Flexibility and sector coupling in energy systems: definitions and metrics

Synthesis report

Report

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SWEET PATHFNDR consortium

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1 Abstract

Globally, all nations agreed to reach net-zero greenhouse gas emissions by 2050. This requires a drastic change in the energy system, including a shift towards intermittent renewable energies, the need for sector coupling, flexibility, and efficiency.

Flexibility and sector coupling are two concepts widely discussed in the literature, however, a common understanding is missing. In this report, we propose definitions and quantitative metrics for both concepts. Flexibility refers to managing the variations in energy supply and demand at different time scales. While sector coupling describes the interconnection of energy supply and demand sectors such as electricity, heat, gaseous fuels, liquid fuels, and solid fuels to shift loads across them.

The application of definitions and metrics are demonstrated for scenario assessment in Switzerland in the PATHFNDR project by using them as inputs or outputs of simulation models as well as policy and market analyses.

2 Flexibility

2.1 Definition of flexibility

In PATHFNDR, flexibility is defined as the ability of the energy system to manage (expected or unexpected) variability in the electricity supply and demand at different time scales, from the very short to the long term, by adjusting the energy supply, conversion, demand, storage or imports / exports from / to neighboring systems.

Contrary to gas and heat markets, where a certain amount of energy can be stored, electricity is "instantaneously" flowing in the electricity network, thus creating a need to balance demand and supply at all time scales. Balancing demand and supply is the fundamental reason for which flexibility has always been an essential aspect of the operation of electric systems (other operational reasons are described in Section 2.1.1). Flexibility in the electricity sector has traditionally relied on the ability of large generation units to ramp their electricity production up or down, thus following the electricity demand. However, the rising use of intermittent power generation (mostly wind, solar, run-of-river hydro) increases the overall supply variability and, simultaneously, decreases the flexibility of the electricity system with the phasing-out of conventional generators.

The future energy system, therefore, requires a new approach to flexibility supply, as opposed to the traditional paradigm where the flexibility needs were taken care of by the large-scale dispatchable electricity generators. This implies the active participation of flexibility providers which, as energy systems interconnect different energy sectors, can be located in all energy markets (electricity, gas, heat and hydrogen) and on both demand and supply sides (Section 2.1.2).

Flexibility also increases the resilience of an energy system by helping the system to react to unexpected events such as the loss of a large generation unit. However, our definition of flexibility only partly overlaps with the definitions of energy system resilience, see e.g., (Gasser et al., 2019). One the one hand, flexibility goes beyond resilience by addressing expected (and not only unexpected) variations of supply and demand. For example, flexible demand can be generally shifted into hours with an expected high electricity generation. On the other hand, resilience goes beyond flexibility by also including aspects of diversity, fuel reserves, and control of cascading effects. For example, a more diverse energy supply helps to compensate supply shortages of one energy carrier with additional purchases of another.

In PATHFNDR, we analyze future scenarios for the achievement of net-zero greenhouse gas emissions in Switzerland. Realizing this stringent emission target increases the need for flexibility in the planning and operation of the energy system. We, therefore, evaluate the role of flexibility in achieving a carbon neutral energy system by calculating indicators at different spatial and time scales.

2.1.1 Flexibility timescales

The need for flexibility occurs at different time scales (from seconds to months or even years) and different spatial scales (across-countries, national, regional or local).

At the shortest timescale, **seconds** (including sub-second), flexibility is needed to keep the (electricity) system frequency within an acceptable range in a stable manner. If frequency deviates too much or for too long from the reference 50/60 Hz value, protection will start disconnecting equipment, eventually leading the system to a black out. Abrupt frequency deviations can appear due to the loss of a large generator or an interconnector. In the current situation, the inertia of thermal or nuclear generators damps any sudden frequency change. However, in the future energy system, during certain hours, renewables will provide most of the electricity and those units that would provide inertia are switched off or in cold reserve. Thus, frequency becomes less stable on the very short time horizon. To avoid resulting frequency instability, flexibility on an almost instantaneous basis is required (e.g., rotating masses, synthetic inertia (ENTSO-E, 2021).

At the **minutes** scale, flexibility is needed to assure system stability and frequency control. In the current system, flexibility is required to balance the unexpected loss of a generator or a consumer, as well as balancing deviations between the actual and forecasted electricity demand or supply. In a future system that relies on renewable generation, these deviations could increase given the larger uncertainty of renewable resources and the higher likelihood of errors in their forecast.

The next flexibility timescale, **hourly**, is necessary to follow the expected pattern of demand and non-dispatchable supply (i.e., wind or PV) over the day. For example, to compensate for the temporal mismatch between the peak solar generation, occurring in the middle of the day, and the peak demand, occurring in the late afternoon or early evening.

At an intermediate scale, **daily**, flexibility helps to address the differences between unit scheduling and generation dispatch between different days. For example, this difference can occur in the generation (e.g., cloudy or sunny days) or in the demand (e.g., workday and weekend days).

Finally, in the **long-term**, seasonal and inter-year flexibility helps to bridge seasonal variations in generation and demand, for example, due to hydropower availability, summer solar intensity, or winter heating demand. Table 1 presents some applications at the different scales requiring flexibility.

