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Comprehensive classifications and characterizations of power system flexibility resources

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ABSTRACT

Due to the increasing integration of renewable forms of generation, ageing network infrastructure, and rapid increase in peak load demand, flexibility is becoming economically more viable and hence significant role player in the future power system. There is vast amount of literature on flexibility covering research, demonstration and validation activities. Nevertheless, there is still no unifying definition of the term "flexibility" and consistent characterizing terms for "flexibility resources". The lack of clarity in definitions and concepts may undermine information exchange amongst stakeholders imposing hurdles on the transition from mature technology to investment decisions and deployment. System operators, for example, require better clarity for the techno-economic evaluation of flexibility resources in their planning processes. This paper, by reviewing prominent flexibility-related publications, proposes a comprehensive flexibility definition and unified characterizing terms for flexibility resources. Furthermore, the paper proposes a taxonomy method which is applied to classify flexibility resources. The presented taxonomy method clears the confusion on "what-is-what" under the concept of flexibility. This paper also presents the benefits of unified characterizing terms in mapping flexibility resources to ancillary services. The benefits are illustrated by considering a realistic use case in a Norwegian distribution network.

1. Introduction

The increased integration of variable renewable energy sources (VRES) distributed across the power system is necessitating the support from flexibility resources and technologies. Power system flexibility is essential to cope with uncertainty and variability of generation from photovoltaic (PV) and wind power [1-11]. Much of the early [12, 13] as well as more recent [14-16] research on power system flexibility has focused on operational reserves to manage the short-term variability and uncertainty in wind power generation, but over the last 10 years the flexibility concept has also been extended to other challenges, uncertainties and resources [3, 6, 9-11, 17, 18]. Another dimension of the current challenge to the power system is that the annual percentagewise increase in peak load demand is higher than the annual percentagewise increase in energy demand [19]. Infrastructure installed to cope with the peak load would therefore be left unused for most of the time throughout the year. Hence, together with ageing infrastructure in the power system, network upgrade or alternative solutions such as flexibility resources are required.

Flexibility resources have been investigated extensively for the past ten years. Reviews on the topic have been presented from different perspectives, including VRES integration of VRES [9-11, 20], distributed energy resources [18, 21], technologies [9, 10], ancillary services [22], markets [6, 23], power system needs [3], and security of electricity supply [17]. Nevertheless, there is still a lack of a commonly accepted definition for the term "flexibility resource" [11, 18]. In addition, there is inconsistent usage of characterizing terms which creates confusion and impedes information flow amongst the different stakeholders. This paper, after conducting an extensive literature review, proposes a unified definition, characterization, and classification of flexibility resources. The paper further showcases how the clear characterization of flexibility resources can be used mapping different ancillary service needs to the relevant group of flexibility resources.

The following gives an overview of the rest of the paper: Section 2 starts by reviewing existing definitions of flexibility and proposing an alternative, comprehensive definition. A flexibility resource is understood as any resource that can provide flexibility according to this definition. Section 3 defines a set of characteristics of flexibility

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Table 1
Necessary criteria for definition of flexibility.

Scope	Criteria	Description
#1	Type of flexibility resource	The definition of flexibility should be broad enough to encompass all relevant sources of flexibility, both on the grid user side (load, generation, storage) and the grid side (transmission, distribution, and grid operation).
#2	Duration of activation of flexibility	Activation for a service of limited duration (from one second up to a few hours) when there is a need in the power system. This should not include more permanent measures for energy efficiency (for example building-specific measures).
#3	Incentive for activation of flexibility	Flexibility is a response initiated by an external signal. This is an important specification, because some resources may have flexibility for their own sake but not responding to external actors/needs. An example is a battery installed for a dedicated self-consumption maximization purpose, and not offering service outward.

resources based on a review of the literature. Different methods for classifying flexibility resources are discussed in Section 4. These classifications consider both the individual resources (such as different types of stationary energy storage assets) and other aspects of flexibility (such as how it is activated). Based on the taxonomy proposed in Section 4, grouping of individual flexibility resources is presented in Section 5. Section 6 first characterizes most of the relevant ancillary services that can be provided by flexibility resources using similar characterizing terms as introduced in Section 3. Then, the taxonomy and characterizing methods developed in the preceding sections are used to match the relevant ancillary services listed in Section 6 to relevant groups of flexibility resources presented in Section 5. This is also illustrated further within the context of Norwegian distribution systems using a simple case. The article is concluded by discussing the implications of the proposed definitions, classification methods and unified characteristics and their potential refinements in Section 7.

2. Definition of flexibility

Coining of terms such as "flexibility" in power systems requires careful consideration of semantics to facilitate common understanding and the adoption of concepts. Hence, looking to the basic definition of the words and evaluating their representation of the concepts is very important. Oxford English Dictionary defines "flexibility" as [24]: "*the ability to change to suit new conditions or situation*". In other words, although future conditions may be uncertain, flexibility implies means to handle this uncertainty. There are various definitions of power system flexibility in the literature, some of which points to this general relationship to uncertainty. Still, most definitions are either somewhat unclear or somewhat narrow in their scope, and they are mostly tuned to the point of view of the different stakeholder groups. Based on the reviewed literature, three criteria relating to different scopes of the flexibility concept are identified to be fundamental for a clear and comprehensive definition of flexibility. These criteria are presented in Table 1.

Utilizing the three criteria presented in Table 1 as a yardstick, the definitions provided in prominent publications are evaluated in Table 2.

The definitions proposed in the reviewed literature are lacking fundamental information necessary for clarity, such as the outlined scopes in Table 1, and are very general at best [11]. Encompassing the three scopes relevant for clarity (Table 1), we will propose the following definition of power system *flexibility*:

The ability of power system operation, power system assets, loads, energy storage assets and generators, to change or modify their

Table 2
Evaluation of existing definitions of flexibility with respect to the criteria in Table 1.

Source	Definition	Remarks
CIGRE WG, 1995 [25]	*"the ability to adapt the planned development of the power system, quickly and at reasonable cost, to any change, foreseen or not, in the conditions which prevailed at the time it was planned."*	Very general
IEA, 2011 [26]	*"the extent to which a power system can modify electricity production or consumption in response to variability, expected or otherwise. In other words, it expresses the capability of a power system to maintain reliable supply in the face of rapid and large imbalances, whatever the cause."*	This definition is closer to the definition of security and not flexibility.
H. Holttinen et al., 2013 [27]	*"ability to accommodate the variability and uncertainty in the load-generation balance while maintaining satisfactory levels of performance for any time scale."*	Scope #1 is unclear. Scope #2 and #3 are missing.
Heussen et al., 2013 [28]	*"the capability of altering their generation/consumption pattern with limited impact on their primary energy service"*	Scope #1 restricting to supply and demand. Scope #2 and Scope #3 are missing or are not explicitly stated.
Eurelectric, 2014 [29]	*"the modification of generation injection and/or consumption patterns in reaction to an external signal (price signal or activation) in order to provide a service within the energy system."*	Scope #1 restricting to load and generation. Scope #2 is missing. Scope #3 is an external signal (price signal or activation).
B. Drysdale et al., 2015 [30]	*"The degree of flexibility,* i.e. *the ability of a load to vary in response to an external signal with minimal disruption to consumer utility, varies between load categories."*	Scope #1 restricting to loads. Scope #2 is missing. Scope #3 is an external signal, type not specified.
EPRI, 2016 [31]	*"the ability to adapt to dynamic and changing conditions, for example, balancing supply and demand by the hour or minute, or deploying new generation and transmission resources over a period of years."*	Scope #1 is unclear. Scope #2 specified from hour or minute. Scope #3 is missing.
Zhao et al., 2016 [16]	*"Flexibility at a given state is the ability of a system to respond to a range of uncertain future states by taking an alternative course of action within acceptable cost threshold and time window. Flexibility is an inherent property of a system."*	Very general
ENTSO-E, 2017 [32]	*"the active management of an asset that can impact system balance or grid power flows on a short-term basis,* i.e. *from day-ahead to real-time."*	Scope #1 is unclear. Scope #3 is missing.
Hsieh & Anderson, 2017 [33]	*"Flexibility is the capability of the power system to maintain balance between generation and load under uncertainty."*	Scope #1 is unclear. Scope #2 and #3 are missing.
CEDEC, 2018 [34]	*"Flexibility is defined as the modification of generation injection and/or consumption patterns, on an individual or aggregated level, often in reaction to an external signal, in order to provide a service within the energy system or maintain stable grid operation."*	Scope #1 restricting to generation and load. Scope #2 is missing but #3 is included in "external signal".
CEER, 2018 [35]	*"the capacity of the electricity system to respond to changes that*	Very general. Scope #1 is unclear. Scope #2 and #3 are missing.

