some extent has shifted from the national to the European electricity system level. This example also highlights the importance of using the indicator at different spatial scales in parallel to get a more complete picture of the development.

Gross temporal flexibility

Fig. 5 shows an overview of the GTF of the four studied regions in 2022. Fig. 5a compares battery and non-battery technologies while Fig. 5b compares BTM and FTM technologies. As shown in Fig. 5a, GLA had significantly higher temporal flexibility compared to other regions in 2022. The GTF of the GLA is approximately 3.3 times, 5.2 times and 32 times that of Australia, the USA and Sweden, respectively. At the same time, the dominance of non-battery technologies stands out in all studied regions. The GLA has the least proportion of battery technologies with a contribution factor of 5 %. By contrast, the contribution factor of battery technologies in Australia and Sweden are 25 % and 27 %, respectively. The dominance of non-battery storage in 2022 is due to the large energy capacity of older PSH systems, in particular in the GLA region. With increasing battery capacities after 2022, this balance is now changing rapidly.

Among battery storage systems, the contribution of BTM and FTM batteries to temporal flexibility varies in countries as shown in Fig. 5b. GLA and Sweden had a comparatively higher proportion of temporal flexibility from BTM batteries in 2022, with values of 73 % and 67 %, respectively. By contrast, in the USA only 11 % of temporal flexibility came from BTM batteries.

Fig. 6 presents the historical GTF provided by FTM and BTM batteries in the four studied regions from 2015. In all regions, FTM and BTM battery installations have expanded. As shown Fig. 6a, the development of FTM batteries in Australia and the USA started to grow rapidly in 2020. Fig. 6b, on the other hand shows the faster uptake of BTM batteries in Australia and GLA between 2015 and 2022.[1]

The potential of EV batteries

The above given numbers of GTF of stationary storage systems can be compared to the potential temporal flexibility provided by passenger EVs and their mobile batteries. For calculation purposes, we assume a capacity of 43 kWh for batteries in BEVs and 10.6 kWh for that in PHEVs, according to the average battery capacity reported in [37]. The results are illustrated in Fig. 7.

EV batteries have a large potential to provide temporal flexibility. For 2022, this effect is more visible in GLA and Sweden, regions with a larger relative share of EVs. By contrast, Australia had in 2022 a relatively small EV fleet.

Coupling GSF and GTF in a flexibility space

Fig. 8 positions the four regions in flexibility space in 2022. Sweden, which is sparsely populated and has large hydropower resources located far away from major population centres that can provide for supply-side temporal flexibility, has a relatively high GSF and low GTF. The more densely populated GLA takes a different position in the diagram with a relatively higher GTF and lower GSF, while Australia is positioned in between Sweden and GLA. The position of the USA can possibly exemplify a region that is still more reliant on fuels providing supply-side temporal and spatial flexibility. As shown in the previous section, all countries demonstrate increasing Grid-side temporal flexibility and are thus moving towards the right side of the diagram, while movements in the vertical direction (spatial flexibility) are slower.

[1] Notably, much has happened since 2022. The installation of stationary battery storage systems has increased dramatically in many regions.