Table 1. Flexibility needs across time and spatial scales (Hillberg et al., 2019; IEA, 2019)

Application requiring flexibility	Time scale	Type of action / operational procedure	Driver	Spatial scale
Maintaining frequency stability	Seconds (including sub-second)	• Inertial response • Primary frequency control	Loss of large generator or interconnector	System-wide (entire synchronous area)
Keeping voltages within acceptable limits	Minutes	Voltage regulation	Increase in power flow in a certain direction: • Progressive: driven by change of demand or supply • Sudden: driven by loss of branch or generator	Local
Avoiding thermal overloading of branches	Minutes to hourly	Power flow control (by means of redispatch or active power flow devices)		Mostly local, action shall have impact on branch under question
Power balancing	Minutes to hourly	• Redispatch of generation and storage units • Demand side management	• Variability of demand and intermittent generation • Forecast errors	Wide-area (country or part of country, cross-country exchange can also be used)
Unit commitment, Scheduling availability of flexibility resources	Daily	• Decision of which generation units are on per hourly slot • Commitment of flexibility providers to be available	• Expected residual demand per hour • Ensuring that enough reserve is available to counteract contingencies and forecast errors	Wide-area (typically, several countries via market clearing) In future, might be relevant also to local
Adequacy of power & energy supply	Long-term	• Seasonal scheduling of hydro reservoirs and long-term storage, such as thermal, natural gas and hydrogen storage (if any) • Ensuring investments in adequate generation and storage capacities	• Seasonal pattern of energy demand (e.g., winter or summer peaks) and availability of energy supply (hydro, wind, solar) • Long-term expected evolution of energy demand	Typically happening at country level, considering the neighboring countries

2.1.2 Flexibility actors

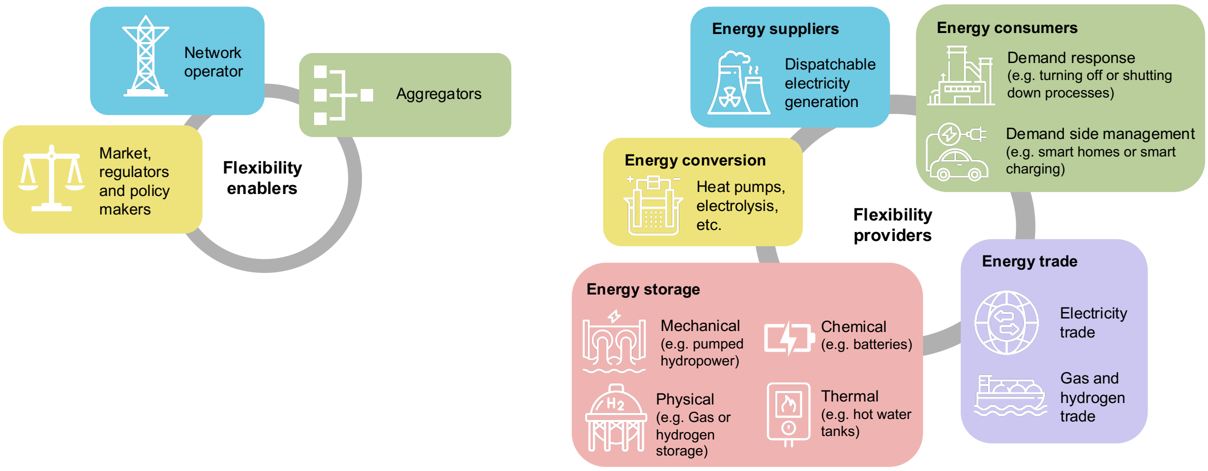

Figure 1. Flexibility actors (PATHFNDR, 2022)

Flexibility enablers

- **Markets, regulators and policy makers:** Currently, the variability of electricity demand and production is matched by varying the power supply accordingly. This is achieved by means of electricity markets, cleared ahead of the actual time of implementation at various time resolutions (5-minute, 15-minute, hourly, daily, weekly, longer-term) and organized at various setups (centralized pools, bilateral, multilateral, over-the-counter). The common theme of these markets is that they all, implicitly or explicitly, rely on forecasting the electricity demand at a selected time horizon. Appropriately set electricity markets are responsible for providing price signals so that flexibility is available when and where needed. However, these price signals might not be enough to incentivize the necessary long-term investments. Hence, regulators and policy-makers should provide additional schemes to ensure the adequacy of the energy system in a reliable manner. Moreover, it is not enough that flexibility is technically available and suppliers and consumers are ready to provide it. If grid operators are only incentivized to increase their grid asset base (i.e., to build more power lines) rather than using flexibility, the required flexibility is unlikely to materialize, even if it would be desirable from an overall system and economic welfare perspective (Oxford Institute for Energy Studies, 2020). Hence, markets and institutions must be in place so that providers of flexibility are incentivized to provide it and that grid operators are incentivized to demand it.

- **Network operators:** Network operators are responsible for identifying the flexibility needs of the systems they operate and ensuring that enough flexibility is available when and where it might be needed. Since network operators have limited operational flexibility options directly at their disposal, they rely on several flexibility providers and enabling processes set by the markets or the regulators. As a result, appropriate operational and control procedures need to be in place, so that flexibility is delivered in a timely manner. Finally, network operators can decrease the flexibility needs by upgrading their network infrastructure, as this will increase the system feasibility limits and will enable higher amounts of cross-region energy transfers. Obviously, network upgrade is a costly and often practically cumbersome option. As a result, it is typically preferable to exploit first the flexibility coming from the flexibility providers (Section: flexibility providers).

- **Aggregators:** Many owners of flexible assets such as households and industry lack the expertise or size to directly act on power markets. Aggregators fill in a crucial role by pooling many assets together to act as a virtual power plant on power markets. Thereby, they help to bring available flexible assets and markets together to harness their full potential.

Flexibility providers

- **Energy suppliers:** Energy suppliers provide flexibility to the system by lowering or increasing their energy supply at a given time. Gas power plants are well-known conventional flexibility providers. New fully dispatchable renewable technologies, such as biogas, hydropower or geothermal, can also provide flexibility to the electricity system.

