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A review of socio-technical barriers to Smart Microgrid development☆

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ABSTRACT

Smart MicroGrids (SMGs) can be seen as a promising option when it comes to addressing the urgent need for sustainable transition in electric systems from the current fossil fuel-based centralised system to a low-carbon, renewable-based decentralised system. Unlike previous studies that were restricted to a limited number of actors and only took a mono-disciplinary research approach, this current review adopts a multidisciplinary, socio-technical approach and addresses the factors that have been hindering the development of SMGs and considers how these barriers interact. This study contributes to the body of literature on the development of SMGs by mapping and discerning technical, regulatory, market, social and institutional barriers for different types of actors, including technology providers, consumers, Distributed Generation (DG) providers and system operators, based on information derived from laboratory reports, demonstration pilots, and academic journals. In addition, attention is paid to how these barriers interact based on real-life experimentation. A holistic picture of barriers and their interaction is presented as well as recommendations for future research.

1. Introduction

Environmental concerns and climate crises have increased in the last decades. CO_2 emissions reached almost 35 billion metric tons in 2019 and are expected to hit more than 43 billion metric tons in 2040 [1]. Internationally, the Paris Agreement requires countries to contribute to maintaining the global average temperature increase below the specified threshold of 2 °C. This demands emergency action by all parties to reduce greenhouse gas (GHG) emissions [2]. At a national level, European Union (EU) members are following the ambitious EU climate action policies that aim to cut at least 40% of GHG emissions (from the 1990 levels); improve energy efficiency by 32.5%; and reach at least a 32% share for renewable energy.

Energy sectors are considered as responsible for a sizable share of CO_2 emissions due to their reliance on fossil-fuels. In addition, electric power systems at a national and international level are encountering energy shortages, unsatisfactory efficiency and ageing distribution systems, which all require substantial capital costs if they are to be addressed [3].

To tackle these problems, scholars have proposed decarbonising the electric system by implementing renewable energy sources (RESs) and improving efficiency by utilising Distributed Generations (DGs) [4]. However, in practice, a transformation to a sustainable system from the current paradigm and technologies in the electric power system without losing any quality of services in terms of power system reliability and stability is a daunting task [3]. The transition from a centralised to a decentralised system can be made in different ways, ranging from Smart Grid (SG) technologies to MicroGrids (MGs) and Virtual Power Plants (VPPs) [5].

Merely integrating RESs into electric systems will not accelerate the transition process because RESs alone are incapable of creating a fundamental change in the system [6]. Large-scale RESs such as offshore wind parks are still set up within power system's traditional and centralised context [7]. However, combining small-scale RESs with energy storage devices and varied loads close to the distribution system's resources would allow the development of an MG [8].

Historically, MGs have only been used to provide electricity for remote locations with limited transmission lines. However, new rationales for the use of MGs have recently emerged, and provide more applications. Cui et al. [9] discern multiple functions for MGs: the nature of the connection with the main utility, a precise energy and power balance within the MG, energy storage, demand management, and a seasonal match between generation and load. The first function implies that an MG works in the grid-connected mode under normal conditions. However, when emergencies occur, MGs can be disconnected from the

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main utility in an islanded mode. This switching between connection and disconnection occurs at the Point of Common Coupling (PCC) (see Fig. 1) [10]. To summarise, MG functions require sophisticated control systems to secure electrical parameters and facilitate the power flow between the MG and the main grid. These control systems are critical for the safe operation of MGs. From an upstream network perspective, an MG is an ideal controllable and coordinated load [11].

Another concept linked to DGs and RESs is VPP. This refers to the remote dispatching of DGs, stored energies, or demands that rely on smart infrastructure and sophisticated control methods. A VPP aggregates all the generated power from different resources and dispatches it according to the specified power generation programme [12]. A VPP cannot be treated as a physical power plant and is not limited to a certain geographical location or a specific set of resources [12].

Achieving the full value of MGs and VPPs depends on the deployment of SGs, which explains why policymakers are focusing on rolling out smart infrastructures to achieve climate and energy targets [13]. Although the current power system is already equipped with Energy Management Systems (EMSs), modern Supervisory Control and Data Acquisition (SCADA) systems, and advanced data processing software such as Advanced Distribution Automation (ADA) for controlling and monitoring purposes, these smart devices do not cover all the parts of the grid, like DGs and end users' equipment in a unified way [12]. In brief, SGs have various objectives, including:

(1) enhancing of the power quality; (2) developing demand response programmes and facilitating the participation of end users; (3) automatic monitoring and two-way communication; (4) accommodating new services and products in the electricity market and (5) integrating DGs and storage devices into the electric grid [2].

Fig. 1 presents a typical SG including MGs. EMS uses SCADA and ADA to optimise RESs and exercise Demand Side Management (DSM) in this system. The SCADA system is usually responsible for the status in the generation and transmission line and cannot manage DGs directly in the distribution system. ADA therefore takes control over switches, valves, and relays of distributed components and enables DSM by sending real-time pricing signals to homes, industrial loads, and even Electric Vehicles (EVs).

Although SGs and MGs are distinguishable technically, we will refer to the concept of Smart MicroGrids (SMGs) as a general term in this study because we are concentrating on the transition in electric systems. For this reason, we have adapted the US Department of Energy (DOE) definition to "A smart power distribution network comprising of various loads, Distributed Energy Resources (DERs) and energy storage devices, which can operate connected or disconnected from the main utility in controlled and coordinated fashion" [14].

Despite extensive attempts at national and international levels to accelerate the transition process towards a decentralised system using RESs, technologies linked to this transition (i.e., SGs and MGs) are still mainly found in the niche market where development and diffusion processes are moving fairly slow. To encourage transition, barriers to niche development need to be identified [15].

Previous reviews of SG and MG barriers are rather fragmented. A large portion of the academic literature [5] has focused on addressing definitions, and the evolution of SG and MGs concepts. Some reviews elaborate on policies towards SMGs based on the drivers and opportunities. Bellido et al. [16] discern the following drivers: (1) the increasing demand for electricity; (2) the need for a reduction in losses; (3) the integration of renewable energy generation systems; and (4) new business opportunities. These drivers have encouraged the US government to formulate policies to secure the supply of energy, improve its resiliency, and keep energy costs low. The policies target increased energy efficiency and are implemented in MG projects. The challenge of integrating large amounts of RESs in electric systems and climate change mitigation has spurred the EU to invest in SMG innovation [17]. In Japan and Korea [18], national security, economic growth and a diversifying energy supply form the basis of policies focusing on SMG development [19].

Investment difficulties in SMGs are also highlighted in the literature. Zhang et al. [2] have examined investment schemes on SG technologies in Europe and the US. Comparing investment issues revealed that the absence of a clear cost-benefit-sharing mechanism and a lack of worldwide technical standards hinder the integration of equipment manufactured by different companies [20]. Other studies highlight fundamental features and adoption issues of SG technologies [19]. In general, these studies address costs, consumer engagement, data protection, privacy, physical security, cybersecurity, compatibility problems with intelligent devices, and technical standards as important factors to evaluate the progress of demand-side management and distributed generation [7] .