(continued on next page)

Table 2 (*continued*)

Source	Definition	Remarks
	may affect the balance of supply and demand at all times."	
IEA, 2018 [10]	*"all relevant characteristics of a power system that facilitates the reliable and cost-effective management of variability and uncertainty in both supply and demand."*	Very general
IRENA, 2018 [4]	*"the capability of a power system to cope with the variability and uncertainty that VRE (variable renewable energy) 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"*	Very general
IEA, 2019 [5]	*"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"*	Scope #1 is unclear. Scope #2 is covering "all relevant timescales" but not specifying a specific duration. Scope #3 is included in "supporting long-term security of supply".
ISGAN, 2019 [3]	*"Power system flexibility relates to the ability of the power system to manage changes."*	Very general

routine operation for a limited duration, and responding to external service request signals, without inducing unplanned disruptions.

We will refer to any resource that has this ability as a *flexibility resource*. The remainder of this article will elaborate the definition of this term.

There are terms which are often confused with flexibility, such as *demand side response* (DSR) / *demand response* (DR), *demand side management* (DSM), *flexible generation* and *energy storage*, on both the supply and demand side. These terms represent only parts of the definitions of flexibility and are not alternative terms [36] [37]. In [8], DSM is described as activities to activate the demand side, comprising actions such as energy efficiency, savings, self-production and load management. Further, load management techniques and DR are examples of DSM solutions. According to [38], there are six typical versions of DSR, such as conversion and energy efficiency, load shifting, peak clipping, valley filling, flexible load shape and electrification. The definition of flexibility proposed in this paper assumes the following:

1 *Energy efficiency* is not flexibility but entails less use of energy to perform the same task, or long-term substitution of electricity with another energy carrier. It usually is a one-time measure rather than frequent activation of available resources. Examples are installation of control system to reduce indoor temperature, new insulation of old buildings and changing to more energy efficient windows.
2 *Load shedding* is a drastic measure directly affecting the primary purpose energy was needed for (i.e. it disrupts routine operation) and is not flexibility. In principle all loads can be shedded, and inclusion of load shedding as flexibility resource will confuse the concept. An example is reduced peak load in emergency situations, without shifting the electricity consumption to another time of the day.
3 *Curtailment of generation based on VRES* is not flexibility; rather it is a measure that disrupts the routine operation of the assets. For VRES, curtailment can also have a high opportunity cost and hence cannot always be considered as a readily available flexibility resource. (See, however, Ref. [9, 14, 39] for discussion and counter-arguments.)

3. Characteristics of flexibility resources

Characteristics of flexibility resources entail the ability of the resources to respond to service requests in volume, time, availability, and cost. Also, they entail the response of the resources exhibited after the service provisioning is ended such as recovery time and rebound effect. Characterizing of flexibility resources is an important step to develop models of the resources. In this section, after listing the most common characterizing parameters observed in the literature, clarifying proposals are presented. Furthermore, in order to support the characterization and modelling of flexibility resources, a comprehensive illustration of important characteristics of flexibility resources and their grouping are proposed.

Various parameters have been defined to characterize flexibility resources, and depending on their focus areas, characteristics of flexibility resources are presented only partially in most of the reviewed literature. For example, in [40] focusing on participation of flexibility resources in the wholesale market, three important dimensions of flexibility characteristics are identified as the absolute power output capacity range (MW), the speed of power output change, or ramp rate (MW/min), and the duration of energy levels (hours of a given MW output). Another commonly used set of characteristics is the "triad" of power (regulation) capacity, ramp rate and ramp duration [12], which was introduced over a decade ago in the context of regulation and load following requirements to manage increasing wind power penetration. In [41], a characterization framework is defined presenting three aspects: the general parameters, the CAPEX parameters and the OPEX parameters. The full list of characteristics found in the reviewed literature is presented in Table 3. The following shortcomings are observed in the reviewed literature: variable understanding of the terms amongst researchers; ambiguous definitions of characteristics and representation of similar characteristics with different terms.

In order to support the characterization and modelling of flexibility resources, a comprehensive overview and classification of important characteristics of flexibility resources is proposed in this paper, before the individual characteristics are described. The classification is illustrated in Fig. 1. The identified main characteristics are grouped into two main categories: technical characteristics and economic characteristics.

The technical characteristics are further classified into three types. They include:

- *Quantitative technical characteristics* entails the capability of flexibility resources expressed numerically with defined units.
- *Qualitative technical characteristics* entails the quality of the flexibility resources expressed in degree of comparison.
- *Control technical characteristics* entails how the flexibility resources are controlled.

The economical characteristics are further classified into two types:

Capital (investment) economic characteristics (CAPEX) entails necessary investments costs related to enabling activation of flexibility, but also investments in flexibility resources themselves.
Operational economic characteristics (OPEX) entails different costs related to activation of flexibility, both costs related to activation and ageing (due to activation), but also costs related to price elasticity and customers willingness to be flexible.

In Table 3, characteristics of flexibility resources are listed with their definitions and units. The table also identifies alternative terms used to describe similar concept in the reviewed literature. Fig. 2 summarizes the overview of quantitative technical flexibility characteristics described above and gives a comprehensive illustration of how many of these characteristics are related.

Table 3
Characterizing parameters of flexibility resources and their respective definitions.

	Flexibility Characteristics	Units	Alternative terms	Definition	References
Quantitative	Direction	+/-		Whether the flexibility resource can provide net increase in power output (+; increase in generation injection or decrease in power consumption) or net decrease in power output (-, decrease in generation injection or increase in power consumption). Some resources can provide flexibility in both directions.	[57]
	Power Capacity	MW, (MVAr)	Power modulation Power capability (for up/down regulation) Flexibility access Consumption rate limits Power reserve Maximum power output / bid size Minimum power output / bid size	Physical capability to deliver changes in power output, e.g. the amount of flexibility. For a flexibility resource the power capacity can be different for different directions. A resource can also have a minimum power output (for both directions). Power capacity can be specified for both active (MW) and reactive (MVAr) power.	[6,3,42,43,44,45]
	Ramping Capacity	MW/s	Rate of change Ramp magnitude Ramp(ing) rate Gradient Power ramping capability	The maximum change in power output per unit of time	[20,6,42,10,46,47,43]
	Energy Capacity	MWh	Energy storage capability Energy storage limits Usable (energy) capacity	The capability of flexibility resource to store or deliver energy, i.e. the maximum energy contents associated with a resource, or limits on the time integral of the power output.	[20,42,48,43,44,47]
	Ramp duration	Second [s]	Ramping period Power ramping duration Ramp(-up/-down) duration Ramp(ing) duration Activation time Activation period Response time Start-up time	Time needed from activation begins to ramp up to full power capacity, i.e. the power capacity divided by the ramping capacity (assuming linear ramping). One can also differentiate between a ramp-up time and a ramp-down time.	[12,43,34,6,42,10,49]
	Service duration	Second [s]	Duration Holding duration Endurance E/P ratio C-rating Full activation period Service provisioning time Max power temporal ratio	How long the flexibility can be provided, e.g. before the energy associated with the flexible resource is spent, or the time span related to overload rating of a component	[3,50,10,34,47]
	Reaction duration		Reaction time Latency (time) Delay time Activation period Mobilization time Response time	Time delay from an activation signal (a request for activation) is sent by the procuring party to the time at which the power ramping begins (i.e. the receiving partner reacts on the signal and activation begins).	[47,34,8,20]
	Rebound effect	MW	Payback effect Load kick-back Load restoration	Refers to the power output of the flexibility resource after the flexibility activation period is ended.	[42]
	Recovery duration	Second [s]	Recovery time Recovery period Regeneration duration	The time period required for the flexibility resource to be ready for the next activation (after the end of the previous deactivation); minimum time between activations.	[42,34]
	Ramp frequency			The recurrent occurring of ramp up and ramp down. It refers to the number of times events of various magnitudes and responsiveness occur.	[10,51]
	Flexibility time			The time period when flexibility is available.	[52,6,53]