- **Energy consumers:** Energy consumers provide flexibility to the system by curtailing or shifting their consumption. This can be achieved by demand response (DR) and demand side management (DSM) measures. Demand response is a reactive process to address a short-term flexibility request, while demand side management is a proactive process that involves long term programs to encourage end users to act more efficiently and to better coordinate their consumption with the expected renewable generation. Examples of DR include turning off lighting, adjusting heating, ventilation, and air conditioning (HVAC) levels, or shutting down a portion of an industrial process. DSM measures can include predictive automation (smart homes), smart charging of vehicles or alternative production schedules in industries. The emerging self-consumption communities and energy communities are also expected to play important role in providing energy system flexibility (Koirala et al., 2016).

- **Energy conversion:** Converting one energy carrier to and from another one is an alternative flexibility provider, e.g., electricity can be converted to heat (via heat pumps), to hydrogen (via electrolysis) (Chapter 3 for more details about sector coupling). Energy conversion can supply flexibility in two ways. First, the conversion process can be flexibly adjusted to follow the needs of the power system, e.g., hydrogen electrolysis can be shut down during electricity shortages and started-up again in electricity surplus situations. Second, electricity can be converted to or from a storable energy carrier (heat or hydrogen), which can compensate temporal mismatches of supply and demand (see description of energy storage below).

- **Energy storage:** Storage is an alternative flexibility provider, providing a tool to overcome temporal mismatch between generation and demand. Energy storage can be achieved in various forms, such as physical (e.g., gas or hydrogen), mechanical (e.g., pump hydro, synchronous flywheels), thermal (e.g., borehole seasonal thermal energy storage, residential hot water tanks) or chemical (e.g., residential or automotive lithium-ion batteries, hydrogen or gas storage). Some of these technologies can only offer flexibility in the short or medium-term, other can support the energy system even at longer time-scales.

- **Energy trade:** Energy imports/exports from/to neighboring system is also a flexibility provider, which plays a similar role to energy storage by allowing to overcome temporal mismatches between supply and demand by either importing (in the case of a shortage) or exporting (in the case of a surplus) energy.

Table 2. Overview of flexibility actors

	Actor type	Actor example
Flexibility enabler	Markets, regulators and policy makers	
	Network operators	TSOs and DSOs
	Aggregators	
Flexibility provider	Energy suppliers	Conventional and dispatchable renewable power plants
	Energy consumers	Demand response and demand side management, such as smart homes, smart vehicle charging, etc.
	Energy conversion	Electrolysis, heat pumps
	Energy storage	Pumped hydro, batteries, vehicle-to-grid, long and short-term thermal energy storage, hydrogen storage, natural gas storage
	Energy trade	Energy (electricity, hydrogen, gas, etc.) imports or exports

2.2 Metrics for flexibility

Flexibility in PATHFNDR can be defined as a feature associated with a technology (e.g., the ramping rate, the maximum on/off time) or a property of the whole energy system (e.g., aggregated shiftable load), as well as a need at a system design stage to mitigate unwanted effects (e.g., curtailing generation and demand). As such, we divide the metrics to quantify flexibility in two categories: flexibility capabilities and flexibility needs/demand (or use). The first category measures the flexibility capability of an energy system and includes metrics at the technology and consumer level (demand response). The second category measures the actual flexibility needs as outputs of simulations of a defined energy system, and includes metrics for the electricity sector and for the entire energy system (Table 3). Other metrics reported in the literature and employed for specific application (e.g., flexibility envelope in control applications (D'hulst et al., 2015) might also be used in PATHFNDR.

Table 3. Flexibility metrics (Edmunds et al., 2020; ENTSO-E, 2021; Gils et al., 2022)

Dimension	Scale	Metric	Use in PATHFNDR	Time scale
Flexibility capabilities				
Technology flexibility	Technology	Ramping rates, up and minimum on/off time	Input parameter and result of the project for some technologies	Minutes-hours
Demand response and demand side management flexibility	National / system level	Amount of load that can be shifted (forward or backward) for a selected amount of time	Result of the project	Days, seasons
Flexibility needs				
Electricity system flexibility needs	Electricity sector	Aggregate ramping capacity measured as the differences between the residual loads in two time slots within a day (e.g., 1-hour, 3-hour and 8-hour apart)	Result of the project	Minutes, hours, years
		Over-generation (ratio of peak to minimum)		Years
		Curtailed available energy		Days, seasons, years
Energy system flexibility needs	Energy system	Storage utilization	Result of the project	Hours
		Energy trade (imports, exports of gas, hydrogen and electricity)		Hours

2.3 Application of flexibility in PATHFNDR

It is expected that the future energy system will require higher (and probably more time- and space-varying) levels of flexibility than today's paradigm. In PATHFNDR, we quantify the flexibility needs corresponding to several future scenarios, we identify the potential of flexibility provision from various sources, while we develop operational procedures for utilization of the available flexibility.

More precisely:

- We identify the aggregated flexibility needs of European countries, Switzerland as a whole and some Swiss regions; in the timescales from hours to years; for a set of considered future evolution scenarios.

- We quantify the amount of flexibility that can be offered by flexibility providers, by means of supplying, consuming, converting, storing, or trading local energy resources.

- We develop operation procedures, allowing the distribution system operators to utilize the flexibility that is available at the various sites for congestion management (i.e., keeping voltages and currents within an acceptable range) in the electricity distribution network.

- We propose and test methods enabling the utilization of local flexibility resources, located at various locations within a country, for provision of flexibility for power balancing.

- We study a broad set of energy supply (e.g., solar PV and thermal, combined heat and power plants) and conversion/storage technologies (electrolyzes and fuel cells for hydrogen storage, electrochemical batteries, short-term and seasonal thermal energy storage), analyzing their potential to provide flexibility at different temporal and spatial scales. We develop modelling methods to enable the evaluation of this potential, including technical and economic aspects.

- We study how flexibility technologies disrupt existing businesses and what innovation strategies and internal organizations help firm to create, deliver and capture value effectively in more flexible and interconnected innovation eco-systems.