Muench et al. [21] carried out a comprehensive barrier review and linked technical barriers to regulatory and institutional barriers. Their review categorised the implementation of SG technologies barriers into: (1) cost and benefit; (2) knowledge; and (3) institutional mechanisms.

According to Curtius et al. [22], having a portfolio of value propositions in place is linked to higher market acceptance. Incentivising industry to increase the range of SG technologies is therefor considered to accelerate overall adoption. Furthermore, amended regulatory frameworks are seen to stimulate innovation capacity. Enabling Distribution System Operators (DSOs) to reclaim their expenses for implementing SG innovations is considered particularly important in fostering SG development [21].

The current literature study is inspired by the fact that previous studies on barriers were rather monodisciplinary and restricted to a limited number of actors. Therefore, we attempt to undertake a multidisciplinary analysis of SMG's barriers with a multi-actor perspective and classification. This review contributes to SMGs' development by addressing the question 'What socio-technical factors hinder adoption and diffusion of SMGs in electric systems?' Answering this question can highlight possible avenues of future research.

This paper is structured as follows. After an explanation of the literature review method, the technical and managerial barriers to SMG technology are addressed in Section 3. Section 4, discusses the regulatory and policy barriers from an actor perspective. In Section 5, the study explores acceptance issues from a social perspective and provides a deeper understanding of the concept of community SMGs - a key concept concerning the social embeddedness of SMG. Based on the identified barriers, Section 6 offers a holistic picture of the actors involved and discusses the interactions between the barriers in practice. Finally, in Section 7 the main findings are presented, and suggestions for future research are presented in Section 8.

2. Methodology

The literature review research process entailed two cycles. First, a database research was performed to obtain an overall understanding of the possible barriers. Scopus, Web of Science, and Google Scholar were used as the primary databases to find articles containing terms and keywords including: "issues", "obstacles", "barriers", "challenges", "Smart Grids", "Microgrids" and "decentralised power systems". Different Boolean operators combined those terms to optimise the results. It was decided to concentrate on studies in European countries and the US as they are considered to be pioneers in SMGs and greater insight would be gained due to the high number of experiments and projects in these countries,. The abstracts of sixty academic papers were reviewed in the first stage. This number was then reduced to 22 after a review of their relevance. Analysis of these papers resulted in a classification of the barriers into the following categories: technical, regulatory and policy, social and institutional.

Each of these barrier classifications was then addressed separately in the second cycle. Snowballing was used to identify the additional relevant articles from the reference list of the papers selected. Due to the large number of SMG projects in Europe and the US, reports of real-life projects were also included as a complementary resource. Table 1 summarises the main references for each identified barrier.

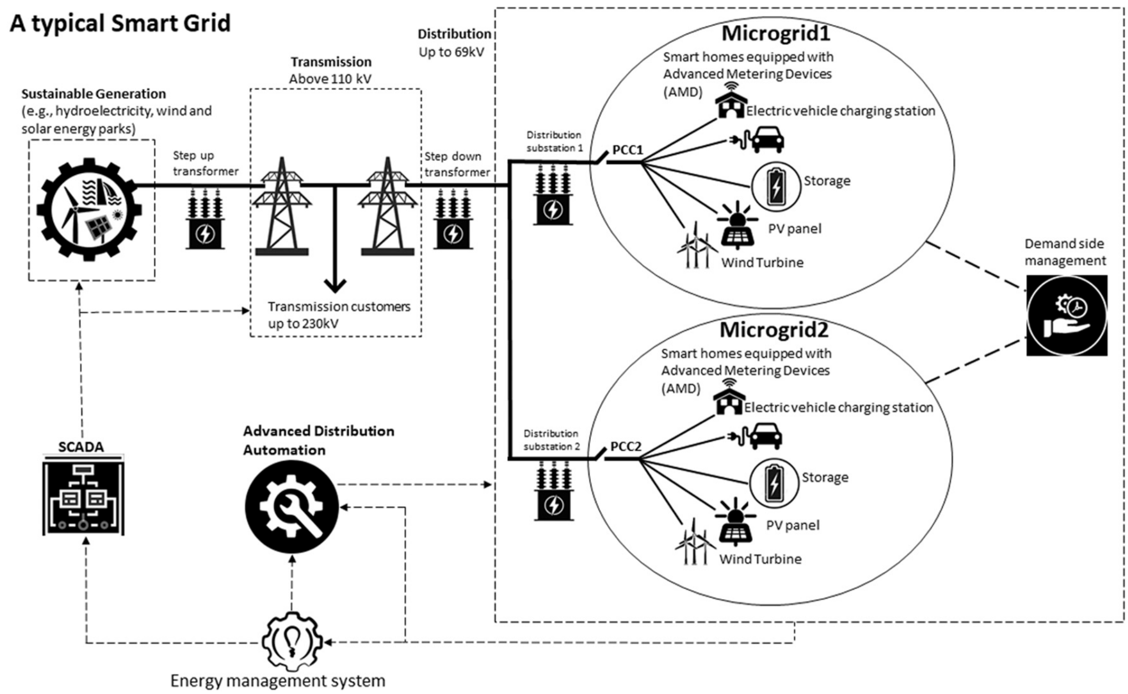

Fig. 1. A typical Smart grid containing Microgrids and equipped with SCADA, ADA and EMS.

Table 1
Summary of barriers to SMG deployment reported.

Barrier	Description	Reference
Overall barriers	Definition and concept of SG and MG, drivers, opportunities and barriers	[1,2,4,5,7,8,12,13,15,19–21,23–32]
Technical barriers of MGs	(1) Complicated design of decentralised controllers with play and plug features; (2) Lack of inertia in DG units; (3) Need for further development of control methods for meshed topology;	[10,33–41]
	(4) Fault current changes by location and capacity of power inverters and lack of grounding system in DC MGs;	[11,42–47]
	(5) Islanding detection techniques should be improved in terms of speed, power quality and costs.	[48–50]
Technical barriers of SGs	(1) Handling large amounts of data requires more investment and knowledge; (2) QoS should be guaranteed; (3) Communication protocols and standards should be updated.	[51–59]
Design framework	Design frameworks need to be updated according to innovations and the impact of human decisions should be added to frameworks.	[60–68]
Need for assessment	(1) Inaccurate assumptions and data deficit due to privacy and security concerns; (2) Assessment metrics can be influenced by external conditions.	[69–76]
Regulatory and policy barriers	(1) Unclear contractual agreements between market actors; (2) High risks for investment and a lack of financial resources; (3) Privacy and cybersecurity should be ensured by adhering to confidentiality, availability the and accountability of data; (4) Inclusion of RESs endangers the interests of system operators and traditional generators; (5) Lack of incentive for consumers to produce flexibility.	[4,6,17,77–106]
Social acceptance barriers	(1) Social acceptance comes in many forms, i.e., community acceptance, socio-political acceptance and market acceptance, and involves more than the persuasion of local residents; (2) Social acceptance at community level depends heavily on identity and members' behaviour, and their active involvement in projects.	[3,90,107–127]
Institutional barriers	(1) Lock-in and inertia to change the power system structure; (2) Difficulties in decision-making and investment; (3) Issues with interaction, involvement and coordination between stakeholders regarding the management of energy flows; (4) Local communities lack capacities and have difficulties in making serious investments.	[116,126,128–134]

3. Technical barriers

While MGs and SGs share various common technology challenges, some of these are exclusive to MGs because of their exceptional capability to work in islanded mode [27]. With regard to SG technologies, Information and Communication Technology (ICT) has been identified as the central element that facilitates the bidirectional flow of information and real-time data process [56]. In addition to technical factors, this section is followed by addressing the importance of possible design frameworks for optimal interoperability and by addressing technology assessment problem.

