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Submetering: Challenges and opportunities for its application to the flexibility services

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Abstract

Purpose of the review: Implementing flexibility services from small resources in the power system requires addressing new technical challenges related to monitoring, baselining, validating their activation, and quantifying the delivery of services. This paper reviews the current usage, challenges, and opportunities of applying submeters, also known as dedicated measuring devices, in the scope of the upcoming European Regulation.

Recent findings: In countries where smart meters are not yet deployed or are implemented but do not deliver the needed data, submeters can foster the participation of small resources in flexibility services. However, there are still few international experiences related to their adoption of these services.

Summary: The successful implementation of submetering requires addressing challenges such as standardization, certification, interoperability, data accessibility, and reliability. Future regulations must set their requirements, assign roles and responsibilities, and provide certification to ensure metrological, standardization, and interoperability requirements.

Keywords: submetering, dedicated measurement device, smart meter, flexibility services, flexibility markets, ancillary services, congestion management, voltage control, distributed generation, demand side participation, regulatory development

1. Introduction

To fight climate change requires an acceleration in the deployment of renewable energy sources (RES) and the electrification of different sectors such as transport, heating, and industrial processes [1]. Many of these resources will be made of small units connected to the distribution grid level, which makes power system operation more challenging: flows become more variable, bidirectional, and unpredictable [2]. As a solution, Distribution System Operators (DSOs) should accelerate investments in digitalization and monitoring activities, which are essential to forecast and anticipate potential congestion or voltage issues and maintain the reliability and quality of the electricity supply [3], [4]. Article 32 of the Electricity Directive (EU) 2019/944 [5] mandates Member States to set incentives for DSOs to procure flexibility services and improve efficiencies in the operation and development of the distribution system. These flexibility services consist of, among others, congestion management or voltage control services that can be provided by one or more flexibility resources (FR) connected behind a connection agreement point (CAP) such as Electric Vehicle (EV) charging stations, water boilers, heat pumps or storage devices or by FR connected at the CAP [6], [7], [8].[1] In both models, some FRs can be grouped in portfolio manners by aggregators or flexibility service providers (FSP) who select FRs to offer their flexibility services to Transmission System Operators (TSO) or DSOs (from now on, System Operators or SOs) [10]. Similar to the flexibility services provided to the TSO, the implementation of flexibility at the distribution grid level requires monitoring solutions to identify FR behavior patterns, (ex-post) validate its activation, and quantify their final delivered flexibility [9], [11], [12]. An ex-post validation of the delivered flexibility is desirable for small FRs providing flexibility services to DSOs.

Intelligent metering systems were introduced in Directive 2009/72/EC [13] as smart meters for settlement and billing purposes at the point of CAP, a consumer/generator with the grid. Later, the Electricity Directive (EU) 2019/944/EC [14] renames *intelligent metering systems* to *smart metering systems.* These systems record the hourly (or higher resolution) flows at CAP and enable the implementation of time-of-use (ToU) network tariffs [9], [15]. Smart meters also represent an efficient and robust solution for implementing flexibility services because of their timely records, which are essential to validate and set the remuneration for the service provided, including the compensation effects related to the efficient provision of flexibility.[2] However, they are unavailable in all jurisdictions, and even where they are, their time resolution might not always be

[1] Flexibility can be defined as the ability of energy resources and consumers to change or adjust their injection or withdrawal to/from to the electricity system in response to an economic signal (market prices, day-ahead and intraday markets or network tariffs), to provide services to system operators or to the markets [6] [9]. A CAP means the point referred to in the Connection Agreement signed between the customer and the systems operator and is the electrically closest to the connecting System Operator’s grid. In some cases, the “main meter” at the CAP is also known as “regulated meter”.

[2] Compensation effects include the financial compensation between the Independent Aggregator (FSP) and the supplier.

enough to monitor fast flexibility services [9].[3] As a complementary solution, submeters, or behind smart meter devices, might be a relevant additional solution, especially for close-to-real-time monitoring of service delivery.

Submeters were originally implemented for energy efficiency purposes, to monitor the individual consumption of water, gas, heating, cooling, or hot water, or even in the improvement towards a more improvement energy consumption in the industrial processes [16], [17], [18], [19]. In the Directive (EU) 2023/1791 [14], submetering is considered a device to measure consumption in individual units of buildings for energy.[4] Lastly, in the Electricity Market Design (EMD) [5] reform proposal, the European Commission introduces submeters through dedicated meter device(s) (DMDs), which means a device linked to or embedded in an asset that provides flexibility services such as demand response on the electricity market or to SOs.[5] Where final customers do not have smart meters installed or where the smart meters do not deliver the necessary detailed data to measure demand response or flexibility services. TSOs and DSOs, upon customer consent, should use the data from DMDs, where available, to settle flexibility services. In these cases, Member States shall establish requirements for DMD data validation processes to check and ensure the quality and consistency of DMD data, including interoperability requirements. EMD also states that in addition to TSO and DSO, independent aggregators and other relevant market participants may use data from DMDs upon the customer's consent [14] and attach to the requirements on data access and sharing stated by the Data Regulation (EU) 2023/2854[20].

In implementing flexibility services, DMDs may enable the metering of flows from any FR behind the CAP. There is still little international experience in adopting DMDs submeters in flexibility services (Australia, New Zealand, the UK, France, Belgium, Scandinavian countries and California). Their implementation is not fully developed in many national regulatory frameworks since there are many open questions about their installation, technical requirements, certification, functionalities, roles, and responsibilities [4], [21]. Literature about the participation of small FRs in providing flexibility services has focused on different challenges: market designs [22], baselining

[3] Smart meters use to meter with the Imbalance Settlement Period (ISP) granularity for energy settlement, which should converge to 15 minutes in all European scheduling areas (European Commission, 2017). Smart metering systems rolled out after July 5th 2019 should also offer standardized or remote near real-time interfaces for *home energy management, demand response and other services* as defined in Art 20 of Electricity Directive (EU) 2019/944 [14]. *Near-real time* means non-validated metering and consumption data provided continuously by a smart meter or a smart metering system in a short time period (usually down to seconds or up to the ISP). In many Member States, system operators have started initiatives to make these interfaces available to involved actors (see e.g. Dutch NextGen Smart Metering initiative, Austrian Digitale Kundenschnittstelle, German Smart Meter Gateway, French Linky interfaces, Italian In-home PLC-based Sinapsi etc.).

[4] In energy efficiency programs, submeters are part of the energy monitoring systems, which include the specific energy meter, a communication system with the cloud and an interface to monitor the consumption. They include a current transformer and a communication connection (e.g. RS-232) and are based on common protocols such as Modbus, TCP, etc. Some submeters also include a small display to monitor the real-time data.

[5] The definition of DMD in [5] does not prevent to use their data for other processes, for instance, in local energy communities.

[23], customer engagement [24], prequalification processes [25], and the role of aggregators [11].[6] However, the use of submeters or DMDs has been little addressed and in a limited manner. Future challenges include technical functionalities that should be performed, operational needs, policy implications, and future regulatory frameworks to exploit all their potential, remove barriers, and minimize unwanted trade-offs. This paper aims to identify potential roles and functionalities of submeters and DMDs related to flexibility services and the pending challenges to enable their efficient integration.