Let us note that flexibility at the timescale of up to a couple of minutes is out of scope of the PATHFNDR project. Most of the work performed in PATHFNDR considers hourly temporal resolution, while selected applications consider a time resolution of down to 15 minutes (only in the case of distribution).

2.4 Literature review for flexibility

2.4.1 Definitions

Literature	Review
PNNL. Grid modernization (2020): Metrics analysis – Flexibility (Edmund et al., 2020)	"The ability to respond to future uncertainties that may stress the system in the short term and require the system to adapt over the long term."
Metrics for quantifying flexibility in power system planning (EPRI, 2014)	"In power systems, flexibility is the ability to adapt to changing conditions while providing electricity safely, reliably, affordably, and in an environmentally responsible manner. In this paper, the definition of operational flexibility is refined to describe a power system's ability to ramp and cycle resources to maintain a balance of active power supply and demand through reliably operating a system at least cost. These changes can be both upward and downward ramps over a wide variety of time scales, ranging from minutes to hours."
IRENA (2018). Power system flexibility (IRENA, 2018)	"Flexibility is the capability of a power system to cope with the variability and uncertainty that VRE generation introduces into the system in different time scales, from the very short to the long term, avoiding curtailment of VRE and reliably supplying all the demanded energy to customers."
IEA (2019). Status of Power System Transformation 2019 - Power system flexibility (IEA, 2019)	Power system flexibility is defined as "the ability of a power system to reliably and cost-effectively manage the variability and uncertainty of demand and supply across all relevant timescales, from ensuring instantaneous stability of the power system to supporting long-term security of supply.

ISGAN (2019). Flexibility needs in the future power system (Hillberg et al., 2019)	Power system flexibility relates to the ability of the power system to manage changes.
	
	Solutions providing advances in flexibility are of utmost importance for the future power system. Development and deployment of innovative technologies, communication and monitoring possibilities, as well as increased interaction and information exchange, are enablers to provide holistic flexibility solutions. Furthermore, development of new methods for market design and analysis, as well as methods and procedures related to system planning and operation, will be required to utilize available flexibility to provide most value to society.
	
	However, flexibility is not a unified term and is lacking a commonly accepted definition. Several definitions of flexibility have been suggested, some of which restrict the definition of flexibility to relate to changes in supply and demand while others do not put this limitation.
	
	The flexibility term is used as an umbrella covering various needs and aspects in the power system. This situation makes it highly complex to discuss flexibility in the power system and craves for differentiation to enhance clarity. In this report, the solution has been to differentiate the flexibility term on needs, and to categorize flexibility needs in four categories:
	
	• **Flexibility for Power:**
	  • Need Description: Short-term equilibrium between power supply and power demand, a system-wide requirement for maintaining the frequency stability.
	  • Main Rationale: Increased amount of intermittent, weather dependent, power supply in the generation mix.
	  • Activation Timescale: Fractions of a second up to an hour.
	
	• **Flexibility for Energy:**
	  • Need Description: Medium- to long-term equilibrium between energy supply and energy demand, a system-wide requirement for demand scenarios over time.
	  • Main Rationale: Decreased amount of fuel storage-based energy supply in the generation mix.
	  • Activation Timescale: Hours to several years.
	
	• **Flexibility for Transfer Capacity:**
	  • Need Description: Short- to medium-term ability to transfer power between supply and demand, where local or regional limitations may cause bottlenecks resulting in congestion costs.
	  • Main Rationale: Increased utilization levels, with increased peak demands and increased peak supply.
	  • Activation Timescale: Minutes to several hours.
	
	• **Flexibility for Voltage:**
	  • Need Description: Short-term ability to keep the bus voltages within predefined limits, a local and regional requirement.

	• Main Rationale: Increased amount of distributed power generation in the distribution systems, resulting in bi-directional power flows and increased variance of operating scenarios. • Activation Timescale: Seconds to tens of minutes.

VSE, "Flexibilities", Basic Knowledge Document, Status March 2020
(VSE, 2020)
	Flexibility is defined as the possibility to i**nfluence the feed-in to the grid or the withdrawal from the grid** by a generation or consumption unit at the request of the grid operator or another actor, either directly (control) or indirectly (incentives or usage restrictions). [SFOE Final Reports on grid aspects and market design, Consentec]
	
	• This flexibility can be provided on a short- or long-term basis.
	• This basic knowledge document describes flexibilities on the one hand as technologies, on the other hand as applications that are able to contribute to energy balancing. A general distinction is made between developed and new flexibilities
	    • The term "developed flexibilities" refers to all known and available technologies that are in widespread use in the overall system and have proven their functionals
	    • The term "new flexibilities" refers to those technologies that are already available today in isolated cases and/or for which there is a useful potential in the future. Technological advances in networking and communications are unlocking unknown or previously untapped flexibility options.
	    • Flexibilities can be both "acting" (Demand Side Management; DSM) and "reacting" (Demand Side Response; DSR). It is irrelevant whether the flexibilities involved (generation units, storage or loads) are integrated or controlled centrally or decentrally in the overall system. Power plants are the classic, centrally acting and reacting flexibilities, which can be used for system services (SDL) or instantaneous reserve.