3.1. MGs control

The development of sophisticated power electronic interfaces has supported the emergence of MG. Most of the RESs units connect to MGs via these power electronic interfaces. These power electronic devices play a critical role in meeting grid requirements in terms of reliability because RESs can potentially undermine reliability of MG due to their

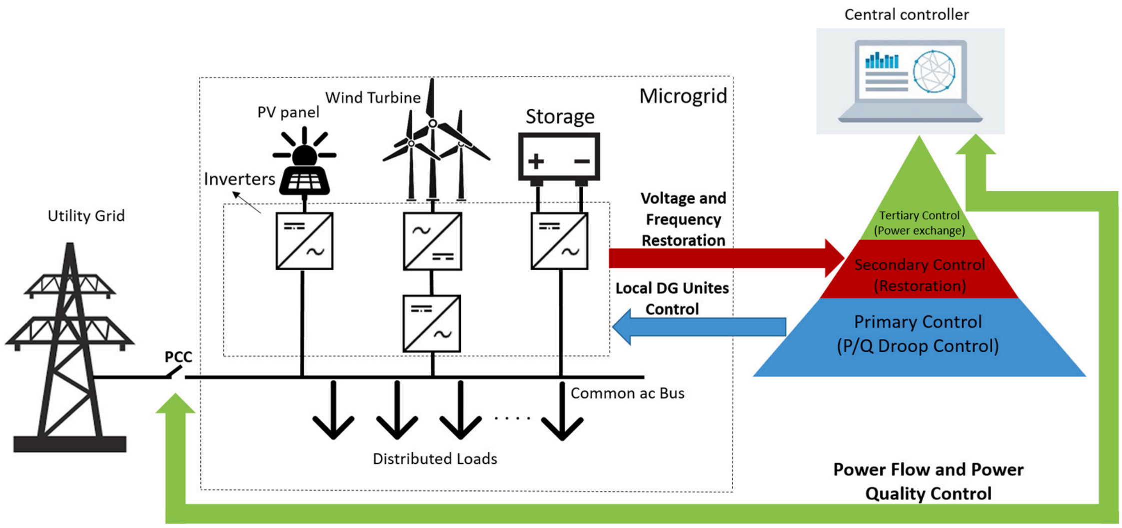

Fig. 2. Principal of hierarchical controller.

intermittent nature. Inverter-coupled RESs, on the one hand, contribute to stability by coordinating RESs and on the other hand, facilitate providing ancillary services such as peak shaving and reactive power compensation [39].

Using drooping characteristics of generators, voltage and frequency can be maintained within the prescribed range when many generation units work in parallel, as in synchronous generators in a traditional electric system [39]. Similarly, in an MG, parallel-connected power converters allow many DG units to function together. As a result, droop control can be used to alter the amount of active (P) or reactive (Q) energy allocated to the system by each DG unit [34].

Droop control methods in MGs adopt reactive power–frequency ($Q-F$) and active power–voltage ($P-E$) to improve load sharing [34]. However, the droop method has also drawbacks. In islanded mode, the voltage and frequency are profoundly affected by loads and the nature of the distribution line in MGs. Therefore, there is always a trade-off between better load sharing and voltage frequency deviation, which, in turn, results in adding a secondary control level to restore voltage and frequency deviations [35].

A secondary controller's conventional approach is to sense the key parameters (i.e., voltage and frequency) in common bus lines. The output of the secondary controller is sent to each DG control units to restore the reference values. This two-level control strategy has been completed by adding a tertiary control level responsible for governing the power flow between the MG and the main grid, for economic optimisation based on the energy price, and optimising power quality at PCC through data exchange with the system operators. Fig. 2 shows how a hierarchical controller works in a decentralised manner with each DG unit controlled depending on the local measurements [37].

To design MGs control, it is crucial to have a flexible controller with a plug and play feature. This means that generation resources can be easily added or removed from the system [38]. A decentralised controller has to be flexible for this purpose, but the design is complicated [37]. In addition, the current MG controllers are designed and tested for radial MG topologies, and meshed topologies need further research [10].

The last point here is that DG units, unlike traditional bulk generators, do not offer natural considerable rotational inertia [41]. Low inertia has implications for frequency dynamics and stability, particularly in an islanded mode. This is due to the fact that frequency dynamics is considerably faster in MGs with low rotational inertia.

Wind turbines (WTs), unlike photovoltaic (PV), have rotational kinetic energy to help maintain frequency stability in MGs. However, because the rotational element of the WTs is isolated from the rest of the system by converters, it cannot provide instantaneous frequency response. The virtual inertia technique is being used to increase frequency control [40]. However, because it requires reserving a portion of available power to maintain frequency, WTs cannot operate at full capacity. Furthermore, the virtual approach must be improved in terms of response time [36].

3.2. Protection

One of the biggest challenges in developing MGs is malfunctioning of protection schemes [42]. Relays in traditional distribution systems work with fixed settings but this type of protection scheme does not operate appropriately for MGs [11]. Fault currents in MGs change according to the location of the faults and fault current capacity of power inverters [42]. In general, the minimum required fault current in MGs is not available for accurate fault detection. Moreover, fault current reduces significantly in the islanded MGs mode, so the overcurrent relays that already set to work with higher fault current may not operate sufficiently [43]. Any delay in updating the relay settings during islanding or synchronisation will lead to MGs blackout. In the grid-connected mode, the substation transformer provides effective grounding. However, this transformer is not available in islanded MGs. The current possible solution is to use inverter-based DGs with transformers in grounding configurations [46]. Other studies [44] proposed new adaptive protection schemes in which the relay settings can be adjusted based on received signals from control systems. These solutions require high investment costs and extensive communication networks. In addition, current protection devices, such as fuses and circuit breakers in DC MGs, faces serious challenges due to the absence of both a grounding system and the zero crossing current [45]. Consequently, any created arc as a result of interruption in the current of DC MGs can hardy be extinguished [33]. To solve the problem of current DC circuit breakers, solid-state circuit breakers (SSCB) have been developed based on semiconductor technology. These devices are feasible options when there is a strict protection requirement. However, they can impose more power losses on the system [47].

3.3. Islanding detection

The islanding of an MG can be categorised as intentional or unintentional depending on their occurrence. The main focus in islanding detection is on the unintentional (unplanned) one because it can distort power quality and the reliability of the electric system [48]. Some standards secure operational requirements. For instance, IEEE 1547 specifies that MG disconnection must not exceed a maximum of 2 seconds [49].