(*continued on next page*)

Table 3 (*continued*)

	Flexibility Characteristics	Units	Alternative terms	Definition	References
			Time availability Start time Availability ratio		
	Minimum up/down time	Second [s]	Delivering time Time availability	Minimum time the flexibility unit can stay in operation or be out of operation during service provisioning.	[6,42]
	Responsiveness	%	Availability Reliability of response	Probability that a flexibility resource responds to an activation signal (or price signal). (The term is also used to refer to price elasticity of demand [54], as a qualitative characteristic [55], and it is related to qualitative characteristics such as predictability and credibility.)	[56]
	Efficiency	%	Charging/discharging efficiency Round-trip efficiency	The fraction of energy converted from electrical energy to the energy form stored in the flexibility resource (or vice versa) and not (lost) to other energy forms.	
	Energy loss	MWh/s		Energy losses per unit of time due to other processes than conversion to/ from electrical energy.	[47]
	Calendar lifetime	years		The useful lifetime of the resource considering calendar degradation (and not degradation due to activation).	
	Usage number	#	Frequency and availability window (e.g. per day, per week, per year, per lifetime) Cycle lifetime Unit cycling restriction	The permitted number of activations of flexibility over a given time period. Can be number of Full Cycle Equivalents (FCE) as a measure of the cycle lifetime.	[13,34]
Qualitative	Location	n/a		Where in the power system the flexibility resource is located	[6,29,57]
	Predictability	n/a		The possible forecasting accuracy of flexibility resources which are normally tied to demand and generation forecasts. This can be related to the accuracy of the flexibility service, a quantitative characteristic defined as the acceptable difference between the required and the delivered response [57].	[6,14,23,58]
	Credibility	n/a		Credibility of an flexibility resource entails the confidence the system operator or other stakeholders have about receiving flexibility services upon an activation request. This qualitative characteristic can also be related to quantitative characteristics such as the accuracy of the service [57].	[41]
	Ownership	n/a		Flexibility resources can be owned by different stakeholders. Ownership in general determines how much information about the resource is available.	[41]
Controllability	Explicit response	n/a	Direct control	The ability of the resource to respond to external control signals. Mostly dependant on additional communication and control technologies.	[6,59]
	Implicit response	n/a	Indirect control	The flexibility resource is primarily controlled indirectly through price signals and the system operators do not have direct control on availability or reaction time.	[38]
CAPEX	Cost of enabling technology	€		Cost of enabling technologies such as: communication, delay switch, smart control systems, etc.	
	Cost of flexibility element	€/MWh, €/MW		Cost related to investment of flexibility resources. E.g. buying battery bank.	
OPEX	Flexibility activation cost	€		The activation cost for each MWh of flexibility provided. (There could also be an activation-independent cost of access to flexibility.)	[60]
	Cycling cost	€/MWh, €/FCE		Cost associated with ageing of flexibility resources due to cyclic operations. E.g. charge and discharge of batteries.	
	Penalty for non-delivery	€		This cost entails the penalty for not delivered flexibility which has been agreed upon binding market or contractual arrangement.	

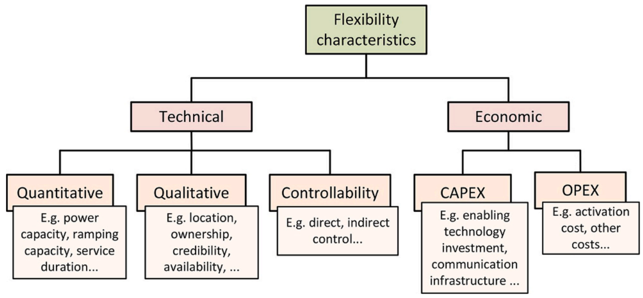

Fig. 1. Classification of characteristics of flexibility resources.

4. Taxonomy of flexibility resources

Taxonomy in general is the practice and science of classification of things or concepts, including the principles that underline such classification. Taxonomy provides the blueprint for organizing and identifying of flexibility solutions. This section elaborates on the different types of approaches one can use to classify flexibility resources. The classifications in the reviewed literature are heavily influenced by the interests and needs of the stakeholders preparing it. Classification in this section can refer to a) the classification of the individual flexibility resources themselves (Section 4.1), or b) the classification of other aspects of flexibility solutions, or in other words how the flexibility resources are utilized (Section 4.2). In order to reduce the existing confusion in the reviewed literature, there will also be an attempt to propose a sufficiently generic classification method (Section 4.3).

In this section, Tables 4 and 5 present the classification methods observed in the reviewed literature for both the individual flexibility resources and other aspects of flexibility, respectively, while Fig. 3 proposes a comprehensive classification method for the individual flexibility resources.

4.1. Taxonomy#1: classification of flexibility resources

The most common classification methods for flexibility resources are presented in Table 4. As one can see in the table, location, roles in the power system, and the activation method they are suited to, are the main criteria.

4.2. Taxonomy#2: classification of other aspects of flexibility

An overview of common classification methods of other aspects of flexibility than the resources themselves is presented in Table 5. The most important classifications are related to location, service capability, motivation, availability, needs and stakeholders/actors involved.

4.3. Proposal for comprehensive classification of flexibility resources

On the basis of the proposed flexibility definition in Section 2, and building upon existing taxonomies summarized in this section, we propose a comprehensive classification method for flexibility resources illustrated in Fig. 3. Its purpose is to allow – with a minimum of ambiguity – the classification of any resources that can provide flexibility according to the definition in Section 2. Thus, it incorporates some of the previously proposed taxonomies summarized in Section 4.1. A comprehensive set of examples is given in Section 5.

For completeness, this classification also includes *enablers* for power system flexibility (e.g. suitable regulation and markets), but it focuses on *flexibility resources*. With the aim of increasing the access to *flexibility resources* new regulations, markets or interconnections could be developed. As the very accessibility of the flexibility resources depend on these *enablers*, we included them to be classified as part of *flexibility solutions*. In addition, those resources where power system flexibility arises from how network assets are operated are classified as *operational flexibility*. These resources are distinguished from what is referred to as *flexibility assets*, which are energy storage assets as well as flexibility