2.4.2 Metrics

Literature	Review
Assessment of Future Flexibility Needs (ENTSO-E, 2021)	The following methodological approaches and metrics are proposed for the determination of ramping and scarcity period flexibility needs and are suggested to be the basis for ENTSO-E's further development, improvement, and fine-tuning; note that although the metrics build on the outputs of chronological simulation studies, they do not suggest or require any adjustment to the simulations themselves as they might be used for Mid-term Adequacy Forecast (MAF), European Resource Adequacy Assessment (ERAA) or Ten-Year Network Development Plans (TYNDP). • **Ramping flexibility needs**: These metrics measure large daily residual load gradients, for example, at sunset in regions with large PV generation capacities. The approach is partly based on experiences from CAISO and EirGrid. Residual load is the load left after subtracting VRE generation such as wind, PV and run-of-river hydro from the demand. Explicit and implicit demand flexibility was considered as part of the dispatchable capacity, and not in the residual load calculation. The treatment of these capacities in the methodology could be further improved. • **Scarcity period flexibility needs**: These are metrics focused on contiguous-day EENS (expected energy not served) problems during scarcity periods, when variable renewable energy (VRE) resources are not available for extended and continuous periods such as windless winter weeks in Northern Europe.
Modeling flexibility in energy systems — comparison of power sector models based on simplified test cases (Gils et al., 2022)	The evaluation of the model comparison focuses on the use of the available flexibility options. In a broader sense, this also includes curtailment of VRE generation and uncontrolled load shedding. The latter is implemented in the models as a slack variable to ensure the balance of power, heat, and hydrogen to keep the mathematical problem solvable. These two indicators are complemented by the system costs and flexibility usage. Depending on the flexibility option, this is represented by electricity, heat or hydrogen generation, storage utilization, storage and grid losses, load shifting, and transmitted electricity. Besides scalar indicators, we analyze hourly use profiles of plant operation. In particular, the use of flexibility options, but also of VRE curtailment and uncontrolled load shedding (corresponding to uncovered load), is compared for selected times of the year. This allows the observation of deviating plant usage behavior.
PNNL. Grid modernization (2020): Metrics analysis – Flexibility (Edmund et al., 2020)	These metrics and examples of users are as follows: • Metrics focusing on flexibility demand:

- Variable energy resource penetration (Tennessee Valley Authority [TVA])
  - Flexibility turndown factor (TVA)
  - Net demand ramping variability (North American Electric Reliability Corporation [NERC] Essential Reliability Services Task Force [ERSTF])
  - Flexible capacity need (CAISO)

- Metrics focusing on flexibility supply:
  - System regulating capability (TVA)
  - Demand response (Federal Energy Regulatory Commission [FERC])

- Metrics focused on the balance between flexibility supply and flexibility demand:
  - Flexible resource indicator (Western Electricity Coordinating Council [WECC])
  - Periods of flexibility deficit (Electric Power Research Institute [EPRI])
  - Insufficient ramping resource expectation (EPRI/academic)
  - Flexibility metric (New England Independent System Operator [ISO-NE])
  - System flexibility (Puget Sound Energy)
  - Loss-of-load due to flexibility deficiency (Pacific Gas and Electric Company [PG&E], San Diego Gas & Electric Company [SDG&E])
  - Binding flexibility ratio (Lawrence Berkeley National Laboratory [LBNL])

- Metrics that use a proxy to indicate insufficient flexibility:
  - Renewable curtailment (Energy and Environmental Economics)
  - Percentage of unit-hours mitigated (FERC) – Control performance standards (NERC).

As with the other metrics, flexibility metrics can be separated into 1) lagging metrics that measure what has happened, and 2) leading metrics that can be used to support long-term planning, day-ahead market clearing, and real-time operational decisions about unit commitment or dispatch. Currently, there are no widely used and mature lagging metrics of flexibility that directly measure the flexibility of the power system. Instead, there are several indirect measures that may indicate when the power system was not sufficiently flexible.

Potentially useful lagging and leading metrics describing operational flexibility are listed below. The exact relationships between these metrics and operational flexibility have not yet been developed.

- Fraction of load under interruptible tariffs – Interruptible tariffs have been used for many years by load-serving entities across the country, generally for large industrial and commercial customers. At any point in time, the interruptible demand divided by total demand is one measure of flexibility in the system. Because large industrial and commercial loads under these tariffs typically have real-time metering, this metric could be computed in real time.

- Demand response – Similarly, demand response is a measure of flexibility in the grid. However, demand-response resources are also available from all customer classes at very disaggregated levels (e.g., individual air conditioners). This disaggregation makes it difficult to estimate how much flexibility is available at any given time because the loads are typically not metered in real time. In addition, availability varies with respect to advanced notice requirements for participating in day-ahead, hour-ahead, or real-time markets.

- Energy storage – Stored energy is a measure of the supply of flexibility at any point in time.

- Generator ramp rates – The aggregate ramping capability (MWs per minute) of the fleet of generators currently online is a measure of the supply of flexibility.

- Headroom – The difference between the maximum output of all dispatchable generators and the current load levels provides a measure indicating how long a given ramp rate can be sustained.

- Price volatility – Large changes in real-time prices may be indicative of insufficient flexibility in the system; in particular, negative prices are indicative of over-generation conditions that may be due to flexibility or transmission line outages.

3 Sector coupling

3.1 Definition of sector coupling

In PATHFNDR, sector coupling is defined as the interconnection between (and within) the energy supply and/or energy demand sectors. In the context of the energy transition, sector coupling specifically refers to sectors that enable the integration of renewable energy sources and thereby, support the decarbonization of energy systems.

The aim of sector coupling is to exploit synergies among multiple energy sectors with the ultimate goal of achieving a deep decarbonization of the energy system. As such, sector coupling fosters the penetration of renewable energy generation, through better allocation of production and storage capabilities (IRENA, 2019). In addition, sector coupling facilitates the electrification of various energy demand sectors such as the transportation and residential sectors (Fridgen et al., 2020; Ramsebner et al., 2021; IRENA, 2019; Wietschel et al., 2018). In combination with other measures, such as flexibility (Chapter 2), sector coupling can help to shape load profiles (e.g., reduce the peak load or seasonal spread) and optimize the electricity prices (IRENA, 2019). Furthermore, sector coupling in combination with energy efficiency (Chapter 4) could help to minimize losses due to energy conversion from one sector to another, and increase the reliability of energy. Ultimately, sector coupling allows for extending the design possibilities to enhance the techno-economic performance and reduce the CO_2 emissions.