Passive, active and hybrid islanding methods are recognised in the literature. Passive methods are based on measuring and monitoring critical parameters such as voltage, frequency, or voltage and current harmonics at PCC. These methods assume that the measured parameter does not exceed predefined thresholds [50].

In active techniques such as Active Frequency Drift (AFD) and Active Frequency Drift with Positive Feedback (AFDPF), a distorted waveform is injected into the system at the PCC. If the MG works in grid-connected mode, the frequency and voltage will remain unchanged due to the stability of the grid, but the voltage or frequency will be drifted up or down in the islanded mode [50].

These different techniques are proposed because proper islanding should fulfil different criteria simultaneously. For example, one of the critical criteria is the non-detection zone which refers to the thresholds of active and reactive power in which islanding cannot be recognised. The second important criterion is the run-on-time which determines the time between opening the circuit breakers at PCC and disconnecting the DGs inside the MG. These criteria are currently hard to apply to the real MGs sufficiently because they have several kinds of DGs with various parameters and are connected to the same PCC [48]. As explained in Section 6 this is problematic in real-life experimentation when islanding techniques for MGs and anti-islanding systems of DGs should work together.

3.4. Smart devices and requirements

From a technical perspective, a successful transition towards a modern power grid is not achievable without smart infrastructure development. The Joint Research Center (JRC) [51] compiled an inventory of the main SG laboratory activities representing trends in the SG domain and the need for further developments. The report implies that pioneers in the field of SG in European countries work extensively on ICT and Advanced Metering Infrastructure (AMI), grid management, electromobility, and smart homes. Wireless technologies, vehicle-to-grid and charging modes, and monitoring techniques were of particular significance to the majority (about 80%) of SG laboratories. And the activities did not show any consensus on the standards used.

Based on a study conducted by the US National Energy Technology Laboratory (NETL) [52], sensing measurement, advance component, integrated communications, Improved Interfaces and Decision Support (IIDS) and advanced control methods form the main pillars of Smart systems. Although these requirements are essential for the realisation of SGs, they cannot guarantee the grid's faultless performance because the infrastructure mentioned above should also have some specific requirements:

1. In a SG equipped with a large number of sensing and measurement devices, the amount of data generated will be considerably higher than the current grid because consumers, generators and distribution systems will generate a large amount of data. Handling the data can by installing additional communication capacity or by data management [53]. An approach proposed for data management is to transform the data into knowledge. This transformation requires specific expertise and techniques that are currently not available [12].
2. The communication infrastructure and networking technologies should have guaranteed Quality of Service (QoS) covering the whole range of the electric system from generation to end users. To detect failures and respond to disturbances, the infrastructure should be reliable, robust, scalable and cost-effective [54].
3. The communication standards and protocols used in SGs should be modified. With current standards, it is challenging to support interoperability between various parts of the electric system. The establishment of worldwide and perhaps open standards could accelerate the penetration of SGs [55].

If these requirements are met, it would be possible to use reliable big data. How this data provides benefits and whether electric utilities are interested in acquiring and storing data depends, however, on their business models. Big data certainly has the potential to control and monitor the system in an optimised manner by, for example, load control, energy management and event detection. However, the best analytic and proper business strategy would have to be implemented to achieve the maximum benefit from digested and stored data [57]. In fact, the potential benefit of SG data exceeds the capital cost of the installation of data generation technologies. Aggregators, consumers and system operators are, however, often reluctant to deploy these technologies because business models taking big data and SG data into account have not yet been developed. In the absence of these business models, investment levels are unclear and lack an effective strategy to integrate data analytics and transfer raw data to meaningful information in operational and decision-making levels. Consequently, current low investments in grid modernisation with smart technologies reinforces stakeholders' inability to handle data economically [58].

Although business strategy plays a salient role in investment for the digitisation of systems, cutting edge technologies also have the potential to significantly reduce costs in data processing flows. In this regard, the Smart Solid-state Transformer (SST) is an Internet of things (IoT) technology that can perform multiple functions such as providing real-time communication and the intelligent management of energy flows. It thus reduces the need for other smart devices in the acquisition and integration of data. Similarly, self-controlled converters can combine grid data with maintenance data and act as an asset management technology to monitor, detect, predict and even mitigate the problems without human interference [59].

3.5. Need for frameworks to reduce complexity in design

SMG designers and project developers have to deal with the complexity of stakeholders' heterogeneity involved in projects. The technical requirements of each stakeholder should be met in relation to others [11]. An absence of structured knowledge in the domain of SMGs design has already been recognised in the majority of demonstration projects. A useful approach to coordinate stakeholders in SMG is to rely on communication infrastructures. Such infrastructure and specifications for different aspects of SMGs (e.g., home era communication, market communication and distribution network) are accessible due to the presence of the advanced ICT [60]. The US National Institute of Standards and Technology (NIST) combined the communication elements and proposed a framework consisting of seven domains [61].

As illustrated in Fig. 3, electricity operation forms the heart of this model and is responsible for reliable and resilient power system operation. Operators carry out this task using SCADA, EMS or other control and monitoring systems. Received data from operators is utilised for voltage and frequency regulation or other similar purposes in markets. Service providers as brokers provide customers with electricity services (e.g., billing) [62].

The bulk generation domain connects the generators to distribution systems through the transmission system but coordination between generation, markets and operations domain is needed to measure the power flow. The transmission domain mainly aims to reduce losses and stabilise transmission lines and transformers. Moreover, having an interface with markets leads to the provision of ancillary services. The distribution domain has connections with operations, transmission, markets and consumers and plays a central role in supporting and managing consumption and generating real-time data used in markets. The last domain consists of end users in various forms (i.e., industrial, commercial and householders). Definitions of customers in SMGs differ

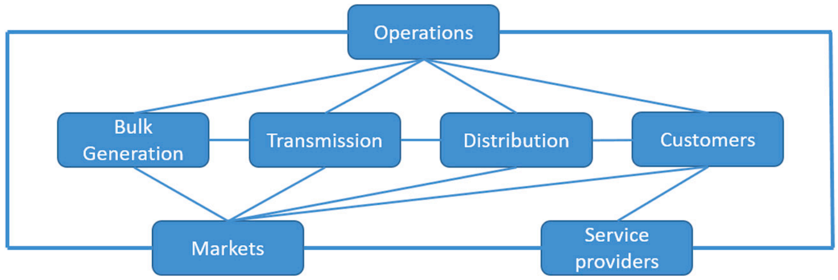

Fig. 3. The NIST seven-domain framework for SG.
Source: adapted from [61].