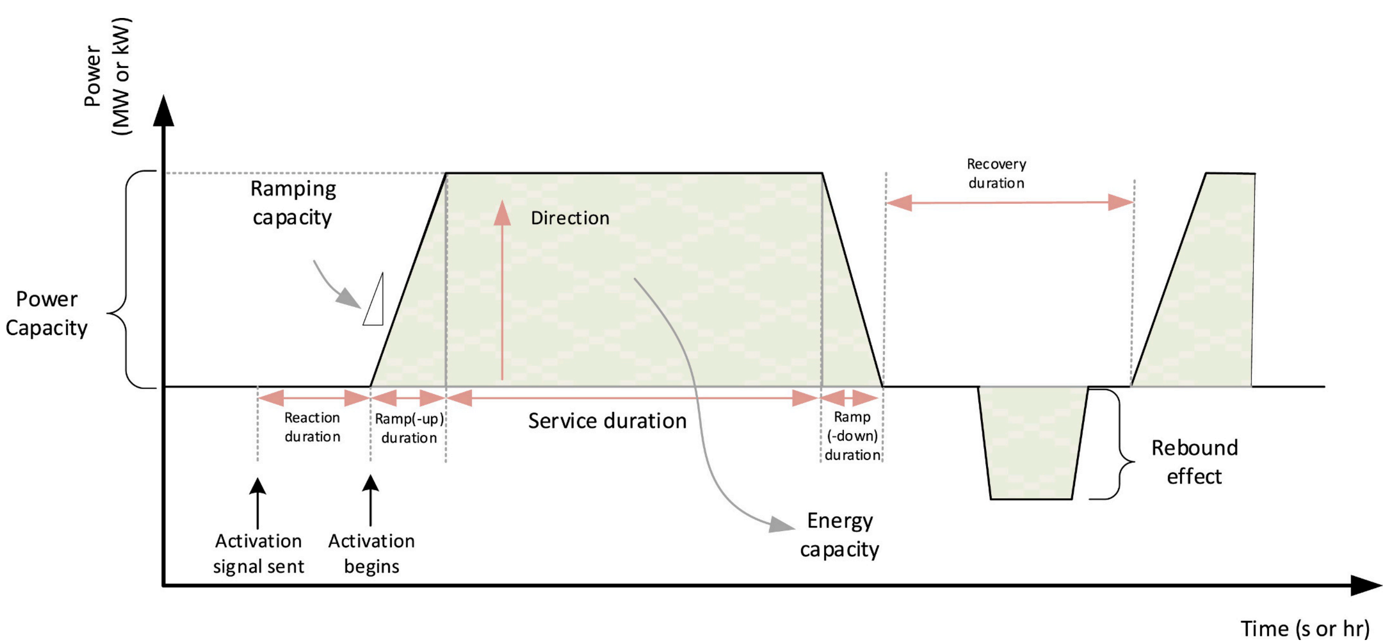

Fig. 2. Comprehensive illustration of important characteristics of flexibility resources.

Table 4
Methods of classifications of flexibility resources.

Classification basis	Definitions	References
Based on their place in the electricity supply chain	This classification entails where the flexibility resources belong in the electric energy supply chain (i.e. demand, supply, network …). These classifications include: *Demand-side flexibility*: Comprises a broad set of means to affect the patterns and magnitude of end-use electricity consumption. *Supply-side flexibility*: Measures and technologies through which the output of power generation units can be modified *Network-side flexibility*: Power system components can also provide important flexibility options by means of network reconfiguration (switching), smartification (both at transmission and distribution levels), dynamic line ratings, wide-area interconnections, meshed operations, etc. *Other sources of flexibility*: The flexibility provided by energy storage systems, properly designed market and regulatory aspects can be included under this group.	[61,62, 9,63,26]
Based on roles of flexibility resources in the power system	This classification introduces two types of flexibility resources based on the role they play in availing the resource. They are the *enablers* and the *actual sources*: While supply, demand and energy storage constitute *actual sources* of flexibility, grid and markets are key *enablers* of flexibility. Another way of classification with the same concept is: *Technical flexibility* refers to the technology in relation to: the ability of supply to follow rapid changes in net load, the ability of demand to follow rapid changes in supply, the ability of energy storage to balance mismatches between supply and demand at all time scales and adequate grid infrastructure to allow least-cost supply to reach demand at all times, anywhere in the power system. *Operational flexibility* refers to how the assets in the power system are operated.	[64,4,65]
Based on direction of load shifting	This classification is based on the direction of load shifting in the timeline. *Advance* (load consumption). Examples: electric storage water/heater *Delay* (load consumption). Examples: Freezer/refrigerator, ventilation and air-conditioning *Advance or delay* (load consumption). Examples paper machines, cold storages, washing machine *Load shedding* (i.e., reduce load consumption). Examples: Electrolytic primary aluminium, chloralkaline process.	[38,66]
Based on mathematical properties in modelling of the energy contents associated with the flexibility resource	There are three types of flexibility under this classification method. A *bucket* is a power and energy constrained integrator. Examples: simplified model of thermal energy storage, air conditioning units, refrigeration units. A *battery* is a power and energy constrained integrator, which must be "charged" to a certain level by a certain time. Examples: electric vehicles, swimming pool circulations and filtering systems. A *bakery* is a batch process, which must be finished by a given time. The process has constant power consumption and a fixed run time. Examples: large industrial production facilities.	[44,67]

resources placed at the demand and supply side of the electricity system.[1]

When using the classification method, the user needs to decide the aggregation level. For instance, one could consider individual resources within a house and classify a behind-the-metre battery storage system as a storage resource. If one on the other hand takes the perspective of the DSO and considers the house on an aggregated level as an end-user, the entire house could be classified as a demand-side resource. We should point out that the method illustrated in Fig. 3 is intended for the classification of individual flexibility resources, and e.g. microgrids [9] are therefore not included as a distinct type of resource in Fig. 3.

5. Grouping of flexibility resources

Taxonomy (classification) methods are required to identify individual flexibility resources as well as to group flexibility resources with certain similarities. In this section, different groups of flexibility resources described in the reviewed literature are presented in Table 6 before a grouping based on the classification method in Section 4.3 is proposed in Table 7.

A grouping of flexibility resources is understood as the result of applying a classification method to a set of individual flexibility resources. However, the classification methods underlying the groupings presented in Table 6 are often not explicit in the cited references. As described also in the previous sections, the review of the literature shows that the existing classifications often are ambiguous and inconsistent, and the entries in Table 6 include disparate sets of technologies, solutions, types of end-users, etc. Furthermore, some resources are classified as belonging to several different groups in the literature, and some resources are missing from groups where they could be natural to include.

Next, a methodical grouping of the flexibility resources will be carried out using the proposed comprehensive taxonomy in Section 4.3. Table 7 presents the grouping of individual flexibility resources according to the classification method illustrated in Fig. 3. Here, examples of flexibility resources (right column) as those listed in Table 6 above are

[1] Note that operational flexibility in this classification should not be understood in the general sense defined e.g. in [43, 45] but rather in the sense that "grid-side flexibility" is defined in [61]. However, we have chosen to avoid the term "grid-side flexibility" since it confuses flexibility due to the operation of grid assets with the role grid assets have in enabling flexibility independently from how they are operated. Therefore, grid interconnection [20] (e.g. between different power systems or distant areas within a power system) is classified as an enabler and not as an actual flexibility resources in Figure 3.

Table 5
Methods for classification of other aspects of flexibility.

Classification basis	Definitions	References
Based on control mechanism	The control can be centralized or distributed. In *centralized mode* consumers communicate directly to the power utility. In the *distributed mode* interactions between users provide information to the utility about the total consumption.	[68,44, 63]
Based on offered motivation	Offered motivation could be price-based or incentive based. With *price-based* motivation, consumers are offered time-varying prices for electricity. *Incentive-based* motivation consist of programs that offer fixed or time-varying incentives to customers that reduce their electricity consumption.	[68,63, 69]
Based on decision variable	Decision variable entails whether to schedule activity or to control the power consumption in real-time. Task scheduling Energy management	[68]
Based on their availability	*Potential flexibility resources*: the flexibility resources exist physically but lacks controllability and also observability. *Actual flexibility resources*: flexibility exist physically and there is controllability and observability, and consequently the resource is ready to be used. *Flexibility reserves*: the part of the actual flexibility resources can be used economically. *Market-available flexibility reserves*: the part of the flexibility reserves that can be procured from power or ancillary services market	[1]
Based on flexibility needs	This entails the type of service expected: *Flexibility for Power*: for short term equilibrium between power supply and power demand. *Flexibility for Energy*: medium to long term equilibrium between energy supply and energy demand. *Flexibility for Transfer Capacity*: short to medium term ability to transfer power between supply and demand. *Flexibility for Voltage*: short term ability to keep the bus voltages within predefined limits.	[3]
Based on the flexibility activation methods	Flexibility can be implicit or explicit based on the type activation approach followed: *Explicit flexibility* that can be mobilized in real time or on short notice, and where the volume is controllable. *Implicit flexibility*, which is related to a long-term expected reduction in load demand in the form of e.g. systematic changes in end user behaviour.	[38]
Actor activating flexibility	Flexibility may be needed and activated by multiple stakeholders. Hence, strong coordination is needed. Flexibility for *distribution system operators*' (DSOs') own use and activated by them Flexibility activated by *commercial parties* Flexibility activated by *transmission system operators* (TSOs)	[34]

methodologically grouped according to the classifications (left columns) shown in Fig. 3.