This paper is organized as follows. Section 2 introduces the potential added value from using submeters in the power system and the main technical and operational challenges behind its implementation in the flexibility markets. Section 3 describes results from a survey made in the Beflexible project scope to contrast the submeters' role and their requirements. Finally, Section 4 explains future research steps and open challenges for implementing submetering.

[6] In the scope of flexibility services, the baseline is the estimated counterfactual position used to calculate the delivered flexibility from an FR [23].

2. Submetering: uses, technical challenges, and interoperability requirements

As defined in the European Regulation, smart meters in the electricity sector must provide two different complementary data with their corresponding aims. See Table 1.

Table 1. Data provided by smart meters. Source own elaboration based on [26], [27], [28]

Type of data	Description	Aim
Main data	Smart meters send that data to Meter Data Collectors (typically DSOs) through Power Line Communication (PLC) daily. Meter Data Responsible (typically DSOs) validate that data and generate replacement values if there are gaps in the time series. Metered Data Administrators (varying responsibilities in Member States) make that data available to eligible parties. Data from these streams may be used for validation of flexibility services, but their granularity is often not lower than 15, 30, or 60 minutes intervals (HEMRM) [29]	Billing of electricity, settlement process, and other services that can be settled within a market time interval.
Near-to-real-time data	Smart meters rolled out after July 5th, 2019, must have an interface known as P1. This interface usually provides granularities of 1s to 5s and other valuable data (see, e.g., typical DLMS/COSEM data sets).	Support energy management, demand response, and other services, including the settlement, validation, and calculation of compensations between FSP and suppliers.

In energy efficiency processes, submeters can be used for (i) disaggregating the consumption behind the “main” meter in a building, facility, apartment blocks, shops, or even also in specific household assets such as electric water heaters, radiant floors, air-conditioning, etc.; (ii) remote operation alerts; or (iii) for savings verifications [17], [18], [19]. Electricity Directive (EU) 2018/2002 [30] considers individual smart meters as a valid tool for the European Commission energy transition agenda, especially for heating, cooling, and domestic hot water, and they enable the implementation of energy analytics or energy information systems (EIS) to monitor and achieve energy savings.

However, when submeters are used in flexibility services, a clear distinction shall be considered between “main” *smart meters* used for energy billing, settlement, and flexibility purposes and *submeters*. Smart meters record energy flows at the CAP, while submeters can monitor and validate the flexibility provided by one (or more) specific FRs connected behind the same CAP.[7] In these cases, submeter data should ultimately be

[7] Future European Regulation implementing flexibility services will allow for multiple FR providing flexibility services behind the same CAP [28].

consistent with the main meter records as, from the grid point of view, the effective delivered flexibility is the change of energy flows at the CAP, where the *smart meter* is installed.[8] See Figure 1.

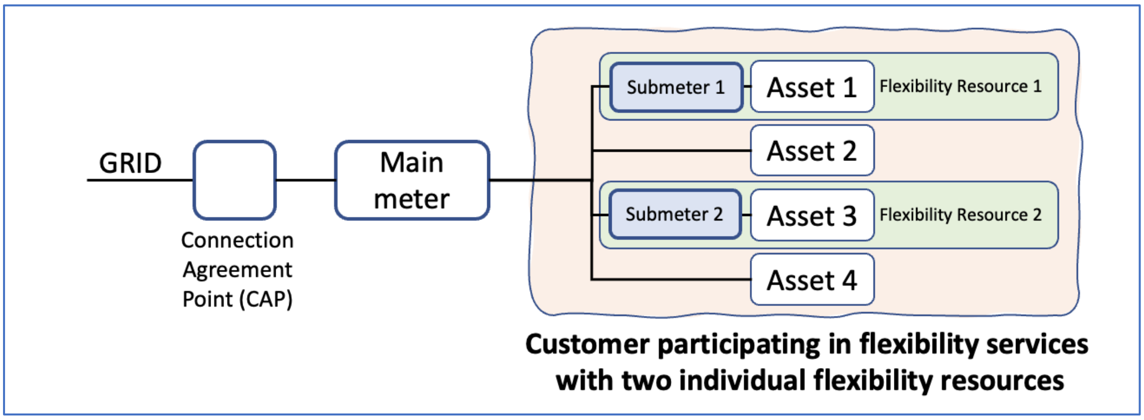

Figure 1. Potential configuration of a customer participating in flexibility services.

Submeters can provide potential added values in supporting the internal FSP management processes when allowed to identify FR behavioral patterns used to make flexibility bids, improve the calculation of baseline complementary to baselines at the CAP if feasible, or enable real-time monitoring of FR during the provision of flexibility services to minimize (ex-post) penalties for not fully delivered flexibility. For SOs, submeters might also provide added value related to observability, load forecasting accuracy, or power system planning under the customer's consent [31], [32]. In this context, regulators state that DSOs should be entitled to access to submetering data [33]. Table 2 identifies potential added value from implementing submeters with more granular data than current smart meters in the flexibility services and associated with the following processes:[9]

1. **Product prequalification**: a technical test (ex-ante) to verify FR (or FR portfolio) compliance with the technical and data exchange requirement for the service delivery.
2. **Baseline calculation**: the counterfactual to calculate the delivered flexibility from FR (or FR portfolio). In cases where smart meters are rolled out, this may be used to validate that the delivery at the boundary point has not happened.
3. **Monitoring**: monitoring the status of FR (or FR portfolio), including electrical parameters such as energy flows, voltages, etc.
4. **Activating**: the delivery of the flexibility service, which includes changing the operation status of FR (or FR portfolio).

[8] Submeter data does not include flows from other devices or electricity losses behind the CAP such as from cables transformers, DC-AC inverters, auxiliaries, or other equipment. Some MSs have initiated projects to make near-real time data from smart meters more easily sourceable for actors in need of that (see Austrian Digitale Kundenschnittstelle, French Linky adapters, Italian In-House PLC Sinapsi adapter or Dutch NextGen Smart Meter project). On a European level, Project EDDIE – European Distributed Data Infrastructure for Energy (https://eddie.energy) is providing a component called Administrative Interface for In-house Data Access (AIIDA) to achieve a uniform European interface for both submeter, but primarily P1 interface data under sovereign control of the final customer and in a non-discriminatory manner.

[9] All listed processes might be defined at FR level. However, in the future implementation of flexibility services, some of these processes might be performed at FR portfolio level (group of FR) or at the CAP level. Anyway, descriptions do not change.

5. **Observability and settlement of the flexibility delivered**: calculating the resultant economic compensation or penalties complementary to measurements at the CAP, if applicable.