In this definition, the energy system is divided into two categories of energy sectors. These are (1) the energy supply sectors, and (2) energy demand sectors, as described in Table 4. The energy supply sectors include energy carriers (or producers) such as electricity, heating / cooling, gaseous fuels (e.g., natural gas, hydrogen, synthetic gas), solid fuels (e.g., coal, wood, biomass), and liquid fuels (e.g., ethanol, methanol, synthetic fuels). The energy demand sectors involve energy consumers such as residential buildings, commercial / trade / services facilities, industry, and transportation. Prosumers, on the other hand, fit inside both categories, as they cover both the supply and demand of energy. The interconnection of these sectors takes place through technologies and infrastructures for energy conversion and storage (e.g., power-to-X, thermal storage), and for energy transportation and usage (e.g., grids, heat pumps, electric vehicles).

Table 4. Overview of energy sectors

Categories	Sectors
Energy supply sectors *(in form of energy carriers / producers)*	• Electricity • Heating / cooling • Gaseous fuels (e.g., natural gas, hydrogen, synthetic gas, biogas) • Solid fuels (e.g., coal, wood, biomass) • Liquid fuels (e.g., ethanol, methanol, synthetic fuels)
Energy demand sectors *(in form of consumers)*	• Households / residential buildings • Commercial / trade / services facilities • Industry • Transportation

Sector coupling can take place (1) across the energy supply and demand sectors, or (2) within the energy supply or demand sectors. The first coupling refers to the interconnection between two or more sectors across the energy supply and demand sectors. For example, vehicle-to-grid links the transportation sector with electricity sector, or district heating links the residential sector with heating sector (represented in Figure 2). The second coupling refers to the interconnection between two or more sectors within the energy supply or demand sectors. For example, power-to-heat (e.g., heat pumps) links the electricity and heating sectors, heat recovery links the residential/commercial and industrial sectors (represented in Figure 2) or vehicle-to-home links the transportation and residential sectors. By linking the energy flows from various sectors, sector coupling can help minimize the transportation and storage of energy, and also reduce the need to further expand power, thermal and gas grids. Emerging solutions of such coupling are power-to-X technologies. These examples are illustrated in Figure 2. Sector coupling is also an additional source of energy system flexibility and can be utilized towards overall energy system benefits.

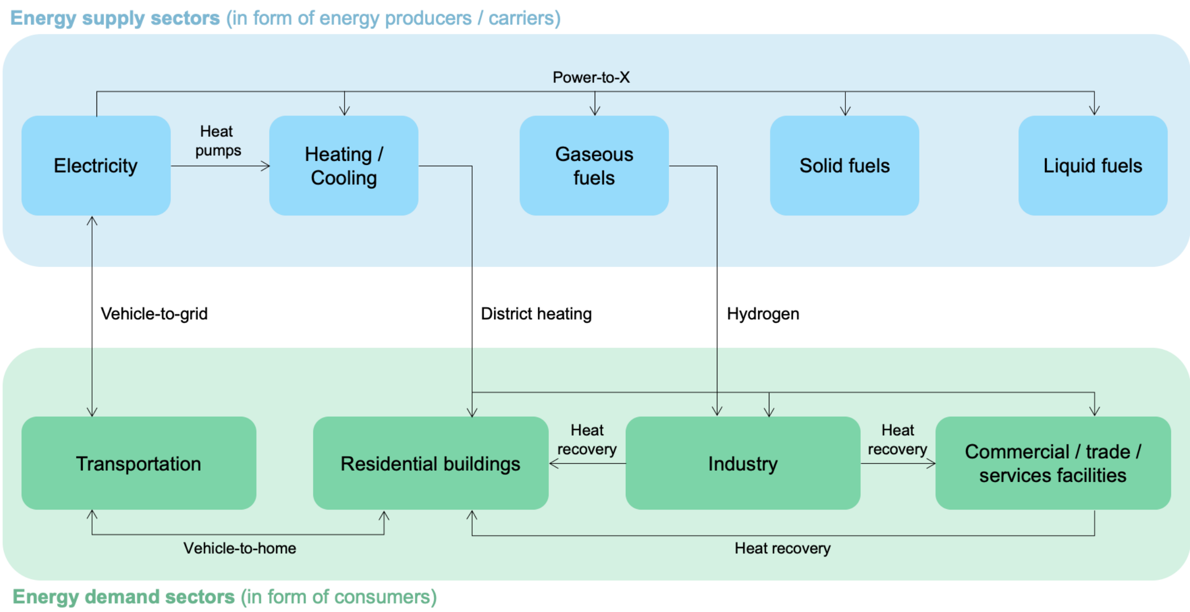

Figure 2. Example of intra- and inter-sectoral coupling described above (PATHFNDR, 2022)

Similarly, to flexibility (Chapter 2), there are also sector coupling "enablers" such as policies, business models, or actors and their networks that enable or promote sector coupling.

3.2 Metrics for sector coupling

PATHFNDR evaluates different climate policy, social, technological, geopolitical and environmental dimensions, offering different scenarios that lead to alternative developments of the Swiss future energy system. For the evaluation of these scenarios in PATHFNDR, sector coupling is an enabler, output, and result, rather than an objective or target. Sector coupling is measured by the energy flows between the supply and demand sectors, i.e., the ratio of energy and power exchanged between different sectors (Table 5). The scale varies between district and national scale, depending where the actual coupling happens.

These metrics assess only the physical and technical coupling of energy systems. The economic means and consequences of sector coupling or cross-sectoral policy impacts are not defined as metrics.