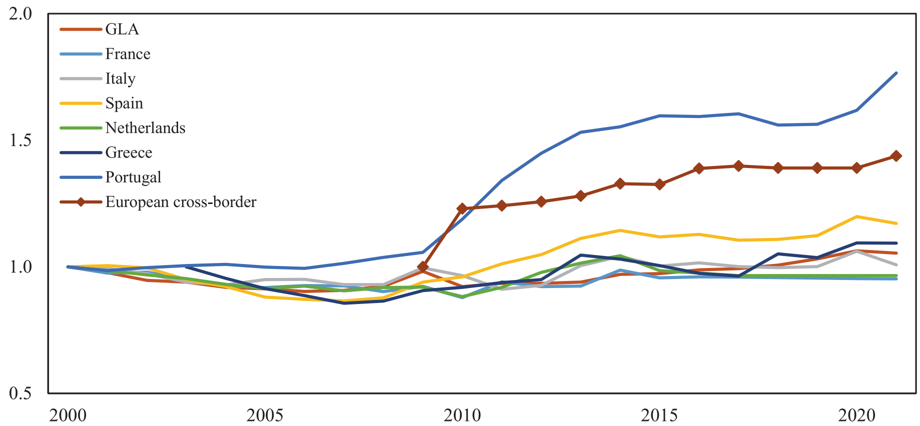
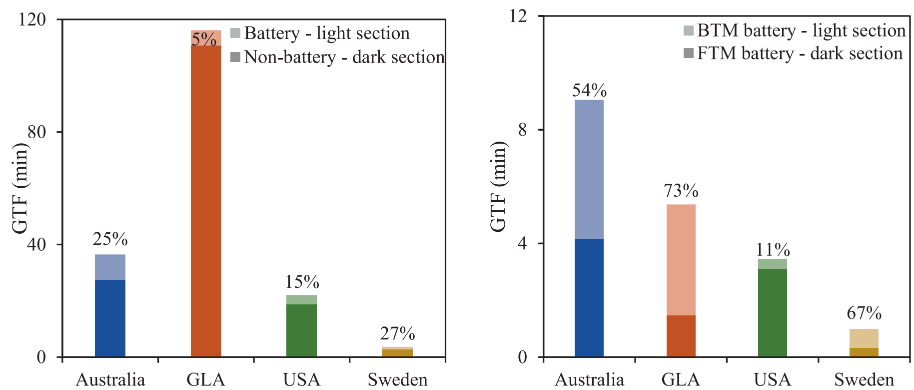


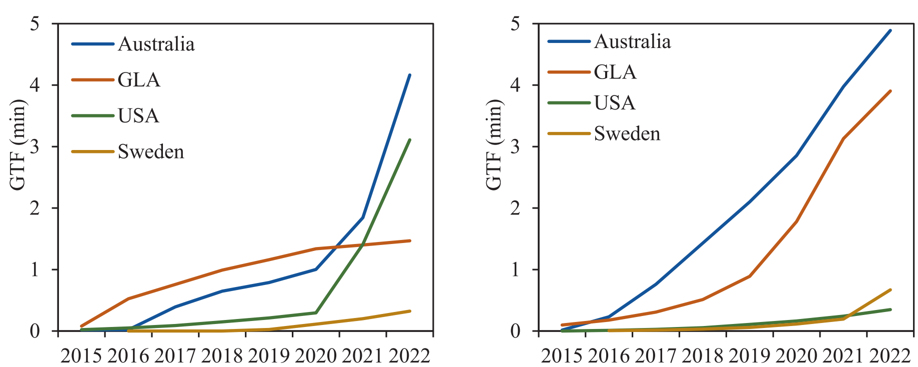
Fig. 4. Increase rate of gross spatial flexibility of European cross-border lines and selected European countries from 2000 to 2022 (relative to 2000) [42–44].



(a) Battery and non-battery technologies

(b) BTM and FTM battery technologies

Fig. 5. Gross temporal flexibility of the four regions in 2022. The percentage represents the contribution of batteries in (a) and BTM batteries in (b).



(a) FTM battery

(b) BTM battery

Fig. 6. Gross temporal flexibility provided by FTM and BTM batteries from 2015 to 2022.