Using submeters presents important technical challenges, interoperability requirements, and the need to define roles and responsibilities between all parties involved. All of them are relevant potential research lines to be further discussed in the literature with either technical pilots or regulatory recommendations. A sole and unreflected use of submeters is currently leading to compromised measurement processes, for instance, in validating balancing services.[10] In the context of smart meters, the widespread adoption of submeters still faces significant technical, operational, and interoperability challenges [35].[11] From data protection to standardized protocols, submeters still need to address the existing gap to be considered a valid solution for certain uses. Standard meters, often called regulated meters, have a long history of recording consumption and relevant electricity supply parameters. Standard meters used for billing and settlement, increasingly in the form of smart meters, must meet strict requirements such as metrological, data protection and availability per the Data Regulation, affordable installation and use, technical conditions, and data interoperability, among others. Specifically, regarding data access and interoperability, Regulation (EU) 2023/1162 [36] was published in June 2023 to establish interoperability requirements and rules for non-discriminatory and transparent procedures for access to electricity metering and consumption data by final customers and eligible parties. Since this legislation applies only to regulated meters and not to other devices such as submeters, the widespread use of the latter will require the development of norms and standards that allow their easy, safe, and accessible use by consumers. In this regard, the EU Commission and the Joint Research Center have been studying the benefits and challenges of the SAREF (Smart Applications REFerence Ontology, and extensions) ontology and its extension for the energy domain known as SAREF4ENER[37], [38].[12] Implementing submeters also requires defining new roles and responsibilities, such as the DMD operator.[13] See Table 3.

Other relevant points that could be explored in the future literature and pilots about submetering include the assessment of electricity losses between CAP and the submetering to better estimate exchange flows at the CAP using submetering data, the validation of its data, how to correct missing or erroneous data, the time synchronization between smart meter and submeters to minimize potential time offsets, the time

[10] As an example, an IBM Independent Audit on Belgian TSO Elia's Transfer of Energy process and systems states that exactly this measurement at the boundary point is an important shortcoming that is just acceptable in status quo, with very low volumes and very low numbers of connected assets. It identifies the need for correction in the future. However, measurement strategies of other System Operators are – currently – similarly compromised [34].

[11] Interoperability refers to the ability of communication networks, systems, devices, applications or components to interwork to exchange and use information and perform their required functions (Electricity Directive (EU) 2019/944).

[12] Smart Applications Reference Ontology (SARED) is a shared model of consensus that facilitates the matching g of existing assets in the smart applications domain. Other matured open data models are being promoted by different actors, to favour real-time streaming exchanges among different flexibles devices, such as the European Customer Energy Management Data Model (S2) standard EN 50491-12-2.

[13] In [36], 'metered data administrator' means a party responsible for storing validated historical metering and consumption data and distributing these data to final customers and/or eligible parties.

availability of submeter data to perform subsequent imbalance adjustment processes or the settlement of the delivered flexibility services, who is assigned the GDPR responsibilities, or customers' willingness to accept their installation [39].

Table 2. List of potential added value from submeters with the corresponding processes in the scope of flexibility services. Source: own elaboration based on literature.

Potential added value	Processes related to flexibility services					**Reference**
	Product prequalification	**Baseline calculation**	**Monitoring**	**Activating FR**	**Measurement and settlement of delivery flexibility**	
Provide near real-time, real-time, or historical data for flexible service availability forecast and monitoring of each FR.	yes	yes	yes		yes	[40]
Data provision for identifying behavior patterns of potential FR or for a more accurate calculation of FR baseline, aligning baseline methodologies to the FR characteristics. This includes combining submetering data with near-real-time records from a smart meter (using the standard interface).	yes	yes			yes	[23], [41]
Provision of valid and accurate data to (ex-post) verify the delivered flexibility from FR or to calculate the corresponding financial settlement.	yes			yes	yes	[25]

Table 3. Technical requirements related to the implementation of submeters to the flexibility services.

Technical requirements	**Description**
Standardization and certification	Manufacturers can exploit benefits from economies of scale if standardization is properly defined at the international and national levels. Standardization covers a wide range of parameters such as security levels, reliability, technical requirements, or functionalities, and this is assessed with certification processes [42]
Metrological and technical requirements	Metrological requirements include their data's accuracy and are essential for valid data. EU law establishes the requirements that measuring instruments must satisfy to be sold or put into use in the EU but might differ depending on the functionalities made by submeters [26]. In general terms, they should comply with the same metrological and technical requirements as smart meters, at least when used for the same functionalities [43].
Data interoperability	Standard data formats and communication protocols ensure data accessibility by all involved parties. Inefficient systems and lock-ins from some vendors should be minimized [4], [35].
Secure data exchange and management	Data governance, GDPR compliance, authentication, data consent, and cybersecurity requirements [44], [45], [46]. For instance, DMD operators shall implement processes and designs to prevent data corruption during acquisition, communication, and storage and ensure compliance with GDPR through data encryption, ensuring confidentiality, and preventing corruption of data during transit of data and on stored data.
Data accessibility	Users or their authorized third parties should have the right to access the data they generate quickly and easily [46].
Affordability	Submetering costs include the cost of the meter hardware and communication and data processing infrastructure required to establish a complete metering system. Meters must be procured, installed, serviced, and maintained, resulting in capital and operational costs. The costs of a metering system depend not only on the technical specifications of the meter and the communications technology used but also on the business management model applied. (Directive (EU) 2019/944) [27].
Reliability	Traditionally, ownership and management of metering equipment has been the responsibility of Distribution System Operators (and, in some cases, of Metering Data Operators), including procurement, installation, operation, and maintenance of the system. This has opened the door for asset management standardization and optimization, resulting in very reliable processes [47].

3. Submetering implementations, challenges, and outlook for future usages

3.1. International applications of submetering

In some countries, the use of submeters is already explicitly specified in the national regulatory framework (e.g., UK, Belgium, or France), but in others (e.g., Australia or New Zealand), they are more commonly allowed by exception or where there are no explicit rules.

Next, we explain the main practices in Australia, New Zealand, UK, Scandinavian countries, France, Belgium and California. Table 4 summarizes all these ongoing applications. Submetering is used for a wide range of flexibility services, allowing the participation of small loads and charging points. Metrological requirements and certification are generally specified to ensure the proper functioning of submeters.

Table 4. Summary of main international experiences where submetering is implemented.

Country	Service	Assets Scope	Metrological requirements	Submeter certification	Ex-post checks	Submeter specified in the national regulation?
Australia	-Fast Frequency control ancillary services (FCAS)	Small, medium, and large units	Yes	Not specified, but AEMO should approve using a submeter	Verification for the FCAS providers	Not specified
New Zealand	-Fast Instantaneous Reserve -Sustained Instantaneous Reserve	Small, medium, and large units	Yes	Not specified	Not specified	Not specified
United Kingdom	Capacity Market and the Balancing Mechanism	Small, medium, and large units	Yes, including metering circuits	Yes, manufacturer certificates	Audits, ex-post statistical validation to ensure resources are independent from other assets	Yes
France	Block Exchange Notification of Demand Response Mechanism	Small loads	Yes, including metering circuits. IEC rules	Yes, IEC rules	Only specific rules and procedures for any change in the submetering system	Yes
Belgium	All services	Not specified	Yes, including metering circuits. IEC	Technical information on submetering facilities should be sent to TSO before commissioning.	Not specified	Yes
Denmark, Finland, Norway, Sweden, Iceland	In pilots	Small loads	Not specified	Not specified	Not specified	Yes
California	Balancing services and specific EV and ToU tariffs	Electric Vehicles charging points	Accuracy standards	Yes, tests made by Nationally Recognized Testing Laboratories	Not specified	Yes
Portugal	Not for flexibility services. Billing and settlement purposes.	Electric Vehicles charging points	Yes	Yes	N/A	Not directly

Source: own elaboration.