6. Flexibility resources and ancillary services

The clarity introduced for the definition and characterization of flexibility resources is expected to create better conditions for mapping flexibility resources to ancillary services. In this section, we begin by defining the terms such as ancillary services and flexibility services. Furthermore, the technical characterizing terms defined in Section 3 are used to define the requirements of ancillary services which later are going to be used for matching purposes.

According to ENTSO-E [80], *"'Ancillary services' refers to a range of functions which TSOs contract so that they can guarantee system security. These include black start capability (the ability to restart a grid following a blackout); frequency response (to maintain system frequency with automatic and very fast responses); fast reserve (which can provide additional energy when needed); the provision of reactive power and various other services".*

The European commission directive 2009/72/EC defines ancillary services as *"all services necessary for operation of a transmission or distribution system"*. In [81], it is further specified that this includes balancing and non-frequency ancillary services, but not congestion management. There seems to be enough clarity on what "ancillary services" means. Nevertheless, there is always a dynamic conversation on the inclusion of new types of services as ancillary services [6].

Within the scope of this paper, ancillary services refer to a range of services supporting the normal operation of transmission and distribution systems on top of the basic functions of power generation and transmission. These services may include frequency support services, voltage support services, load and generation balancing services, congestion management and other emerging services.

There are also other terms which need to be defined here to facilitate clarity. These terms are: "system services" and "flexibility services". System services is another term which is often used in the literature interchangeably with ancillary services and system support services. However, in [82], clear distinction is made between ancillary and system services. According to this Eurelectric report:

- Ancillary services are all grid support services required by the transmission or distribution system operator to maintain the integrity and stability of the transmission or distribution system as well as the power quality. These needs can be fulfilled by connected generators, controllable loads and/or network devices.
- System services contain all services provided by a system (or a network) operator to users connected to the system.
- Ancillary services are provided from users to system operators, and system services from operators to all users.

In [28], "flexibility service" refers to products participating in ancillary services markets, provided by flexibility resources. It is stated in [2] that, flexibility services meet changes in demand that occur on hourly (ramping) and sub-hourly (regulation) time scales. Based on the aforementioned definitions, in this article, flexibility service is defined as products provided by flexibility resources and can be offered as ancillary services within existing markets or other arrangements.

Some literature, without subscribing to the standard ancillary services market products, has proposed their own terms to define the service capabilities of flexibility resources. In [50], system value of electric storage systems has been categorized as arbitrage value, reserve value, capacity value and network related value.

6.1. Ancillary services technical requirements

Table 8 presents a list of ancillary services that can be provided by flexibility resources. It furthermore attempts to define their characteristics and requirements in terms of the characteristics of flexibility

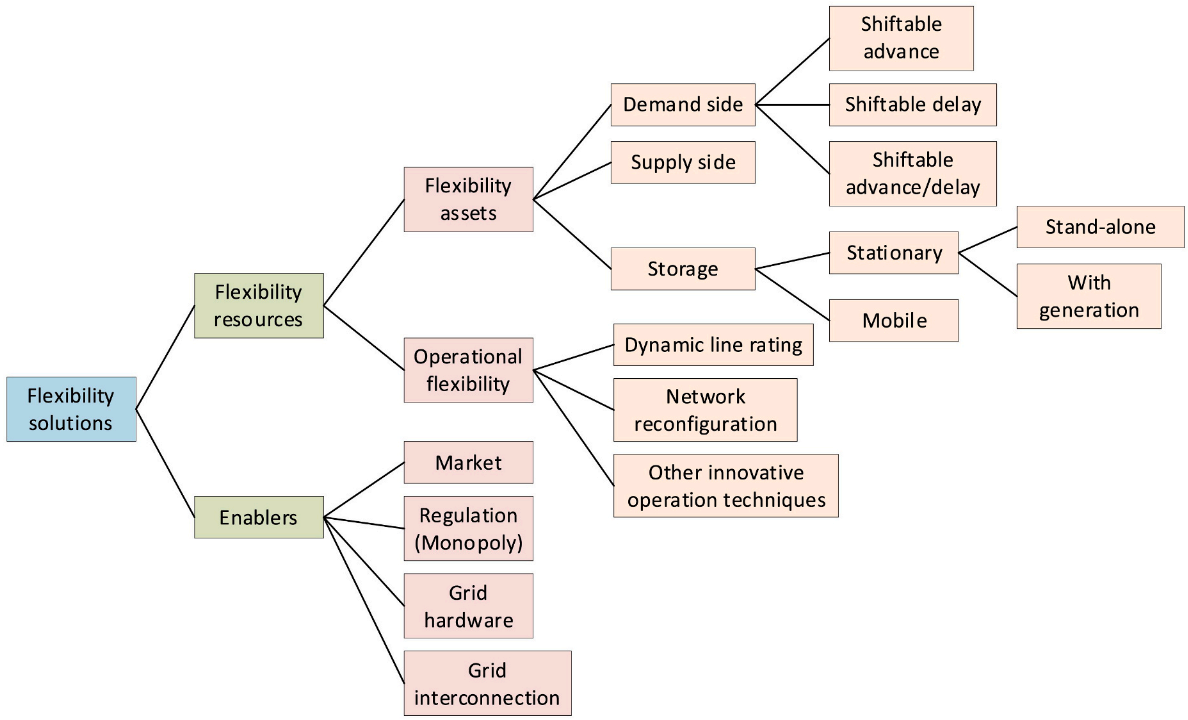

Fig. 3. Proposed comprehensive classification of flexibility resources and their enablers.

resources defined in Section 3. The list of ancillary services is based on the review of existing and potential future services in [22] and is supplemented by some additional services listed in other sources [10, 17, 23, 83-85]. Note that for some of the existing services (balancing or frequency regulation services in particular), the terms used to label the service vary greatly between different countries and markets [33].

For each combination of service and characteristic in Table 8, the relative relevance or importance of this characteristic is qualitatively indicated by the colour of each cell, where a darker colour means that the characteristic is more important to consider for the service. Although this is a highly simplified qualitative assessment, it serves the purpose of i) highlighting the main distinctions between the requirements of different ancillary services and ii) enabling their mapping to the flexibility resources that can provide the services. The characteristics in Table 8 include most of the quantitative, technical flexibility resource characteristics discussed in Section 3 excluding some redundant characteristics. For instance, *ramp capacity* and *energy capacity* are omitted because these characteristic follow from the *ramp duration* and *service duration*, respectively, for a resource with a given *power capacity*. Fig. 4 visually summarizes indicative characteristics of the services presented in Table 8.

The qualitative characteristics of credibility and predictability are very important for all the services and were therefore omitted from the table for the sake of space and clarity.[2] The qualitative characteristic of location was on the other hand included, since the relevance of the location of a resource varies significantly between the services. For frequency regulation services, it is of very little importance as long as the resource is connected to the synchronous system in question. For congestion management services, the resource needs to be relatively close to the bottleneck in question and needs to be located at a specific side, depending on the direction characteristic of the resource. How close is "relatively close" depends on the system: For distribution congestion management, the importance of location in absolute terms is higher than for transmission congestion management. Finally, Table 8 also indicates whether the service is relevant for TSOs (T) and/or for DSOs (D).

[2] See, however, Ref. [54, 57] for a discussion of the related quantitative service characteristics accuracy and precision and Table 3 for clarification of the relationship between these characteristics.