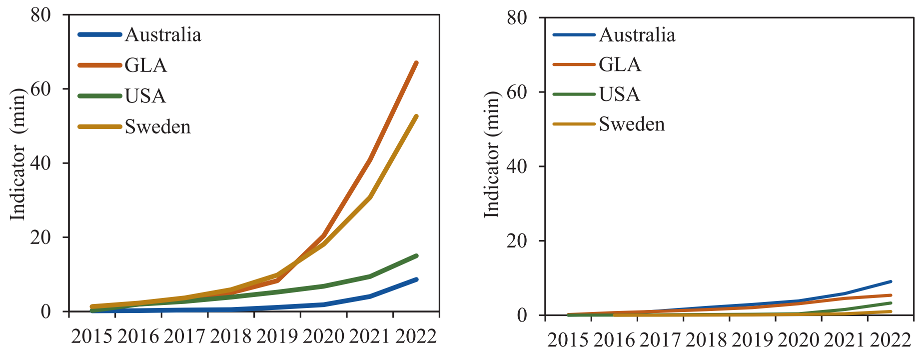
Discussion

Strengths and weaknesses of the proposed indicators

The examples provided in this study demonstrate that the GSF and GTF can offer an overview of the direction and status of flexibility strategy trajectories. The normalisation to electricity consumption enables monitoring change over time as well as comparison between regions.

The long-term time series of the GSF for Sweden, for example, brings to light different periods of Swedish transmission history, from the rapid ramp up of spatial flexibility when the transmission grids expanded in 1950s followed by a downturn in the 1960s and 1970s when demand growth outpaced grid expansion and a last period of relative stability from the 1980s and onwards. Similarly, the GTF applied to batteries shows the take-off and rapid expansion of stationary battery storage systems in many regions over the last decade.

The comparison between regions reveals different starting points as well as different development trajectories. The less densely populated Sweden, with large hydropower resources located far from major



(a) Mobile battery (b) Stationary battery (FTM+BTM)

Fig. 7. Gross temporal flexibility provided by mobile and stationary batteries.

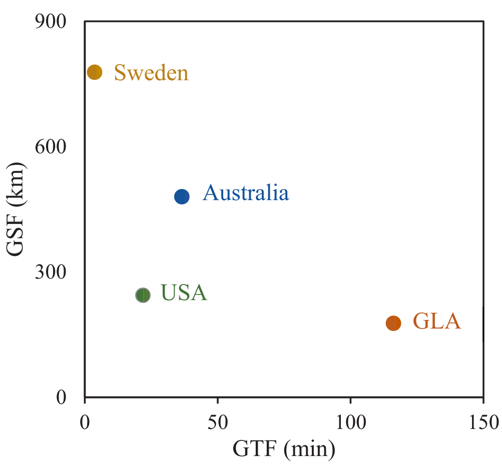


Fig. 8. Grid-side flexibility space of the four regions in 2022.

population centres, was in 2022 in the upper left corner of the flexibility space with relatively high Grid-side spatial flexibility and low Grid-side temporal flexibility. This can be compared to the more densely populated GLA region, with access to pumped storage hydro, resulting in a lower GSF and a higher GTF. Comparing the GTFs over both geography and time discloses other aspects such as the slower uptake of battery storage technology in Sweden compared to the other regions in the observed time period.

The comparison can also be made between different system levels. As an example, between 2008 and 2022 the GSF of cross-border connections in the EU is shown to grow faster in relative terms than the GSF of domestic grids in many EU member states.

Furthermore, the contribution of different technologies can be discerned. Still in 2022, non-battery technologies, mainly PSH, dominated the GTF in all regions. Within the stationary battery sector, the pattern is more diverse with FTM systems dominating in the USA and BTM systems in GLA, while Australia demonstrates rapid growth of both FTM and BTM systems. The comparison to the diffusion of vehicle batteries reveals the large potential contribution of these if vehicle-to-grid technology is implemented. Additional flexibility sources might be added in the future. Sidortsov et al. [38], for example, estimate the technical potential of using abandoned underground mines as PSH reservoirs to 271,040 GWh of storage capacity in the USA alone. Additionally, the first commercial advanced adiabatic CAES project, commissioned in 2022, improved round-trip efficiency to 60 %, compared to 30 %–40 % for traditional diabatic CAES [39]. The GTF could be used to track the future contributions of alternative storage technologies.