Australia

The Frequency Control Ancillary Service markets include some very fast response services, necessitating high-speed metering to verify the delivery of these services [48]. The Market Ancillary Service Specification (MASS) for Australia's National Electricity Market Operator (AEMO) specifies that measurements should be ordinarily taken close to the connection point but allows alternative measurement methodologies.[14] In these cases, a potential flexibility provider must request the AEMO's approval before using submeters. AEMO specifies metrological requirements for these submeters, but their certification is not specified.

New Zealand

In New Zealand's Instantaneous Reserve markets, Transpower's standard contract terms are silent on where the metering should located. They only require that the response of the relevant equipment should be measured[15]. This opens the door to the use of submetering.

The United Kingdom

The UK has elaborate procedures for using submeters, defined separately for ancillary services, the Capacity Market (CM), and the Balancing Mechanism (BM).

In CM, the priority is verifying that the agreed capacity has been delivered, while the impacts on energy settlement are ignored. Participants must provide documentation, including single-line diagrams showing the metering locations, and the CM Settlement Body can request on-site audits [51].[16] According to the national regulation, the petitioner should provide the manufacturer test certificates of the submeter, including technical information about its typical errors and the calibration tests performed by a third party, and the manufacturer certificates of the transformer metering, detailing their accuracy class, test certificates and the range of errors from the design characteristics of the transformers. Some participants have criticized the arrangements not for these safeguards but for overly stringent meter specifications, leading to very expensive and disruptive installations.

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[14] The MASS specifies that all the measurements of Local Frequency, Generation Amount and Load Amount "*must be measured at, or close to, each relevant connection point and summed to calculate the Aggregated Generation Amount or Aggregated Load Amount. Where any part of an Aggregated Ancillary Service Facility shares a connection point with a variable load or generating unit, it is the gross active power flow to or from the relevant plant that forms the aggregated response by the Aggregated Ancillary Service Facility and must be measured directly.*"[49]
[15] Transpower, Instantaneous Reserve Ancillary Sevice Schedule, 27 September 2023, available from [50], see §5.3
[16] See §3.9.4(i) and Schedule.

In the BM, a recent code change (P375) allows submeters to measure responses to dispatch instructions, fully reflecting their impact on normal energy settlement [52]. As part of this reform, a new metering code of practice was introduced to allow for cheaper meters in smaller assets, including metering functionality embedded into end-user equipment such as EV chargers. One of the reasons to adopt this approach is to allow smaller, controllable assets to be separated from other activities, providing more accurate volumes of the balancing energy provided by the Balancing Service Provider (BSP). The compliance tests for metering protocol approval [53] include all the compliance tests for meter manufacturers, communications, etc., needed to get the corresponding compliance certificate.[17]

France

From June 2021 until December 2023, RTE carried out a pilot on the use of submetering to monitor the load reductions made by aggregators [54]. This aimed to test how aggregated small FSPs could participate in the Block Exchange Notification of Demand Response (NEBEF) mechanism [55]. In this service, each aggregator should identify the technical requirements of all the submetering systems, including the submetering device with their measurement accessories and communication devices. The TSO should have previously qualified all the submetering systems.

Belgium

Submeters are enabled in two mechanisms designed to address the risk of a structural shortage in the Belgian control area in the winter: Strategic Generation Reserve (SGR) and Strategic Demand Reduction (SDR) [56]. Elia identifies three possibilities for the use of a submeter to monitor the active power with a frequency of 15 minutes [57]: (i) a submeter with Elia's standard that communicates with the Elia metering data management system (MDSM); (ii) a private submeter that communicates with a datalogger that fulfills the Elia standard, and subsequently communicates to the Elia metering MDMS using predetermined communication protocols. A private datalogger is allowed but must have an external synchronization clock with an accuracy better than 20 milliseconds; (iii) a private submeter that communicates with a GSM modem that, in turn, communicates to the Elia MDMS. Candidates participating in the Strategic Reserve with submeters should provide technical information for commissioning the submeter and the communication devices with the Elia metering data management system.

[34] states that Elia might have paid activations that have not caused a load reduction or the load was only shifted within a CAP without a real net effect on the grid offtake. This

[17] In the UK, the administer the Balancing and Settlement Code (Elexon) performs statistical monitoring to identify if some resources that participate in the balancing markets are not acting independently of other assets onside.

is explained because the submeter is the only source to validate the activations and recommends a complementary validation with CAP records.

Denmark, Finland, Norway, Sweden, Iceland

In Denmark, third-party aggregators have used submeters on heat pumps [58]. NordREG[18] has also considered using submeters to measure the real-time consumption of specific flexibility resources, especially for fast flexibility services.

In the real-time monitoring of flexible resources, [41] distinguishes between two situations: First, when the aggregator has a commercial agreement with the customer's Balancing Responsible Party (BRP), the agreement should include how the flexible resource consumption is metered. NordREG considers this choice quite unlikely due to potential disputes between two contracting competitors. Second, when an aggregator splits the balance responsibility for the customer, the regulatory framework should distinguish between the metered responsibilities between the aggregator, BRP, and BSP for the same customer. In this last case, submeter data is directly submitted to the settlement process without any intermediate statistical estimation as in the single-meter approach. The DSO could install this additional meter, but this solution is considered costly and a barrier to successful aggregation implementation. NordREG highlights that other less expensive submeter solutions should be explored.

NordREG discusses the possibilities of using the existing smart meter at the point of connection to the grid to send the submeter data or using separate communication links handled by the aggregators. In both cases, NRAs state that submeters should be paid for by the aggregators, and their costs should be internalized by them. This approach would also incentivize aggregators to implement the most efficient ways to individually meter, always ensuring that the benefits of aggregation must outweigh its costs.

NordREG recommends making a cost-benefit analysis and assessing the technical feasibility of metering and submetering requirements, differentiating between small, medium-sized, and large consumers. NRAs highlight a trade-off between higher accuracy requirements and increased system costs, especially for small consumers, as they have low loads. For these cases, the potential impact of any inaccuracies on markets is less significant than for large consumers [41].

California

Submeters are implemented for balancing services and in the specific ToU tariffs for EV owners. The California Public Utilities Commission approved the implementation of

[18] The Nordic Regulators (NordREG) includes the NRAs from Denmark, Finland, Norway, Sweden, and Iceland

submeters for customers with plug-in EVs [59]. The customer or a third party can own and operate the submeter.

Regarding certification of non-publicly accessible EV chargers, they can fulfill the tests used by the California Department of Food and Agriculture, Division of Measurements and Standards (CDFA-DMS) instead of adopting ANSI certificate tests. Tests can be performed by nationally recognized testing laboratories or comparable facilities such as government laboratories, field test sites, manufacturers, or third-party laboratories.