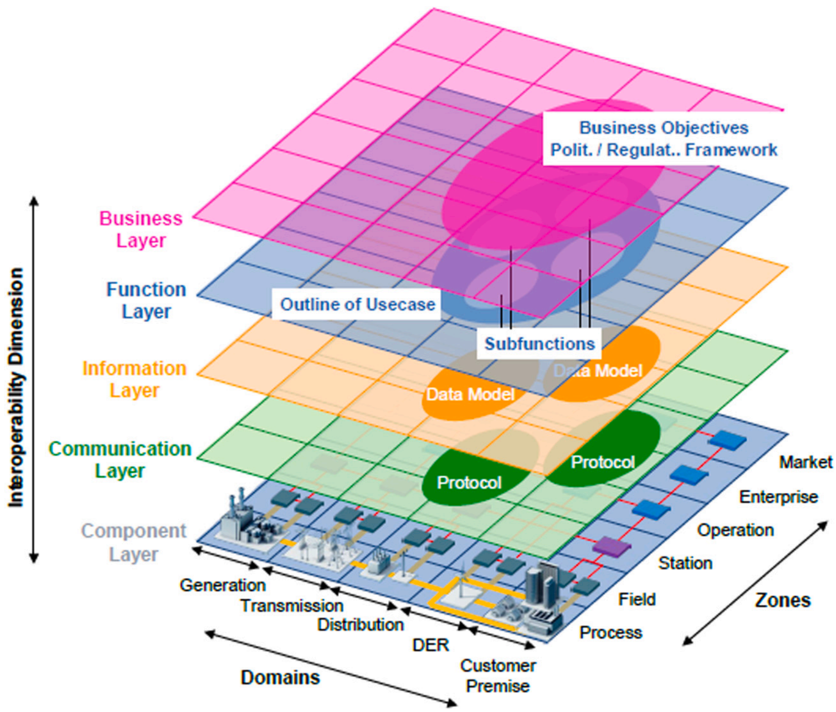

Fig. 4. Smart grid Architecture Model (SGAM).
Source: adapted from [66].

from traditional costumers in the centralised electric system because distributed generation, storage devices along with ICT can be integrated into this domain [63].

Another serious attempt to reduce the complexity is made by the coordination of ETSI (European Telecommunications Standards Institute), CENELEC (European Committee for Electrotechnical Standardisation), and CEN (European Committee for Standardisation) where a developed framework supports the European Smart Grid plans [51]. The finalised version of this framework is called the Smart Grids Architecture Model (SGAM) (see Fig. 4) which accelerates the process of development and facilitates the enhancement of standards. This three-dimensional model is built based on concepts of interoperability and tarpaulin (plane). It completes the NIST framework by adding new elements aligned to the automation pyramid.

The SGAM plane consists of two dimensions, namely Zones and Domains. Zones reflect power system management levels, and Domains represent the electricity energy supply chain. Aspects of communication, information, function, and business are combined in the third dimension, and each aspect is considered in an individual plane [62]. Although SGAM is highly accepted within the SMG community [62], continuous innovation needs updated models. The successful expansion, design and implementation of SMG projects depends on effective interoperation [65]. This is a demanding task due to the number of actors and elements in SMG and the dynamic behaviour of elements that increases the system's complexity. In certain studies, the concept of "System of Systems" (SoS) is used to describe the attributes of such a system [64]. For many years, the SGAM model's utilisation has shown that the dynamics of elements and the complex nature of SMGs brings about unexpected behaviour that is hard to reflect in such models. To avoid the undesirable effects of unpredictability, researchers advocate the combining of different models [65].

The SGAM model and the NIST framework exclusively address the technical aspects of SMG systems and ignore the impact and role of human decisions on the behaviour of such systems [67]. Furthermore, the SGAM model uses a non-semantic and static approach. The former means that there is no common understanding and vocabulary among the layers and domains. Therefore, it is unclear how to transfer and exchange data in transparent ways, for example, with customers. The latter implies that the time dimension is not considered in SGAM. Consequently, the transient effects of the ICT infrastructure and the effect of changes in smart electric systems cannot be communicated properly [68].

These shortages in the SGAM model are rooted in the heterogeneity of data and protocols as well as the methods that are used to analyse and interpret data that can be adopted. A possible approach to dealing with the heterogeneity between layers and domains is to implement web technologies, particularly Ontology Web Language (OWL) and combine them with standards such as IEC 61850 and IEC 61968 to collect and exchange data from different applications using different interfaces [62].

3.6. Need for assessment

Examples of failure in SMG projects can be found globally. Most premature failures happen in the early phase of the operation and are mostly linked to short-sighted policies towards high-tech projects [69]. Politicians may misuse the number of installed high-tech projects, including SMG projects as an instrument in their party manoeuvres and influence public opinion with impressive statistics [70]. This explains the lack of quality where projects are not supported financially to assess the project outcomes, so the quality of the project will deteriorate [70]. Consequently, no one will take responsibility for failed projects, and the reputation of the technology will be damaged [69].

The project promoter will not be able to prove the viability of projects and such projects will potentially not be entitled to further funding [76]. In contrast, the proper evaluation of outcomes leads to, first, legitimised projects that can benefit from future funding. Second, it leads to the establishment of trust and responsibility among all the actors involved. Third, it confirms the implemented technologies or innovations. Finally, it resolves the conflicting visions and expectations among the actors.

Prior to implementing any assessment, it should be considered that this is a daunting task due to many serious challenges [70]. Having a reliable evaluation is a matter of proper assumption and data accumulation. Experiences of former assessments indicate that the impact of variables on the final results varies in different time intervals. This is particularly noticeable in a Cost-Benefit-Analysis (CBA) where factors such as discount rate, estimated inflation, the energy price, carbon pricing, and tariffs are significantly time-variant [71]. In other words, if the projects last for a long time, which is the case for many SMG projects, the accuracy of the assessment will be affected.

Another acknowledged argument is the interpretation of the results. Sometimes the key performance indicators (KPIs) do not show tangible improvement but this can be deceptive since KPIs depend on external conditions. For example, environmental KPIs depend on the amount of energy generated from renewable distributed generators, and this directly depends on regulation and policies (e.g., incentives for DGs to sell their energies inside the SMG, and not to the main grid) [72].

The final point in this regard is that of data deficit due mainly to privacy or security concerns. In such circumstances, the evaluation will be based on expert judgment, and the accuracy of this judgment is not always reliable [75].

3.7. Summary of technical barriers

To summarise, the technical barriers to SMG development can be classified as: (i) barriers to MGs in particular; (ii) barriers to SGs in general; (iii) the design framework; and (iv) barriers to the assessment of SMGs. Barriers to MGs pertain to a complicated design of decentralised controllers with plug and play, a lack of inertia in DG units, malfunctioning protection schemes, the need for the development of further control methods for meshed topology, a lack of grounding system in DC MGs, and outdated islanding detection techniques in terms of speed, power quality and costs. Barriers to SGs pertain to the need for increased knowledge and investment to handle higher amounts of data, QoS yet not being guaranteed, outdated communication protocols and standards. Design frameworks do not yet include novel SG and SMG functionalities and need to be updated, and do not yet deal with the potential impact of human decision-making. Finally, current assessment frameworks use inaccurate assumptions and have data deficits. These are to some extent related to short-sighted, politically influenced evaluations of high tech SG projects, but also to privacy and security concerns. And assessment metrics can be influenced by external conditions influenced by political agency, in particular selecting and using certain KPIs.

4. Regulatory and policy barriers

Categorising regulatory barriers is not straightforward because regulations influence actors in energy markets in different ways. A tangible example is the integration of RESs in an electric system where support schemes try to increase the share of RESs. However, allowing RESs to connect to the network without considering connection point in terms of transmission and distribution capacity may require network reinforcements and excessive additional costs for system operators. Conversely, any undue restriction brings about economic barriers for RES providers [77].