Table 5. Sector coupling metrics

Term	Energy exchange without losses	Energy exchange with losses	Power exchange
Metric	Ratio of energy exchange without losses between two or more sectors	Ratio of energy exchange with losses between two or more sectors	Ratio of power exchange between two or more sectors
Calculation	$\frac{\text{energy exchange}}{\text{total energy supply/demand}}$	$\frac{\text{energy exchange} \times \text{energy conversion efficiency}}{\text{total energy supply/demand}}$	$\frac{\text{peak power at energy exchange}}{\text{total power capacity}}$
Description	The energy exchange ratio is the ratio between energy exchange in each sector without conversion losses and the total energy supply / demand in each sector.	The energy exchange ratio is the ratio between energy exchange in each sector with conversion losses and the total energy supply / demand in each sector.	The power exchange ratio is the ratio between peak power of the energy exchange in each sector and the total power capacity in each sector.

3.3 Application of sector coupling in PATHFNDR

In PATHFNDR, the role of sector coupling for carbon-neutral energy scenarios is evaluated by quantifying the energy exchange between sectors, and energy conversion efficiency. Various simulation models and tools, as well as experimental setups and real demonstrators are used for this purpose.

More precisely:

- We assess the techno-economic potential of sector coupling, considering the electricity, heating, gaseous fuels, industrial and residential sectors at national and cantonal level in Switzerland into account. A particular focus lies on the chemical industry due to its high energy consumption, waste heat potential, and the need for chemical feedstocks as energy carriers and/or storage. Future heating demand and trends as well as a wide range of technology options and heat sources (e.g., hydrogen, synthetic natural gas, heat pumps) are explored. In addition, the techno-economic potential of the transportation sector and demand for electricity, gaseous fuels, and other energy carriers used in transportation is evaluated at the international, national and cantonal levels. The Calliope model is used for the assessment at the international level, the SecMOD model, and the Nexus-e model are integrated to study the national and cantonal levels. Furthermore, the impact of these results is assessed at the municipal level in terms of the use of technologies or the required infrastructure for the transformation of the heating sector. The EXPANSE model is used for evaluation at the municipal level.

- We investigate the coupling of the electricity, heating, gaseous fuels, residential, commercial, industrial and transportation sectors by combining energy distributions networks with energy conversion technologies at the local level (district, village, city, or site), such as combined heat and power (CHP), power-to-gas units, and storage. Infrastructure planning algorithms for site owners and distribution utilities are developed such that the optimal combination of energy sectors is identified. In addition, algorithms to operate the various local level energy technologies in a coordinated manner are developed. Finally, the operation of selected multi-energy systems are emulated by means of the ReMaP Simulation Framework. In this way, the extent and value of sector coupling are identified.

- We evaluate the techno-economic potential of technologies for sector coupling, considering emerging conversation and storage technologies that link the electricity, heating, gaseous fuels, residential, commercial, industrial and transportation sectors. These technologies include hybrid thermal energy storage systems, power-to-x for heat recovery (e.g., from data centers, or cooling operations), electric vehicle charging technologies, or geothermal storage. The performance of the different technologies is simulated with the Ehub and ReMaP modelling platforms, and their real-world assessment is conducted on experimental setups such as the EPFL Smart Grid, the PSI Energy System Integration (ESI), and Empa NEST and move demonstrators.

- We analyse sector coupling at the firm level in terms of value chains, business opportunities, and technological innovation. This analysis includes examining the disruptive potential of cross-sector technologies (e.g., hydrogen, electric vehicles) for existing businesses and value chains. New insights into how coupling between different sectors can unfold are explored by linking different technology value chains, their drivers and barriers, as well as future trends and their potential effects. Value chain coupling is assessed in terms of supplier-costumer-relationship, markets or regulation, actors and their networks.

- We assess the social and economic impacts of alternative policies and transition policy mixes to address the needs of sector coupling at the international and national levels. In addition, the public acceptance (including people's attitudes and beliefs towards sector coupling) of emerging technologies (e.g., e-mobility and power-to-x) is analyzed through informed citizen panels.

3.4 Literature review for sector coupling

Literature	Review

A holistic view on sector coupling
(Fridgen et al., 2020)
	Problem:
	• The growing share of intermittent renewable energy sources (RES) impact the stability of the energy supply systems.
	• The spatial challenge of the growing share of RES is the energy supply at the wrong location.
	• The temporal challenge of the growing share of RES is the energy supply at the wrong time.
	
	Definition:
	• Sector coupling refers to the connection and interaction of energy-demanding sectors (electricity, gas, heat, cooling, traffic, industry, buildings) to increase the flexibility of supply, demand and storage.
	• In a holistic view, "sector coupling is the multi-dimensional concept for governing cross-, inter-, and intra-sectoral energy flows of all grids that transport energy in any form, of energy transformation and storage, as well as for increasing the flexibility of energy supply and demand to tackle the challenges of a future energy supply that is based on renewable energy sources."
	• Cross-sectoral energy flows refers to the merge of intra- and inter-sectoral energy flows.
	• According to the German Association of Energy and Water Industries, sector coupling is the coupling of electricity, heat, mobility, and industrial processes in industrial, household and transport sectors.
	• It is linked to the terms "smart energy systems" and "multi-energy systems".
	
	Examples:
	• Power-to-X:
	    • Power-to-gas
	    • Power-to-heat
	    • Vehicle-to-grid
	    • Power-to-product (energy converted for the consumer)
	
	Impact:
	• SC can minimize losses of a spatial energy transportation by applying cross-sectoral energy flows.
	• SC should consider all grids that transport energy in any form.
	• SC can reduce the planning of infrastructural excess capacities and thus, avoid further expansion of the electricity grids.
	