WiFi or cellular networks can perform submeter data communication. Moreover, submeter data is required to be stored onsite for 30 days and remotely for 90 days in case of any billing dispute. It is important to highlight that in case an issue is not resolved, the customer is billed at the main meter rate during the affected period. The utilities are required to publish a list of approved submetering equipment.

Portugal

In Portugal, the e-mobility regulation [60] enables the possibility of using submeters embedded in the EV chargers for billing and settlement purposes when public EV chargers are installed under a private supply point (e.g., hotels, shopping centers), having a unique meter in the connection point manage with the DSO. In this case, the DSO must consider the measurements of the EV chargers to calculate the energy difference for billing. This regulation aims to differentiate EV charger consumption from private premises.

The EV chargers submeters must fulfill the metrological regulation referred to in the e-mobility regulation.

3.2. Survey on current European use of submetering, expected usage, and challenges

Due to the few implementations of submetering in flexibility services, potential implementations of submetering and their challenges have been analyzed in the Beflexible project [61]. The respondents of the survey are DSOs from Austria, Greece, and the Netherlands, DSOs from Beflexible participants from Italy (two), Spain (two), and Sweden. Also, the Italian TSO and one retailer participated in the survey.

The objective of the survey is to know the current use of submetering in different European countries and understand the point of view of different agents regarding the expected use of flexibility services, as well as the main technical requirements and barriers that it should fulfill as an enabler of flexibility markets.

European electricity markets are organized as a sequence of markets where the nominated energy market operators (NEMOs) manage the wholesale energy markets, and SOs manage technical constraints to guarantee the system's safe and reliable operation and supply security.

TSOs manage frequency control markets (i.e., balancing markets), some congestion management or redispatching processes at transmission networks, and other ancillary services markets such as firm capacity, voltage control in transmission networks, black start, and inertia. On the other hand, DSOs are starting to procure flexibility services, and their use of submetering is still limited. As explained in the previous section, submetering can provide added value to the FSP, the owner of the FR, the customer, and the SO (buyer of services).

Table 5 shows the current use of submetering in the surveyed countries. At the DSO level, submeters are used in DSO congestion management in Austria and Sweden and voltage control in Austria. Balancing services are not forbidden in some countries like mFRR in Spain. All these international experiences are potential cases to be analyzed in future research.

Table 5 Current use of submetering in survey countries. Completely black-filled circles mean submetering is used, white circles submetering is not used, and half-filled circles are not applicable, meaning there is no market for the specific service—source: own elaboration based on responses to the survey.

Role		Congestion Management (TSO)	Congestion Management (DSO)	Other i.e. Voltage control	Balancing services FCR	aFRR	mFRR	RR	Emergency Demand Reduction Measures
Prequalification	Yes		●●	●			●		
	No	○	○		○○	○○	○	○○	○○○
	NA	◐◐	◐◐◐	◐◐◐					◐
Forecast of needs	Yes		●●	●			●		
	No	○			○○	○○	○	○○	○○○
	NA	◐◐	◐◐◐	◐◐◐					◐
Bid collection	Yes		●●	●			●		
	No	○			○○	○○	○	○○	○○○
	NA	◐	◐◐◐	◐◐◐					◐
Monitoring	Yes		●●	●			●		
	No	○			○○	○○	○	○○	○○○
	NA	◐	◐◐	◐◐					◐
Activation	Yes		●●	●			●		
	No	○			○○	○○	○	○○	○○○
	NA	◐	◐◐◐	◐◐◐	◐◐	◐◐	◐◐	◐◐	◐
Settlement	Yes		●●	●					
	No	○			○○	○○	○	○○	○○○
	NA	◐	◐◐◐	◐◐◐					◐

There was no consensus when the respondents were asked about the future use of submetering in flexibility services. Respondents generally consider submeters useful for need forecasting, monitoring, and activation. Less support is given to prequalification and bid collection and even less for settlement, where only two DSOs consider it to play a role for settlement purposes, as shown in Table 6.

Table 6. Expected submetering use. Black-filled circles mean submetering is expected to be used, white circles submetering is not expected to be used, and half-filled circles mean neutral position regarding the use of submetering for the particular market phase—source: own elaboration based on responses to the survey.

Role		Congestion Management (TSO)	Congestion Management (DSO)	Other i.e. Voltage control	Balancing services: FCR	aFRR	mFRR	RR	Emergency Demand Reduction Measures
Prequalification	Yes	●	●●	●		●	●●	●	●●●
	No	○○	○○○○○○	○○○○○	○○	○		○	○○○○○○
	Neutral	◐	◐	◐◐					
Forecast of needs	Yes	●	●●●●	●●●●		●	●		●●●●●●●
	No	○○	○○○	○○	○				○
	Neutral		◐	◐◐	◐	◐	◐	◐	◐
Bid collection	Yes		●						
	No	○	○○○○	○○○○	○				○○○○
	Neutral	◐◐◐	◐◐◐	◐◐◐◐	◐	◐◐	◐◐	◐	◐◐◐◐◐◐
Monitoring	Yes	●●●	●●●●●● ●	●●●●● ●		●	●		●●●●●●●
	No				○				○
	Neutral	◐	◐	◐◐	◐	◐	◐	◐	◐
Activation	Yes	●●	●●●●●	●●●●●		●			●●●●●
	No	○	○○	○○	○				○○
	Neutral	◐	◐	◐◐	◐	◐	◐	◐	◐◐
Settlement	Yes		●						
	No	○○○	○○○○○○	○○○○○○	○	○			○○○○○○○○
	Neutral	◐	◐	◐◐	◐	◐	◐	◐	◐

Table 7 shows the answers regarding the agent best placed to install submeters. Although the TSO was provided as an option, it was chosen by only one participant, mainly as smart meters are installed by the DSO or an independent meter operator in case of resources connected to distribution networks. The respondents show a positive attitude toward most of the additional options proposed. Only the Austrian DSO did not favor the DSO, FSP, or manufacturer installing submeters for congestion management or voltage control usages.

Table 7. Responsible agent for installing submeters. Source: own elaboration based on responses to the survey.

Agent	Congestion Management (TSO)	Congestion Management (DSO)	Other i.e. Voltage control	Balancing services: FCR	aFRR	mFRR	RR	Emergency Demand Reduction Measures
TSO			●					
DSO	●	●●●●	●●●●					●
Independent aggregator	●●●●	●●●●●●	●●●●●	●	●●●	●●●	●●●	●●●●
Meter operator (if different from TSO/DSO)	●				●	●	●	●●
Market operator	●●●	●●●●●	●●●●	●	●●	●●	●●	●●●
Consumer	●	●●●●	●●●	●	●	●	●	●
Manufacturer (embedded in a device)	●●	●●●	●●●		●	●	●	●●●
Supplier	●	●	●	●	●	●	●	●

Regarding the standards that submeters should meet (see Table 8), almost all respondents agree that they must fulfill the same requirements as smart meters for all flexibility services. Furthermore, concerning the certification process, the respondents consider different options: certification bodies, grid operators themselves, or a list of requirements specified by the grid operators. Only a few respondents consider that submeters should not be allowed to be embedded in the devices, and the majority agree that the submeter data can use the same smart-meter data infrastructure.