Previous studies mentioned regulatory challenges for liberalisation and competition, the sharing of energy and ownership, interconnection with the larger energy infrastructure and the integration of renewable energy [6]. These categorisations do not cover the interactions between actors or the side effects of regulations.

Therefore, we adopt a different approach based on the challenges encountered concerning the creation of SMG markets [79] (i.e., investment barriers) and the challenges of SMG markets' healthy functioning [80] (i.e., performance barriers). Investment barriers are directly linked to a lack of incentives that demotivate actors from participating in energy markets [78]. On the other hand, performance factors address issues that lead to the malfunctioning or even the collapse of the markets. These factors are attributed to unregulated markets in terms of responsibilities, financial agreements, cybersecurity and privacy issues. Table 2 presents an overview of performance and investment barriers.

4.1. Market structure

Based on [81], Fig. 5 illustrates a simple schematic of how SMGs potentially work in electricity markets. It has four levels related to certain actors and their role in electricity markets; i.e., as prosumers, aggregators, markets, and as operators. The local SMG market is the first place for trading electricity. If the required infrastructure for such a market is already in place, not only will the local prosumers enjoy its benefits, but the system operator will face less congestion and overloading issues in distribution lines. However, this is not the case for most of the SMG plans because the mechanism of peer-to-peer trading is not available globally [82]. Real-world examples of such mechanisms include the blockchain-based MG energy market in Brooklyn (US) [104], the Piclo platform in the UK, and a project at De Ceuvel in the Netherlands, but this is far from the way today's market models operate [82].

Some agents work as mediators between prosumers and the market level at the aggregator level. The actors at this level are the same as those found in the traditional electricity market (i.e., Balance Responsible Parties (BRPs), energy suppliers) with the expectation of aggregators as the new market entrant [94]. The existence of aggregators is on the grounds that prosumers may not be able to put small chunks of flexible generation and consumption together as a tradable product on the electricity market [95]. Various combinations and arrangements of actors at the aggregator level are proposed but how this is optimised with minimum conflict with other actors integrating aggregators into the electricity markets is debatable [83].

Small electricity producers can participate in the retail market to support network operations when the network faces an energy imbalance. Moreover, SMGs bulk generators may participate in the wholesale market and offer their energy resources to TSOs. In both

Table 2
Classification of barriers to SMG market uptake [79].

Performance barriers	Description
Imperfect market	Property rights are poorly defined (e.g., unclear financial adjustment between end users, suppliers, BRPs and aggregators)
Incomplete information	Market parties do not have access to (perfect) information (e.g., how flexibility is handled and distributed in networks, and who should have access to this data)
Imperfect competition	One or only a few parties have, and exercise, market power (e.g., a lack of intermediaries at aggregator level can lead to an oligopoly of aggregators)
Cybersecurity and privacy issues	Consumers do not engage in the market when privacy and cybersecurity are not taken seriously. Polices should ensure confidentiality, reliability, integrity and accountability of information
Investment barriers	Description
Uncertainty	A high degree of uncertainty about future revenues and costs (e.g., unclear and sometimes negative outcomes from CBAs, and uncertainties related to energy costs)
Lack of incentives for consumers	Marginal costs (e.g., the carbon price is not reflected in the overall electricity pricing) Dynamic pricing schemes do not show conclusive results across different countries
Conflicts between market actors	Undue arguments against DGs from utilities Integrating more RESs exposes distribution system to additional costs Lack of infrastructure for local trading inside SMGs The fast phasing out of traditional generators may lead to a lack of energy capacity Net metering schemes can lead to unfair cross-subsidisation of consumers to cover utility service costs FIT schemes can be terminated or changed offering lower and unattractive tariffs to DG RE producers. Moreover, they can also have a long-term negative impact on energy markets, becoming very costly in the end

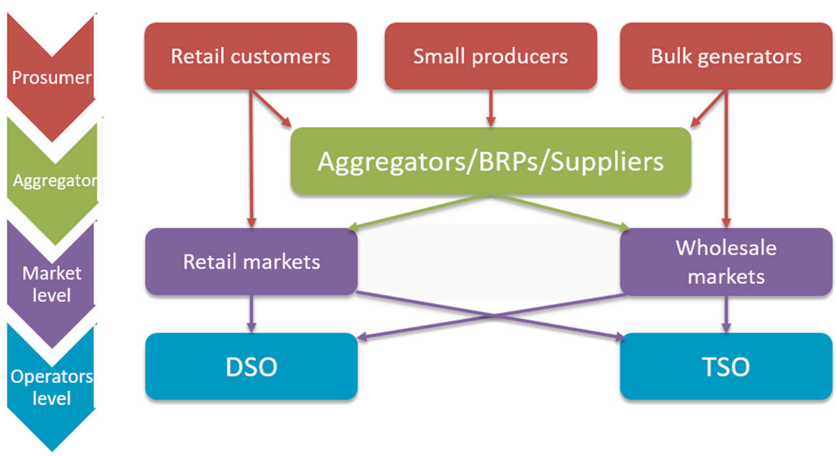

Fig. 5. Overall market structure of SMGs.
Source: adapted from [81].

retail and wholesale markets, BRPs are responsible for balancing energy production and consumption within their portfolio.

Finally, DSOs and Transmission System Operators (TSOs) confirm the information about maintaining the balance between supply and demand at the operators level [96].

4.2. Market performance barriers

Having the SMG market structure in mind, the current structure of SMGs is incomplete because contractual arrangements and financial adjustments are unclear [98].

To begin with, prosumers and their interactions with suppliers and aggregators need to be reconsidered [29]. Laws and regulations stipulate consumers' rights and support them in energy markets. However, it is unclear whether these laws and regulations apply to the relationship between aggregators and consumers [97]. In a simple arrangement at the aggregators' level where aggregators, BRPs and suppliers work independently, consumers will have two different contracts with suppliers and delegated aggregators. These contracts may infringe with each other if their terms and conditions are not coordinated nor aligned [29].

Mismanagement of the flexibility created by aggregators can lead to an incomplete market. TSOs and DSOs should be able to confirm selected and activated flexibilities, particularly when congestion occurs [97]. How aggregators distribute flexibility data in electric systems remains unclear. In regulated markets, BRPs and suppliers are financially and technically responsible for balancing supply and demand [99]. However, it is argued that the aggregators may cause imbalances by creating and distributing flexibility that is not aligned with BRPs and suppliers' activities. Aggregators may, therefore, have to pay compensation to them [81].

Even though the presented market structure in Fig. 5 is assumed to be competitive because of the coexistence of multiple suppliers and intermediaries at the aggregator level, it may still face imperfect competition. For instance, considering the aggregators' uncertainties, there will be an insufficient number of entities acting as aggregators, which runs the risk of developing an oligopoly of aggregators. This could have implications for the aggregators, particularly regarding sharing their profits from activated flexibility with consumers [83].