Finally, if the scope is extended, the Grid-side flexibility can be compared to Supply and Demand-side flexibility. For example, one reason behind the relatively low level of Grid-side temporal flexibility in Sweden in the studied period is likely due to the already mentioned large availability of Supply-side temporal flexibility provided by hydropower water reservoirs. The Supply side GTF provided by hydropower amount to some 2200 h as compared to a GTF of less than one minute for stationary batteries in Sweden 2022.

While useful for monitoring the evolution of flexibility strategies at a high-level to capture development directions in the energy transition, the proposed indicators lack many nuances of flexibility. An important aspect such as response time of temporal flexibility technologies is for example not considered. Neither can it be used to identify key bottlenecks in transmission and distribution grids that hamper real world utilisation of potential flexibility. To account for these and many other performance criteria of the electric grid other categorisations and indicators are required.

Calls for data availability

An additional research goal was to test the availability of public data required for easy indicator construction and updating. Based on our investigation, we find that current public data may not be sufficient to support easy indicator construction. We observed a lack of national-level databases of energy storage facilities for Sweden and Australia, as well as accessible and complete databases of transmission lines for all countries. This increases the effort required in data collection and validation and thus hinders wider application.

One solution to enhance data availability can be seen in Germany, where incentives are used to promote data sharing. In the KfW funding project conducted from 2013 to 2018 recipients were requested to submit their system data to the Institute for Power Electronics and Electrical Drives of RWTH Aachen University in order to receive funding for installation of PV battery storage systems [40]. The constructed database was subsequently replaced by the Marktstammdatenregister (MaStR) Platform. From 2019, all authorities and actors in the energy sector are juridically required to register requested information on MaStR [41]. Additionally, since the end of 2021, the payment of subsidies will be withheld by the connection network operator until the storage system is registered in the MaStR, which further ensure registration rate on the platform. All these actions together improve data availability in the energy sector in Germany and create a comprehensive and reliable data basis for energy transition.

In principle, it should be easier to create official databases of transmission grid lines, given the lower number of gridlines and fewer actors involved. It may however require that some governmental body instruct TSOs to publish this data on a regular basis.

Conclusion

The long history of evolving energy systems is also the history of adding new forms of flexibility strategies. Contemporary fossil fuel-based electricity systems allow more temporal and spatial flexibility due to the storability, controllable generation and multiple transportation methods of fossil fuels, as opposed to preceding run-of-the-river hydropower-based energy systems with limited flexibility. Nowadays the transformation to an intermittent renewable electricity system has called for new types of flexibility strategies. Flexibility measures could include energy storage technologies, electric grid solutions, complementary energy supply technologies and demand side management strategies. While the deployment of all kinds of measures is forecasted to grow in the coming years, many alternative development directions are possible. To provide foresight and allow for strategic path selection and adaptation, there is a need to monitor development trajectories of flexibility strategies.

To monitor broad trends in flexibility strategies in different regions of the world this study develops two indicators: gross spatial flexibility (GSF) and gross temporal flexibility (GTF). The two indicators are constructed to capture the most fundamental features of spatial and temporal flexibility in electricity systems, which are the ability to shift electricity in space and time. By normalising the ability to carry electricity to average power demand, these indicators also aim to enable comparisons across time and across regions and countries of different size.

The indicators are tested on a sample of countries including Australia, Germany-Luxembourg-Austria (GLA region), Sweden and the USA. The results show that these two indicators are able to capture the direction and status of flexibility strategy trajectories and at the same time enable comparisons across time and across regions of different sizes. At present, publicly available data is not sufficient to support easy indicator construction. The German MaStR platform is an exception and could serve as inspiration to database construction in other countries.

CRediT authorship contribution statement

Chunshuo Ge: Writing – original draft, Software, Methodology, Investigation, Conceptualization. **Anders Nordelöf:** Writing – review & editing, Supervision. **Björn Sandén:** Writing – review & editing, Supervision, Methodology.

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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Data availability

Data will be made available on request.

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