Table 8. Submetering requirements. Black-filled circles mean submetering is expected to have the specified requirements, white circles mean submetering should not follow the specificities indicated, and half-filled circles mean neutral position regarding the requirements for submetering—source: own elaboration based on responses to the survey.

					Balancing services				
Submeter devices must…		Congestion Management (TSO)	Congestion Management (DSO)	Other i.e. Voltage control	FCR	aFRR	mFRR	RR	Emergency Demand Reduction Measures
Be the same of smartmeters or with same requirements	Yes	●●●	●●●●●●●●●	●●●●●●●●		●●	●●	●●	●●●●
	No								○
	Neutral	◐				◐	◐	◐	◐
Be certified by third parties	Yes	●●●	●●●●●●●●●	●●●●●●●●		●●	●●	●●	●●●●●
	No								
	Neutral								
Be certified by grid operators	Yes		●●●●	●●●					
	No								○
	Neutral	◐◐◐	◐◐◐◐◐	◐◐◐◐◐		◐◐	◐◐	◐◐	◐◐◐◐
Be specified in a list by grid operators	Yes		●	●					
	No	○				○	○	○	○○
	Neutral	◐◐	◐◐◐◐◐◐◐◐	◐◐◐◐◐◐◐		◐	◐	◐	◐◐◐◐
Be optionally installed by grid operators	Yes		●●●	●●●					●
	No	○○	○○○○	○○○		○○	○○	○○	○○○
	Neutral	◐	◐◐	◐◐					◐
Be embedded in devices, i.e. EV charging points	Yes	●	●●●	●●●		●	●	●	●
	No		○○	○					
	Neutral	◐◐	◐◐◐◐	◐◐◐◐		◐	◐	◐	◐◐◐◐
Same communication infrastructure as smartmeter	Yes	●	●●●	●●●		●	●	●	●●●
	No		○						
	Neutral	◐◐	◐◐◐◐◐	◐◐◐◐◐		◐	◐	◐	◐◐

This survey shows the different options related to the use, installation, and requirements for submeters. Each table identifies potential topics and opinions to be discussed in future technical or policy developments, which are useful for practitioners, regulators, or policymakers.

4. Conclusions and next steps

In this paper, we study the potential benefits of implementing submetering in the power system, particularly in the implementation of flexibility services from small flexibility resources (FRs). This is a relevant topic, but little has been explored in the engineering and economic literature. Submeter usage is expected to increase in the near future as submetering rules are included in the next European Regulation. However, this requires minimum standardization levels, defining interoperability requirements, roles, processes, and responsibilities regarding data exchange, as well as certification requirements to exploit economies of scale by manufacturers. This could foster the participation of small FRs in the flexibility markets.

In Europe, the EMD reform considers it a priority that consumers actively participate in the electricity markets and provide flexibility to the market or system operators, mainly using smart meters. However, national regulations should set the conditions and requirements for the efficient, reliable, and safe usage of submeters, or DMDs as they are called in the EMD, to facilitate the use of submeters for flexibility purposes, especially where smart meters are not yet rolled out. The survey shows a diverse view across European countries on using submetering for different market purposes, allocating roles and responsibilities for market participants and system operators, and requirements.

Beyond Europe, submeters are not forbidden by national regulation in some countries, but there is a lack of regulation to implement them and properly exploit all their potential benefits. However, practitioners and regulators need studies and analysis to set the most efficient regulation to establish metrological regulations, roles, and responsibilities while keeping the regulatory burden and implementation costs as low as possible.

Anyway, the implementation of submeters should not leave in the background the use and accessibility of near-real-time data from smart meters using standardized or remote interfaces. Combining submeters with smart meters might provide high added value for customers, FSP, TSO, and DSO and ultimately facilitate the development of flexibility services.

Future research lines include policy implications related to the implementation of submeters, their coexistence with the current smart meters at the point of connection, specific requirements for certification, and to ensure reliable usage in the power system while becoming a key element to enabling small FRs to participate actively in the different markets.

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References

[1] I. E. A. IEA, 'Renewables 2023 Analysis and forecast to 2028', 2024. Available: https://iea.blob.core.windows.net/assets/96d66a8b-d502-476b-ba94-54ffda84cf72/Renewables_2023.pdf. [Accessed: Feb. 08, 2024]

[2] I. J. Pérez-Arriaga *et al.*, 'Utility of the Future. An MIT Energy Initiative response to an industry in transition', Dec. 2016. Available: http://energy.mit.edu/wp-content/uploads/2016/12/Utility-of-the-Future-Full-Report.pdf. [Accessed: Dec. 16, 2016]

[3] D. Davi-Arderius, T. Jamasb, and J. Rosellon, 'Renewable Integration and Power System Operation: The Role of Market Conditions', 2024, Available: https://research.cbs.dk/en/publications/renewable-integration-and-power-system-operation-the-role-of-mark. [Accessed: Feb. 08, 2024]

[4] M. Llorca, E. Giovannetti, T. Jamasb, D. Davi Arderius, and G. Soroush, *Energy Sector Digitalisation, Green Transition and Regulatory Trade-offs*. 2024.

[5] European Parliament, 'Amending Regulations (EU) 2019/943 and (EU) 2019/942 as well as Directives (EU) 2018/2001 and (EU) 2019/944 to improve the Union's electricity market design', 2023/0077(COD). Available: https://www.europarl.europa.eu/doceo/document/ITRE-AM-749127_EN.pdf. [Accessed: Nov. 24, 2023]

[6] ACER, Agency for Cooperation of Energy Regulators, 'Framework Guideline on Demand Response'. 2022. Available: https://acer.europa.eu/sites/default/files/documents/Official_documents/Acts_of_the_Agency/Framework_Guidelines/Framework%20Guidelines/FG_DemandResponse.pdf

[7] M. Rezaeimozafar, R. F. D. Monaghan, E. Barrett, and M. Duffy, 'A review of behind-the-meter energy storage systems in smart grids', *Renewable and Sustainable Energy Reviews*, vol. 164, p. 112573, Aug. 2022, doi: 10.1016/j.rser.2022.112573

[8] D. Davi-Arderius, M. Troncia, and J. J. Peiró, 'Operational Challenges and Economics in Future Voltage Control Services', *Curr Sustainable Renewable Energy Rep*, vol. 10, no. 3, pp. 130–138, Sep. 2023, doi: 10.1007/s40518-023-00218-1

[9] ACER, Agency for Cooperation of Energy Regulators, 'Demand response and other distributed energy resources: what barriers are holding them back?', 2023. Available: https://www.acer.europa.eu/sites/default/files/documents/Publications/ACER_MMR_2023_Barriers_to_demand_response.pdf. [Accessed: Jan. 18, 2024]