6.2. Market phases for ancillary services

Different markets for ancillary services have specific requirements in terms of bidding time horizon and acceptable service provisioning time. This will significantly filter the set of flexibility resources which can participate in a specific market. Conversely, new market platforms may be designed to accommodate and tap the potential of certain flexibility resources. Hence, in this section there will be a short introduction on different markets where flexibility resources can contribute. Market characteristics are intrinsically related to the characteristics of the ancillary services the market is availing. Hence, one can infer the requirements of the different market types as well as the adequacy of the technical characteristics of flexibility resources for participating in the markets using Table 8. Some of the market characteristics in the reviewed literature include: market gate closing time, delivering time, and product time duration [6]. Flexibility resources can be categorized according to their abilities to provide power capacity or energy related grid services. Flexibility resources offering capacity related services are suited for short-term markets (e.g. on the ancillary service markets), while resources offering energy related services are suited for long-term markets such as balancing mechanisms and trading DR in the bulk electricity market [23].

Ancillary markets are handling flexibility from very short to medium term in the operational phases. Different markets and market phases are illustrated in Fig. 5. As shown in the figure, the different markets operate at different time periods which is essentially tied with the services the

Table 6
Grouping of resources identified as flexibility resources in the literature.

Identified as: (group)	Resources (sub-groups)	References	Comment
Dispatchable power plants	Ramp output up and down on demand • Simple cycle gas or diesel turbines • Coal/biomass power plants • Combined-cycle gas plants • Hydropower plants	[26, 31, 61]	A power plant is dispatchable if it can respond to commands from a system operator at any time, within certain availability parameters to increase or decrease output for a defined period.
Energy storage systems (ESS)	Can be: • Pumped hydro • Redox flow cells • Advanced capacitors • Superconducting magnetic energy storage • Flywheels • Electro chemical storage • Compressed air storage systems • Hydrogen • Thermal Storage • Thermochemical storage • (Domestic space and water heating)	[20, 70, 71]	The rate of charge and discharge capabilities vary for the different storage systems. Hence, suitability for service provisioning varies amongst the listed systems. Electrical vehicles (EVs) can be defined as mobile energy storages but are missing in this list of ESS.
Demand side response (DSR)	• Electrical vehicles • Shiftable loads (laundry, dish washer, tumble dryer, vacuum cleaner, stove …) • Air-conditioning • Commercial refrigeration • Heat pumps	[10, 72]	DSR means changes in electric use by demand-side resource from their normal consumption patterns in response to changes in the price of electricity, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized [73]. Domestic space and water heaters are loads with thermal storage capacity, which are good candidates for DSR.
Demand response program (DRP)	• Time-of-use (ToU) • Real-time pricing (RTP) • Critical peak pricing (CPP) • Direct load control (DLC) • Interruptible/curtailable (I/C) service • Demand bidding / buyback programs • Emergency demand response programs (EDRP) • Capacity market programs • Ancillary services (A/S) market programs	[8, 9, 55, 74, 75]	DSR is often classified in terms of DRPs. The main types of DRPs are price-based and incentive-based programs [74]. DRPs can also be grouped into voluntary programs, mandatory programs and market clearing programs [75].
Electrical vehicles (EV)	• Grid-to-vehicle (G2V) • Vehicle-to-grid (V2G) • Vehicle-for-grid (VfG)	[54, 56, 57, 76-78]	Electrical vehicles can be considered as mobile ESS. VfG has been defined as a type of mobile ESS that is utilized by the system operator [77].
Interconnection	Flexibility comes from its ability to transfer power in both directions. Notice time required for changing direction of power flow is a limiting factor in DC interconnections.	[4, 62, 79]	This refers to the cables or lines (transmission assets) and not the conversion assets (e.g. HVDC converters).
Operational flexibility	• FACTS • HVDC • Transmission Expansion Planning (TEP) • Coordinated voltage control • Optimization and Rescheduling functions in the power system operation • Distribution network reconfiguration	[61]	The flexibility essentially emanates from the capability to change the way the operation is carried out to accommodate uncertainties in the power system. TEP, however, represents long-term and not short-term (operational) flexibility.
Distributed energy resources (DER)	• PV • Wind • Micro-CHP unit	[5, 23, 39]	These examples could also be classified as distributed generation (DG). Some DERs can be dispatchable power plants. Energy storage systems and demand-side resources can also be classified as DERs.
Load sector	• Residential / households / residential loads • Industry / industrial loads • Tertiary / service sector	[38]	Overlap with group "Customer types".
Customer types	• Industrial customers • Commercial and other non-residential customers • Residential customers • Electric transport • Data centers	[8]	Overlap with group "Load sector". In this grouping, data centres can fall in the commercial customer types. EVs are mobile loads with energy storage capacity and not a specific customer type. EVs for home charging should be included in residential customers, and charging stations should be commercial customers. A broader customer type could be "transport".
Industrial loads	• Aluminium electrolysis • Steel production • Pulp production	[1, 63, 38]	Sub-group of the groups "Load sector" or "Customer types".
Enablers	• Flexibility market • Regulations • Incentive systems	[6, 62]	The sheer existence of flexibility resources is not sufficient in its own. Market structures and regulatory instruments are key in availing technical potential.
DSO's "toolkit"	• DSO technical solutions (to enhance the efficiency of the grid and the system) • Tariff solutions (incentivise users to use the networks as efficiently as possible) • Connection Agreement solutions (agreement to access flexibility to prevent congestions) • Rules-based solutions (Compulsory rules in network codes and regulation to impose flexibility technical requirements) • Market-based solutions (cost-efficient and innovative solutions driven by competition for the provision of services)	[34]	This grouping describes the toolkit DSOs can use to operate and plan their networks in a more flexible way, where flexibility resources are utilized. The actual tool (or combinations of tools) that can be used are dependant on regulatory framework in the country, the degree of decentralisation in each country and the local situation.

Table 7
Grouping of flexibility resources according to the taxonomy proposed in Section 4 with examples.

Classification (group and sub-groups)		Examples
Flexibility resources	Demand side – shiftable advance	Hot water storage, electric vehicle, space heating (heating cables in the floor, electric panel heaters)
	Demand side – shiftable delay	Freezer/refrigerator, ventilation, air conditioning
	Demand side – shiftable advance/delay	Washing machine, dishwasher, clothes dryer, paper machine
	Supply side	Dispatchable power plants (thermal and hydropower)
	Storage – stationary stand alone	Pumped hydro, flywheels, electrochemical storage, hydrogen storage
	Storage – stationary with generation	Battery + PV systems, Concentrated Solar Power (CSP), Battery + wind power plant
	Mobile	Electrical vehicle, electrical vessel (ferry etc.)
	Operational flexibility	Network reconfiguration, dynamic line rating
Enablers	Market	Existence and design of frequency regulation / fast frequency reserve markets, real-time or balancing market, day ahead (spot) market, markets for other ancillary services, local markets, etc.
	Regulation (Monopoly)	Market regulation, requirements on electrical loads and generators. Monopoly regulation (of grid companies / system operators) – grid tariffs (e.g. energy tariff, capacity-based tariff, time of use tariff, critical peak pricing)
	Grid hardware	FACTS, HVDC converters
	Grid interconnection	HVDC interconnections, HVAC interconnections (between areas or power systems)

markets are addressing. Together with Table 8, the information presented in Fig. 5 helps to build a complete picture of which flexibility resource can participate in which market arrangement. Flexibility resources providing services in the operational phases can contribute to managing uncertainties realized after market gate closing, e.g. by providing ramp capacity services and operational reserves to manage sudden wind power ramp events [14, 15, 86]. These markets include services such as primary (FCR) and secondary (FRR) reserves, with a response typically shorter than 2 min. Such short-term markets can contribute to manage uncertainties related to outage occurrence of large power injection (or consumption) units during operation. However, for services that critical for ensuring system security it is also relevant to consider the new operational uncertainties introduced by flexible resources [17]. Tertiary reserves (RR) are used to release activated Frequency Restoration Reserves back to a state of readiness and they are activated within 15 min to hours. Congestion management can be handled via balancing markets on both distribution and transmission grid levels. The more long term markets are related to price setting such as capacity payment and markets in the price hedging and spot phase.