4.2.1. Cybersecurity and privacy issues

Market penetration of sensors, smart meters and ICT are necessary to exchange data between other systems and devices. However, this inevitably paves the way for exposure to denial-of-service attacks, viruses, malware, phishing and other forms of cybercrime. Also, regular measuring and analysis of costumers' energy consumption patterns by smart devices may violate their privacy, and raise security issues [12].

This may scare customers away from participation in demand response programmes.

It is, therefore, evident that protection and defence systems should be continuously upgraded with communication protocols and standards, but adopting the required policies and regulations in SMG markets should not be taken for granted. In general, policies should be deployed to incentivise cybersecurity innovation, clearly define the responsibility of actors in data management, improve privacy regulations and facilitate public–private collaboration [105]. To reach these goals with consistent policies the NIST in the US, for example, asks responsible parties to comply with a set of criteria [85].

First, the ‘confidentiality’ criterion requires personal privacy and proprietary information to be accessed only by authorised entities. The usage information pattern between costumers and aggregators must be protected and handled in a confidential manner. Otherwise, this information can be used for malicious purposes such as theft.

Second, reliable and timely access to information has to be ensured. This is referred to as ‘availability’. For example, if the information flow is blocked in the data network, there is an increased likelihood that the control system’s operation is disturbed.

A third criterion pertains to ‘integrity’. Information must be protected against destruction and modification. Lack of integrity means information can be altered in undetected and unauthorised ways. This can make SMGs vulnerable to attacks, with attackers seeking to shut down essential parts of the grid, for example by creating maximum voltage deviations. This can be realised by injecting active or reactive power into the grid. The risk of a successful attack increases when system operators cannot determine power injection integrity. Integrity of data is maintained if a legitimate source generates it. Finally, more protection against attackers is provided by increasing the ‘accountability’ of information. This means that each action performed by actors or devices can be traced and recorded. This allows grid operators to easily adduce information in court against attackers [85].

4.3. Investment barriers

Utilities and policymakers run CBA to decide whether to invest in SMG technology. The current SMG market is characterised by high uncertainty, perceived risks and a relatively long payback period. This is not desirable for (risk-averse) investors [79]. For example, the Belgian government ignored the European directive and postponed the deployment of smart meters because the evaluation of the smart meters rollout programme did not reveal a CBA positive outcome [80].

The issue at stake here is that although the results of CBAs are used, they can hardly be considered reliable. This is mainly due to the complexity of running a CBA on SMG technology in an immature market. A CBA can also only provide a monetary assessment. Other added values of SMGs in terms of city governance cannot be expressed quantitatively. For example, the electric system resiliency cannot be accurately estimated [100].

Moreover, large investors, such as DSOs and technology manufacturers will only invest in a risky and unclear market when regulations allow them to have higher remuneration rates, which is not the case in many countries [86].

In this regard, different incentive-driven policies have been adopted in the EU and the US. Broadly speaking, they can be divided into cost-based, incentive-based and hybrid-based regulations [79]. Most of EU member states like Germany and Spain, have adopted cost-based regulations in energy prices. This model puts a cap on operating expenditures (OPEX) [86]. Although utilities will enjoy a consistent and fair return on capital investments, it prevents them from reaping benefits. Therefore, cost-based regulations, which are mainly implemented in the form of Rate of Return (ROR), provide investors with weak incentives to reduce costs and increase efficiency because profits are linked to maximising sales.

Currently, most EU member states have switched to incentive-based regulations. This incentive works on the assumption that firms will improve their performance by taking advantage of available information [24]. The predominant types of incentive-based regulations pertain to the price-cap model, yardstick regulation, revenue caps and revenue or profit-sharing schemes [24]. Since this type of regulation can improve the OPEX, it can be implemented in combination with cost-based regulations and forms a hybrid model to deal with (capital expenditures) CAPEX and OPEX simultaneously [78]. As argued by [97], the general issue with these incentives is that they are only implemented in countries with buoyant economies like Germany, the UK, and Denmark.

In a broader perspective, two possible solutions are envisioned to address underinvestment in modernising electric systems with smart technologies. One approach is to reduce the risk of investments by engaging more actors along the value chain, for instance, by using a sharing mechanism, investment returns might be split between utilities and costumers. However, if the returns do not reach the target level, the net loss could be shared [86]. Another solution is the unbundling of the electricity network. Even though this takes place during the liberalisation of electricity networks, it might lead to a reduction in R&D on the short run because business firms are likely stick to their traditional business as usual activities. The consensus is that unbundling boosts investment eventually. In a fully liberalised electricity market, tasks, uncertainties and investment risks are not assigned to one single agent. And in such a competitive market, actors need to adopt a more innovative approach [106].

4.3.1. Incentives for consumers

Exclusively focusing on consumption and generation patterns of prosumers is the prevalent policy with regard to engaging local communities and consumers [87]. Concepts of DSM, Demand Response (DR) and flexibility are intrinsically related to this. However, flexibility has been used more recently to cover almost all aspects, including energy storage and ancillary services [88].

A major challenge for the activation of flexibility is the participation of consumers. The current pricing system discourages consumers from changing their consumption patterns because the marginal costs such as carbon price are not included [101].

To address the lack of incentive, dynamic pricing is proposed and implemented in some countries (e.g., Nordic, Estonia and Spain) [89]. Widely adopted dynamic pricing programmes such as Time-of-Use (TOU), Critical Peak Pricing (CPP) and Real-Time Pricing (RTP) allow for price differentiation between times of peak load and baseline demand [90]. The benefits of dynamic pricing are twofold. First, direct financial benefits for the costumers can be reflected in their energy bills. Second, by reducing peak demand, the use of expensive peaking facilities will likely be avoided and the average wholesale energy price will consequently be reduced [12].

In practice, records of dynamic pricing plans are not conclusive, though. Some dynamic pricing projects have experienced minimal positive outcomes, while others ended up with a considerable reduction in peak load [91]. The success rate of dynamic pricing can be attributed to social acceptance factors such as privacy concerns and consumers’ sensitivity to any tariff changes. Consumers also criticise policymakers for failing to provide transparent information about the exact advantages of dynamic pricing when comparing it to flat pricing [101].

4.3.2. Conflicting incentives between RESs, traditional generators and network operators

In general, current regulations allow utilities to impose rules, sometimes unduly, to supposedly ensure the system reliability [24]. Sometimes, this argument is used against the integration of RESs, for example, by regulators who suggest protecting the market from RESs by means of special taxes [92].

It is naive to dismiss the challenges of integrating RESs into the electrical grid. Nevertheless, many of the arguments against RESs are exaggerated. Creating understanding of grid operations and market structures can help regulators and policymakers to avoid believing and adopting these fallacies. Electrical grids as a whole are capable of providing reliable power generation all the time. However, this does not mean that each individual generator is always reliable which might be related to being involved with maintenance or other technical issues [92]. According to Silverstein et al. [103], the majority of outages (over 90%) occur in distribution and transmission levels and not in generation. Moreover, generators provide ancillary services (e.g., grid-balancing) as a byproduct. As more RESs are integrated and SG technologies are diffused, reliance on ancillary services can be increased. Thus markets can deal with the intermittent nature of RESs [92]. For example, PV, WTs, and EVs can play the role of traditional spinning generators and increase the operating reserve. Power inverters that are installed within these technologies can provide services such as reactive power compensation, voltage regulation, flicker control, active power filtering and harmonic cancellation.