[10] S. Kerscher and P. Arboleya, 'The key role of aggregators in the energy transition under the latest European regulatory framework', *International Journal of Electrical Power & Energy Systems*, vol. 134, p. 107361, Jan. 2022, doi: 10.1016/j.ijepes.2021.107361

[11] O. Rebenaque, C. Schmitt, K. Schumann, T. Dronne, and F. Roques, 'Success of local flexibility market implementation: A review of current projects', *Utilities Policy*, vol. 80, p. 101491, Feb. 2023, doi: 10.1016/j.jup.2023.101491

[12] P. C. del Granado *et al.*, 'Flexibility Characterization, Aggregation, and Market Design Trends with a High Share of Renewables: a Review', *Curr Sustainable*

Renewable Energy Rep, vol. 10, no. 1, pp. 12–21, Mar. 2023, doi: 10.1007/s40518-022-00205-y
[13] European Parliament and the Council, *Directive 2009/72/EC of the European Parliament and of the Council of 13 July 2009 concerning common rules for the internal market in electricity and repealing Directive 2003/54/EC*. 2009. Available: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:211:0055:0093:EN:PDF. [Accessed: Mar. 08, 2013]
[14] Council of the European Union, 'REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Regulations (EU) 2019/943 and (EU) 2019/942 as well as Directives (EU) 2018/2001 and (EU) 2019/944 to improve the Union's electricity market design'. 2023. doi: 10.5040/9781782258674. Available: https://data.consilium.europa.eu/doc/document/ST-14339-2023-INIT/en/pdf. [Accessed: Jan. 10, 2024]
[15] N. Morell-Dameto, J. P. Chaves-Ávila, T. Gómez San Román, P. Dueñas-Martínez, and T. Schittekatte, 'Network tariff design with flexible customers: Ex-post pricing and a local network capacity market for customer response coordination', *Energy Policy*, vol. 184, p. 113907, Jan. 2024, doi: 10.1016/j.enpol.2023.113907
[16] T. Brudermueller, M. Kreft, E. Fleisch, and T. Staake, 'Large-scale monitoring of residential heat pump cycling using smart meter data', *Applied Energy*, vol. 350, p. 121734, Nov. 2023, doi: 10.1016/j.apenergy.2023.121734
[17] X. Li, J. Yu, A. Zhao, S. Hou, and Y. Mao, 'Time series prediction method based on sub-metering in building energy performance evaluation', *Journal of Building Engineering*, vol. 72, p. 106638, Aug. 2023, doi: 10.1016/j.jobe.2023.106638
[18] T. Walser and A. Sauer, 'Typical load profile-supported convolutional neural network for short-term load forecasting in the industrial sector', *Energy and AI*, vol. 5, p. 100104, Sep. 2021, doi: 10.1016/j.egyai.2021.100104
[19] N. Zaeri, A. Ashouri, H. B. Gunay, and T. Abuimara, 'Disaggregation of electricity and heating consumption in commercial buildings with building automation system data', *Energy and Buildings*, vol. 258, p. 111791, Mar. 2022, doi: 10.1016/j.enbuild.2021.111791
[20] *Regulation(EU) 2023/2854 on harmonised rules on fair access to and use of data and amending Regulation (EU) 2017/2394 and Directive (EU) 2020/1828 (Data Act)*. 2023. doi: 10.5040/9781782258674. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L_202302854&qid=1708704932169. [Accessed: Feb. 23, 2024]
[21] European Smart Grids Task Force, 'Demand Side Flexibility Perceived barriers and proposed recommendations', 2019. Available: https://energy.ec.europa.eu/system/files/2019-05/eg3_final_report_demand_side_flexiblity_2019.04.15_0.pdf. [Accessed: Feb. 08, 2024]
[22] J. P. Chaves Avila, M. Troncia, C. Damas Silva, and G. Willeghems, 'Overview of market designs for the procurement of system services by DSOs and TSOs. OneNet D3.1', 2021. Available: https://onenet-project.eu/public-deliverables/. [Accessed: Dec. 28, 2022]
[23] L. Lind, J. P. Chaves-Ávila, O. Valarezo, A. Sanjab, and L. Olmos, 'Baseline methods for distributed flexibility in power systems considering resource, market,

and product characteristics', *Utilities Policy*, vol. 86, p. 101688, Feb. 2024, doi: 10.1016/j.jup.2023.101688

[24] D. Stampatori *et al.*, 'Recommendations for customer engagement strategies. OneNet D11.5', 2023. Available: https://onenet-project.eu/public-deliverables/

[25] M. Troncia, S. Bindu, J. P. C. Ávila, G. Willeghems, H. Gerard, and M. Lacerda, 'Techno-economic assessment of proposed market schemes for standardized products D11.2', 2023.

[26] European Parliament and the Council, 'Directive 2014/32/EU of the European Parliament and of the Council of 26 February 2014 on the harmonisation of the laws of the Member States relating to the making available on the market of measuring instruments (recast)Text with EEA relevance', 2014.

[27] THE EUROPEAN PARLIAMENT AND OF THE COUNCIL, *Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU (recast) (Text with EEA relevance.)*, vol. 158. 2019. Available: http://data.europa.eu/eli/dir/2019/944/oj/eng. [Accessed: Jan. 18, 2024]

[28] EUDSO Entity and ENTSO-E, 'Draft Proposal for a Network Code on Demand Response - version for public consultation', 2023. Available: https://consultations.entsoe.eu/markets/public-consultation-networkcode-demand-response/supporting_documents/Network%20Code%20Demand%20Response%20v1%20draft%20proposal.pdf

[29] 'bridge "Harmonized Electricity Market Role Model" (HEMRM) A Differential Analysis with Respect to the ENTSO-E – ebIX – EFET Model Regulation Working Group'. Available: https://ec.europa.eu/energy/sites/default/files/documents/bridge_wg_regulation_eu_bridge_hemrm_report_2020-2021.pdf. [Accessed: Apr. 23, 2022]

[30] *DIRECTIVE (EU) 2018/ 2001 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL - of 11 December 2018 - on the promotion of the use of energy from renewable sources*. p. 128.

[31] C. L. Athanasiadis, T. A. Papadopoulos, G. C. Kryonidis, and D. I. Doukas, 'A review of distribution network applications based on smart meter data analytics', *Renewable and Sustainable Energy Reviews*, vol. 191, p. 114151, Mar. 2024, doi: 10.1016/j.rser.2023.114151

[32] Y. Zabihinia Gerdroodbari, A. B. Pengwah, R. Razzaghi, R. Heidari, and L. L. H. Andrew, 'A method to control distributed energy resources in distribution networks using smart meter data', *International Journal of Electrical Power & Energy Systems*, vol. 153, p. 109293, Nov. 2023, doi: 10.1016/j.ijepes.2023.109293

[33] CEER, Council of European Energy Regulators, 'Paper on DSO data exchange relating to flexibility and NRAs' role', 2024. Available: https://www.www3.ceer.eu/documents/104400/-/-/bb297f56-e8b0-327c-6d6b-aa1514a3f402

[34] Elia, 'Audit on the Transfer of Energy process and systems', 2021. Available: https://www.elia.be/-/media/project/elia/elia-site/electricity-market-and-system---document-library/transfer-of-energy/2021/20210903_toe-audit-report-external-2020.pdf