	Limitations:
	• Energy goals and economic incentives need to be unified.

Demand-side flexibility for power sector transformation	**Problem:**

(IRENA, 2019)	• Decarbonization of the energy sector is challenged by the increasing penetration of variable renewable energy (VRE) together with the increasing electrification of end-use sectors. • These challenges could affect the reliability (variability and uncertainty) of the power system. • The share of renewable energy in global annual electricity generation will need to increase form 25% today to 86% in 2050. • The share of electricity in final energy consumption will need to increase from 20% today to 49% in 2050. • The increase of sector coupling and flexibility could help to mitigate potential mismatches in both the supply and demand sides. **Definition:** • Sector coupling refers to the integration of the demand coming from the electrification of various sectors (heat, transport) that could be increased, reduced or shifted in a specific period of time. • SC and flexibility could facilitate the integration of VRE by reshaping the load profiles, reduce peak load and seasonality, and reduce electricity generation costs by shifting periods with high to low prices. **Examples:** • Power-to-heat is competitive for industrial, commercial and residential sectors. • Power-to-hydrogen is competitive for the industrial sector. • Electric vehicles are competitive for commercial and residential sectors. • Smart appliances are competitive for commercial and residential sectors. • Industrial processes is competitive for the industrial sector.
Renewable energy systems: a smart energy systems approach to the choice and modeling of 100% renewable solutions (Lund et al., 2014) **Smart Energy Systems. it-Information Technology** (Schmeck, 2013)	**Definitions:** • Alternative definition of the term sector coupling by means of the definition of a "Smart Energy System": A Smart Energy System is defined as an approach in which smart electricity, thermal and gas grids are combined with storage technologies and coordinated to identify synergies between them in order to achieve an optimal solution for each individual sector as well as for the overall energy system.
The sector coupling concept: A critical review (Ramsebner et al., 2021)	**Definition:** • A concept to integrate variable renewable electricity (VRE) through transformation into suitable energy carriers such as heat, gas, and liquids. • "From our literature review, we conclude that the concept is rooted in the increasing share of VRE in the overall energy system. We therefore suggest considering SC as a concept to promote the integration of large-scale renewable electricity by increasing its direct use or indirect application through transformation into a suitable energy carrier, such as heat, gas, and liquids. Consequently, we do not consider renewable energy, which does not include electricity as a main input, such as waste heat or biofuels, as a main aspect of the SC concept but rather of MESs." **Sectors:** • Transport, residential, industry, and trade/services (based on final demand, common in energy economics). • "With respect to the sectors that are considered in SC, we find the approach that is common in energy economics (transport, residential, industry, and trade/services) suitable for analyses regarding the techno-economic and system perspective, because these represent the final demand. For specific technological research such as P2G, however, a focus on the energy carriers – such as electricity, heat, and gas – may of course be useful." • This literature review collected 14 definitions of sector coupling.
S**ector coupling: how can it be enhanced in the EU to foster grid stability and decarbonise?** (Van Nuffel et al., 2018)	**Definition:** • To distinguish between coupling of end-use sectors with the energy supply sector on the one hand and further coupling of the energy supply sectors on the other hand, we will refer to these two strategies as 1) end-use sector coupling and 2) cross-vector integration. This is a pragmatic approach to highlight these complementary strategies, but other categorizations are possible.
Sektorkopplung: Definition, Chancen und Herausforderungen (Wietschel et al., 2018)	**Definition:** • The ongoing process of replacing fossil energy carriers with largely renewably generated power or other renewable energy carriers and sustainable forms of energy use. This also includes integration among consumption sectors as, for example, using excess heat in new or known cross-sectoral applications. **Sectors:** • Defines sector coupling as the use of renewable electricity in the transport, heat, and industrial/services sector. • Differentiates sector, infrastructure, and technology perspective on sector coupling.

	• Consumption sectors: households / residential, commercial / trade / services, industry, transport. • Energy carrier sectors: power, heat, fuels • Infrastructure sectors: power grid, gas grid, heat grid, information and communication grid
Sektorkopplung – Was ist darunter zu verstehen? (Wietschel et al., 2019)	**Definition:** • In the context of the definition of sector coupling, it must first be determined which sectors are being discussed or how "sectors" are defined. • In contrast to this established classification, the use of the term "sector" in the context of sector coupling is often inconsistent. **Sectors:** • The classical (consumption) sectors of the energy industry, which can be found e.g., in the energy balances, are the transformation sector, households, commerce, trade, services, industry and transport.
Integration erneuerbarer Energien durch Sektorkopplung: Analyse zu technischen Sektorkopplungsoptionen (Wietschel, 2019)	**Sectors:** • Consumption sectors of the energy industry: transformation sector, households, commercial, retail, services, industry and transport.
Linking the power and transport sectors – Part 1: The principle of sector coupling (Robinius et al., 2017) **Positionspapier: 10 Thesen zur Sektorkopplung** (BDEW, 2017)	**Definition:** • The energy engineering and energy economy of the connection of electricity, heat, mobility and industrial processes, as well as their infrastructures, with the aim of decarbonization, while simultaneously increasing the flexibility of energy use in the sectors of industry and commercial/trade, households and transport under the premises of profitability, sustainability and security of supply. Definition according to the BDEW (Bundesverband der Energie- und Wasserwirtschaft).
Integrated electricity, hydrogen and methane system modelling framework: Application to the Dutch infrastructure outlook 2050 *(Koirala et al., 2021)*	**Sectors:** • To accelerate the energy transition, it is important to increase the level of integration between different energy sectors such as electricity, heat, methane, and hydrogen, not only in terms of markets but also in terms of infrastructures. • Electricity, hydrogen, and methane system will be more integrated in future and by interweaving these sectors will provide much needed flexibility.

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