6.3. Mapping of flexibility resources to services

In the previous sections of this paper, ancillary services and flexibility resources have been characterized using a single consistent set of characterizing terms. In this section, one ancillary service and one flexibility resource will be selected to evaluate the suitability of the flexibility resource in delivering the selected service. Previous attempts of qualitative mappings between flexibility resources and services have been presented e.g. in [21]. However, in that work, a comprehensive and consistent methodological basis for the mapping was lacking. The main purpose in this section is to demonstrate the benefits of the clearly defined characterizing terms in mapping of the right resource to the right service. This is not an attempt to conduct full-fledged matching of the full lists of ancillary services and flexibility resources, as this task is left for future work.

The selected flexibility resource is a battery energy storage system owned by a distributed energy resources owner or operator. The selected ancillary service is primary voltage control in distribution systems. In general, voltage control is one of the services requiring fast response in the ranges of milliseconds to tens of minutes [10] [3]. Storage can both inject and absorb active and reactive power in the network to help solve under-voltage, over-voltage, voltage unbalance, power factor correction, harmonics and mitigate flicker. The characteristics defined in this paper can be used in the process of selecting flexibility resources for a service as illustrated in Fig. 6: For screening purposes, one can start by qualitatively mapping the capabilities of the flexibility resources to the requirements of the services as exemplified in Table 9. In Table 9, a darker colour means a) that the characteristic is more important to consider for primary voltage control services or b) that a battery storage system has higher capabilities as measured by this characteristic. With regards to matching level between service and capability, green indicates good match while yellow indicates that the capability probably is insufficient.

6.4. Illustrative example of mapping of flexibility resources to services in a norwegian distribution system

To illustrate the application of the classification and characterization methodologies proposed in this article, we will consider a simple use case relevant to Norwegian DSOs: Flexibility resources as a measure to support the integration of electrified maritime transportation. Infrastructure for charging of electrical ferries is being installed in several small Norwegian coastal towns or villages that are supplied by distribution grids with insufficient power capacity for the power demand peaks during charging. See Fig. 7 for an illustration. As an example, the area may have a base load demand around 2 MW, but charging ferry when at quay (for approximately 7 min) requires an additional 4 MW. If the grid capacity is 5 MW, there is either a need for congestion management services or for costly grid reinforcement measures. We first consider the characteristics defined in Section 3 to illustrate the qualitative mapping outlined in Section 6.3. For this case, geographical location is obviously important for the flexibility resources that are to provide the congestion management service, and they need to be located within the relatively small area between the quay and the bottleneck in the distribution grid. Since the flexibility is needed to manage congestion due to thermal limitations in this case, the reaction and ramp duration is not required to be very short (i.e. a few second). On the other hand, a high power capacity relative to the energy capacity is needed to cover the needs during the ferry charging period. The classification of flexibility resources in Section 4.3 is then considered in assessing the relevance of different flexibility resources, as summarized in Table 10.

7. Discussions and conclusions

Flexibility resources are playing a greater role in the secure and reliable operation of the future power systems. One significant problem in the reviewed literature is the large disparity in the definitions and classifications of flexible resources and the services that they can provide. Existence of incoherent terminologies and definitions is natural when new concepts and technologies are under development. Nevertheless, at certain level of technology maturity, the usage of terms and concepts amongst stakeholders will have significant implications, with impacts ranging from economic, legal and information flow.

Greater investment decisions are being made in system operators'

Table 8
Characterizing ancillary services with respect to technical characteristics of flexibility resources.

	Direction	Power Capacity	Ramp duration	Service duration	Reaction duration	Rebound effect	Recovery duration	Efficiency	Energy loss	Calendar lifetime	Usage number	Location	DSO/TSO Relevance
Synthetic inertia													T
Fast Frequency Reserve (FFR)													T
Frequency Containment Reserve (FCR)													T
Frequency Restoration Reserve (FRR)													T
Replacement Reserve (RR)													T
Ramp Margin/Control (RM)													D/T
Fault ride-through (FRT) capability													D/T
Congestion management													D/T
Primary voltage control													D/T
Secondary voltage control													D/T
Tertiary voltage control													D/T
Phase balancing													D
Damping of harmonics													D
Mitigation of flicker													D
Damping of power system oscillations													T
Reduction of power losses													D/T
Power factor control													D
Emergency power													D/T
Black start capability													D/T

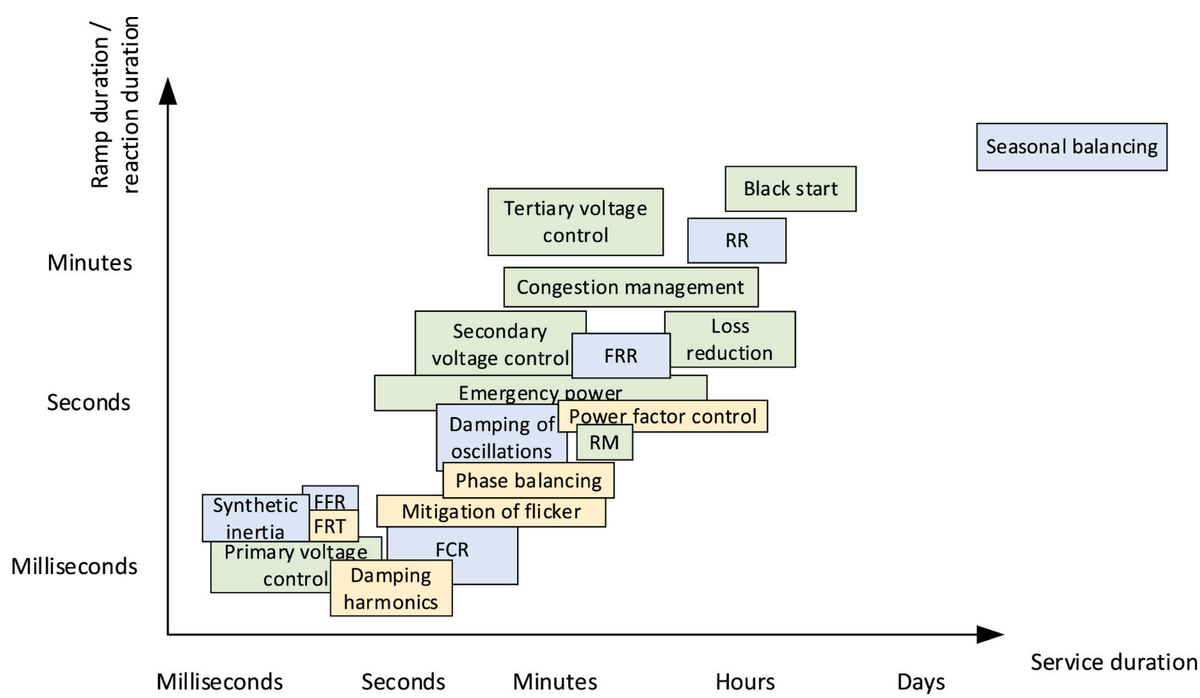

Fig. 4. Indicative characteristics for ancillary service provision, visually summarizing Table 8. Colour code: blue – transmission system services, yellow – distribution system services; green – transmission or distribution system services. (Seasonal balancing services are also included in the figure for giving a perspective on the time scales involved.). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