[35] V. Rief *et al.*, 'Regulatory and Demo Assessment of proposed integrated markets. OneNet D3.4', 2023. Available: https://onenet-project.eu/public-deliverables/

[36] European Commission, *COMMISSION IMPLEMENTING REGULATION (EU) 2023/1162 of 6 June 2023 on interoperability requirements and non-*

discriminatory and transparent procedures for access to metering and consumption data. 2023. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32023R1162. [Accessed: Feb. 08, 2024]

[37] SAREF, 'SAREF Portal'. Available: https://saref.etsi.org/. [Accessed: Feb. 23, 2024]

[38] ETSI, 'SmartM2M; Smart Applications; Reference Ontology and oneM2M Mapping', 2020. Available: https://www.etsi.org/deliver/etsi_ts/103200_103299/103264/03.01.01_60/ts_103264v030101p.pdf. [Accessed: Mar. 01, 2024]

[39] G. Gosnell and D. McCoy, 'Market failures and willingness to accept smart meters: Experimental evidence from the UK', *Journal of Environmental Economics and Management*, vol. 118, p. 102756, Mar. 2023, doi: 10.1016/j.jeem.2022.102756

[40] Å. L. Sørensen, K. B. Lindberg, I. Sartori, and I. Andresen, 'Analysis of residential EV energy flexibility potential based on real-world charging reports and smart meter data', *Energy and Buildings*, vol. 241, p. 110923, Jun. 2021, doi: 10.1016/j.enbuild.2021.110923

[41] NordREG, 'Nordic Regulatory Framework for Independent Aggregation', 2020, Available: http://www.nordicenergyregulators.org/wp-content/uploads/2021/05/A-New-Regulatory-Framework_for_Independent_Aggregation_NordREG_recommendations_2020_02.pdf

[42] K. Blind, F. Ramel, and C. Rochell, 'The influence of standards and patents on long-term economic growth', *J Technol Transf*, vol. 47, no. 4, pp. 979–999, Aug. 2022, doi: 10.1007/s10961-021-09864-3

[43] EIC, 'EIC 62053-21: Electricity metering equipment (a.c.) –Particular requirements –', 2023. Available: https://webstore.iec.ch/preview/info_iec62053-21%7Bed1.0%7Den_d.pdf. [Accessed: Mar. 01, 2024]

[44] M. Shokry, A. I. Awad, M. K. Abd-Ellah, and A. A. M. Khalaf, 'Systematic survey of advanced metering infrastructure security: Vulnerabilities, attacks, countermeasures, and future vision', *Future Generation Computer Systems*, vol. 136, pp. 358–377, Nov. 2022, doi: 10.1016/j.future.2022.06.013

[45] G. Ramyasri, G. Ramana Murthy, S. Itapu, and S. Mohan Krishna, 'Data transmission using secure hybrid techniques for smart energy metering devices', *e-Prime - Advances in Electrical Engineering, Electronics and Energy*, vol. 4, p. 100134, Jun. 2023, doi: 10.1016/j.prime.2023.100134

[46] D. Lee and D. J. Hess, 'Data privacy and residential smart meters: Comparative analysis and harmonization potential', *Utilities Policy*, vol. 70, p. 101188, Jun. 2021, doi: 10.1016/j.jup.2021.101188

[47] Directorate-General for Energy (European Commission), Tractebel Impact, C. Alaton, and F. Tounquet, *Benchmarking smart metering deployment in the EU-28: final report*. LU: Publications Office of the European Union, 2020. Available: https://data.europa.eu/doi/10.2833/492070. [Accessed: Nov. 24, 2023]

[48] A. Rangarajan, S. Foley, and S. Trück, 'Assessing the impact of battery storage on Australian electricity markets', *Energy Economics*, vol. 120, p. 106601, Apr. 2023, doi: 10.1016/j.eneco.2023.106601

[49] M. Gatt, 'Executive General Manager Operations', 2023.

[50] Transpower, 'Instantaneous reserve'. Available: https://www.transpower.co.nz/system-operator/information-industry/electricity-market-operation/ancillary-services/instantaneous. [Accessed: Feb. 08, 2024]

[51] UK Government, 'Informal Consolidated Version of the Capacity Market Rules July 2023', 2022.

[52] Elexon BSC, 'P375 "Settlement of Secondary BM Units using metering behind the site Boundary Point"'. Available: https://www.elexon.co.uk/mod-proposal/p375/. [Accessed: Feb. 08, 2024]

[53] Elexon, 'BSCP603: Meter Operations and Data Collection for Asset Metering Systems - Elexon Digital BSC', 2023. Available: https://bscdocs.elexon.co.uk/bsc-procedures/bscp603-meter-operations-and-data-collection-for-asset-metering-systems. [Accessed: Feb. 08, 2024]

[54] RTE, 'Participate in the submetering experiment - RTE Services Portal', *Portail Services RTE*. Available: https://www.services-rte.com/en/learn-more-about-our-services/participate-in-the-submetering-experiment.html. [Accessed: Feb. 08, 2024]

[55] RTE, 'Participate in the NEBEF mechanism - RTE Services Portal', *Portail Services RTE*. Available: https://www.services-rte.com/en/learn-more-about-our-services/participate-nebef-mechanism. [Accessed: Feb. 08, 2024]

[56] Elia, 'PROCEDURE FOR CONSTITUTION OF STRATEGIC RESERVE Applicable for the tendering in 2021 as of the Ministerial Decree to constitute Strategic Reserve for the Winter Period 2021-2022'. 2021. Available: https://www.elia.be/-/media/project/elia/elia-site/public-consultations/2020/20201211_procedure-for-constitution-of-strategic-reserve-for-winter-2021-2022/20201211_procedure-of-constitution-of-sr-2021_en.pdf

[57] Elia, 'General technical requirements of the submetering solutions', 2015. Available: https://www.elia.be/-/media/project/elia/elia-site/electricity-market-and-system---document-library/adequacy---strategic-reserve/2015/general_technical_requirements_submetering.pdf

[58] Nordic TSOs, 'Unlocking flexibility Nordic TSO discussion paper on third-party aggregators', 2017. Available: https://www.fingrid.fi/globalassets/dokumentit/fi/tiedotteet/sahkomarkkinat/2017/nordic-tso-discussion-paper-on-third-party-aggregation.pdf. [Accessed: Aug. 01, 2022]

[59] C. P. U. C. CPUC, 'Order Instituting Rulemaking to Advance Demand Flexibility Through Electric Rates'. 2022. Available: https://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M496/K285/496285639.PDF. [Accessed: Feb. 10, 2024]

[60] Entidade Reguladora dos Serviços Energéticos, *Regulamento da Mobilidade Elétrica*. Available: https://www.erse.pt/media/nkvpo0s4/consolidado-rme_vs-erse-2023.pdf. [Accessed: Mar. 01, 2024]

[61] 'BeFlexible', *BeFlexible*. Available: https://beflexible.eu/home/. [Accessed: Dec. 28, 2022]