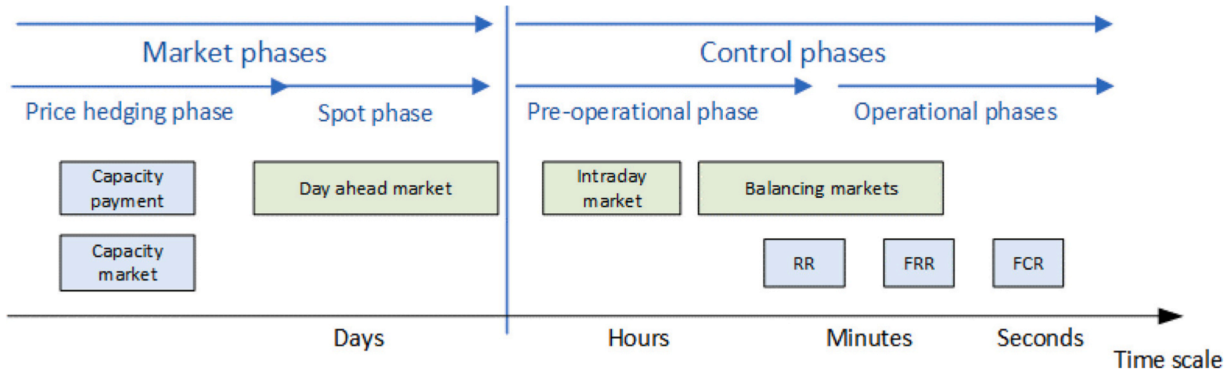

Fig. 5. Indicative characteristics for different markets and market phases. Colour code: blue – transmission system services, green – transmission or distribution system services.

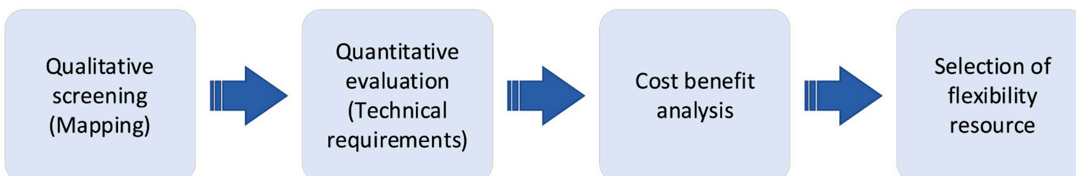

Fig. 6. Selection process of flexibility resources for a required service.

Table 9
Mapping the capabilities of battery storage system to requirements of voltage control in distribution system.

	DSO/TSO Relevance	Direction	Power Capacity	Ramping Capacity	Energy Capacity	Ramp duration	Service duration	Reaction duration	Rebound effect	Recovery duration	Ramp frequency	Efficiency	Energy loss	Calendar lifetime	Usage number	Location
Battery storage system: Capability	D															NA
Primary voltage control	D/T															
Matching level																

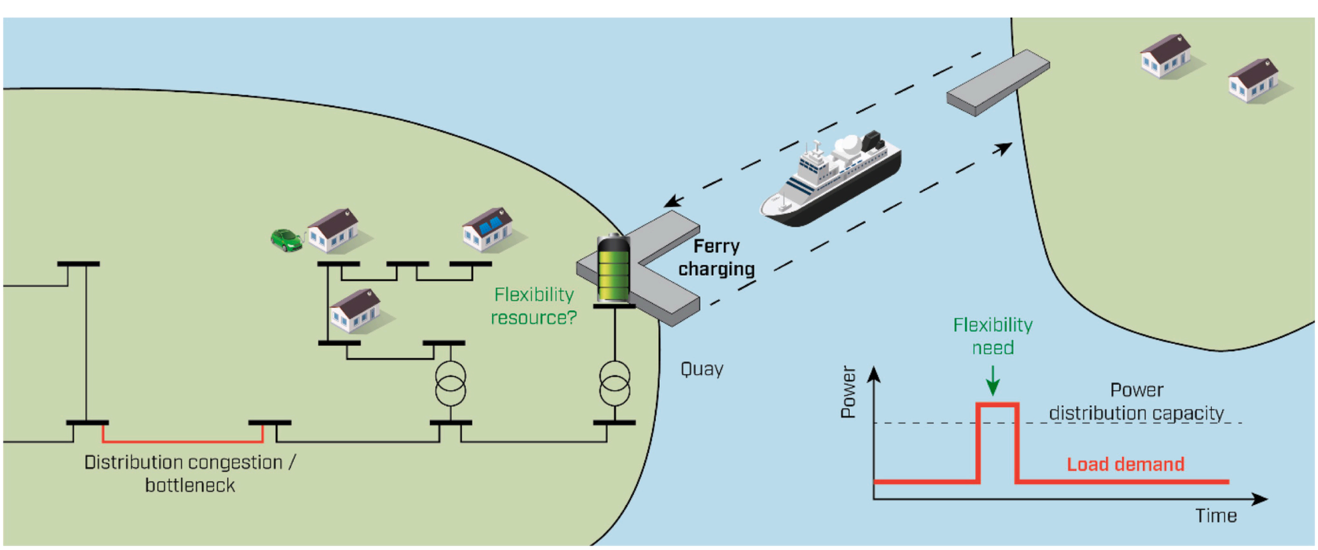

Fig. 7. Simplified system sketch illustrating the use case.

Table 10
Assessment of flexibility resources for use case.

Flexibility resource	Assessment
Storage – mobile	The electrical ferry itself could be considered to be a mobile storage flexibility resource. However, whether it can provide flexibility in this case depends on whether it can "modify their routine operation […] without inducing unplanned disruptions" according to the definition proposed in Section 2.
Storage – stationary – stand-alone	Battery storage systems, located in the quay areas, is the type of resource currently considered as a standard flexibility solution for such use cases. Batteries typically have more than adequate controllability and duration characteristics, but the CAPEX for achieving the required power capacity may currently make this solution very costly. Usage number and cycling costs may also be significant depending on the ferry charging schedule.
Supply side	Due to the direction characteristics of the required congestion management service (i.e. increased net power injections are needed in the area), there are no potential supply-side resources in the area in this case.
Demand side	Either shiftable advance and/or delay demand-side resources can be relevant since the flexibility time is predictable for the ferry charging case. The large share of the load used for water and space heating in the town could make it possible to achieve the required power capacity. Alternatively, demand-side resources could be seen as a supplement to storage resources to reduce the total cost of the solutions. However, explicit response (direct control) of the flexibility resource as well as high credibility and predictability is necessary for the DSO to be able to rely on demand-side resources alone.
Operational flexibility	Utilizing operational flexibility such as network reconfiguration is not relevant due to the topology of the distribution system, but operational flexibility in the sense of dynamic line rating could be a relevant supplement to other resources.

planning activities, and high-impact regulatory and policy instruments are being put in place by authorities in relation with flexibility resources. Hence, clarity in the definitions of the very concept of flexibility and its characteristics is of high importance. This article has attempted to contribute to this clarity by reviewing state-of-the art definitions and flexibility classification methods and using these as a starting point. A comprehensive definition of flexibility is proposed together with a consistent set of terms describing flexibility characteristics and a taxonomy approach enabling clearer classification of flexibility resources. These improvements in clarity of terms and concepts will facilitate the adoption of results and methods from research activities concerning flexibility solutions by system operators. This in turn will lead to greater confidence in flexibility solutions, resulting in increased integration of renewable generation and electrified transportation and reduced cost towards end users.

The multifaceted proposals in this article can be considered as a step towards establishing a unified understanding of flexibility resources. Nevertheless, further refinement can best be achieved by considering relevant use cases and by performing more detailed quantitative and qualitative evaluations. Applying the characterization and classification methods presented here to a more complete mapping of the right resources to the right services is therefore proposed for future work. The simple and practical use case presented in this article nevertheless showcases the benefits of the clarity in definitions and characterizing terms in the processes of mapping flexibility resources to ancillary services.

CRediT authorship contribution statement

Merkebu Zenebe Degefa: Conceptualization, Investigation, Methodology, Visualization, Writing - original draft, Writing - review & editing. **Iver Bakken Sperstad:** Conceptualization, Investigation, Methodology, Visualization, Writing - original draft, Writing - review & editing. **Hanne Sæle:** Conceptualization, Investigation, Methodology, Visualization, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

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

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