From a utility perspective, the incomes of DSOs and TSOs derived from network tariffs or connection charges must be guaranteed. Consequently, DG providers could consider the option of local electricity trading inside SMGs [80,93]. In practice, however, many DSOs and incumbent energy providers oppose this alternative because of perceived losses in financial revenue. For example, DSOs expect to receive fewer Use of System (UoS) fees.

It has recently become more difficult for traditional generators to compete with other generators using RESs. Wind and solar DGs, on the other hand, have low operating costs, and do not need to purchase fuel. They bid lower prices on energy markets than traditional generators. Giving priority access to RESs exacerbates the situation for traditional power stations, which can be seen as a positive result of policies targeting the phasing out of polluting power stations, but it leads to power security risks, if this happens very quickly. In this respect, the Capacity Market is an alternative option for system operators when it comes to coping with reliability issues. This market works alongside the energy market and ensures sufficient generation or load-management capacity (e.g., with storage devices) when the system is subjected to stress [92].

The problem with creating the Capacity Market is comparable with fallacies encountered with the use of RESs. While market regulators consider the financial risks traditional generators encounter, and the early warning of possible supply interruption, it is hard for them to decide whether there are risks due to lack of capacity, and to what extent this is related to the use of RESs [92].

Compensation for DG is crucial to regulatory authorities [77]. The primary incentive schemes for DG/RES to participation in the electricity market are net-metering and the feed-in-tariff (FIT) [5]. In the net-metering scheme, producers of RESs obtain tradable green certificates according to their net energy consumption and production. Utilities often oppose these supporting schemes arguing that DGs and RESs do not pay the proportionate UoS fees for the utility services that they receive [5]. This results in unfair cross-subsidisation of consumers who do not possess RESs [17]. Moreover, depending on the price volatility in evolving markets, net metering producers may face uncertainties in terms of seeking revenue.

In contrast, RES producers can have investment certainty in FIT schemes by receiving a fixed price per unit of their supplied power over a period of time [102]. Although FIT has been proven to be an effective tool to accelerate RES and DG production, it is not without problems. Price adjustment mechanisms are the major challenges in setting a guaranteed price based on imperfect information. Setting prices too high may lead to eroded support for the scheme. This was the case in Germany where FIT was successfully implemented initially, but over time became less affordable with German taxpayers becoming reluctant continue to paying for it [102].

4.4. Summary of regulatory barriers

To summarise, there are multiple issues with policy and regulatory frameworks that hamper SMG development. First, there are unclear contractual agreements between market actors. Second, there is underinvestment by market actors because they experience high risk on the one hand and a lack of or no access to sufficient financial investment capital on the other. Third, there are multiple risks regarding handling, storing and sharing data. This is related to risks related to cybercrime, privacy and confidentiality issues, but also to the accountability and availability of data. Fourth, DSOs and traditional power generators (i.e., electricity market incumbents) have little and conflicting incentives to invest and experiment with SMG innovations. DSOs, for instance, are restricted by law to explore and test certain functionalities of SMGs like energy storage options. Finally, there is a lack of economic incentives in domestic electricity markets to implement flexibility. For example, pricing mechanisms in domestic electricity markets do not reward it, and although household prosumers are allowed to use self-generated electricity or feed it into the electricity grid in many Western-European countries they are not allowed by law to sell it to their neighbours.

5. Social acceptance and institutional barriers

5.1. SMGs as common pool resource

Public acceptance has been used as an indicator of social acceptance since the introduction of RESs. The concept of public acceptance, which stresses aggregated individual acceptance, focuses on the individual energy-producing technologies [107]. For example, several studies have been conducted on the acceptance of wind [123], solar [124] and hydropower [112]. Although studies on social acceptance of RES production sites have enabled scholars to investigate spatial scale and local ownership factors, this approach is incapable of addressing SMGs' acceptance as a complex integrated energy hub [90].

Establishing SMGs is not a matter of one actor's or agency preference because SMGs include various activities such as generation, storage, ICT and control, and demand response in a locally distributed structure. To establish SMGs, collective action is required to address this complexity [109].

Collective action has been described [110] as a decision-making process in which all actors can reflect their interests in reaction to other actors. Institutional change is an essential precondition to creating collective action to establish an SMG environment. New institutional approaches towards social acceptance of SMGs deal with electricity as a Common Pool Resource (CPR), instead of a private economic good. The benefit of such reconsideration is to acknowledge the systemic character at hand, and to facilitate the process of policymaking leading to the removal of legal and institutional obstacles. The second advantage stems from features of CPRs where exclusion of each actor is difficult and exploitation by one user reduces resource availability to others [110]. The concept of CPRs implies that the decision-making process is not monocentric. Instead, different layers of actors shape governance in a highly polycentric and semi-autonomous manner with several decision-making centres. Such polycentric systems expedite cooperation and trust among actors and could stimulate innovation and the adoption of SMGs [111].

5.2. Acceptance at multiple levels in society

The most compatible model of social acceptance with CPRs is suggested by Wüstenhagen et al. [111], where socio-political and market dimensions are added to the community dimension (see Fig. 6). The socio-political level relates to policy actors and the regulatory authorities' role in providing productive policies in the form of laws and directives for acceptance of innovations and technologies at other levels.

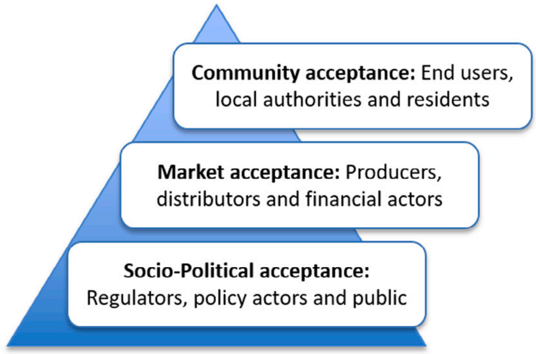

Fig. 6. Triangle of social acceptance of SMG technology at different levels in society [101].

At the market level, market actors accept SMG technology and invest, providing that policy actors set up conducive and non-discriminatory policies and regulations [111].

However, this model is criticised because it is not clear how different levels interrelate. More specifically, it cannot explain acceptance at the international, national and local scale [113]. Additionally, the role of acceptance through intermediaries is neglected. Intermediaries using their agencies and capacities, can influence the acceptance of innovations like SMGs by transferring acceptances to actors at other levels of governance. For example, building professionals and commercial building companies use agents (capability to act in SMG markets) and their capacities (knowledge of the value of SMGs for householders). However, their role is not included in the suggested model [114]. Finally, the role of communication is neglected. Knowledge developed at both the individual and collective level must be articulated. Without communication, knowledge is pointless. Communication about key innovations like SMGs is vital and is clear in theories like the social representation theory [112] and diffusion of innovation [135]. Attention is paid in these to explaining the process by which a new idea or technology is developed and revealed by communication among actors. Communication should be included in the model because different levels may use different communication channels due to their different social positions.

5.3. Acceptance of SMGs and community energy

The concept of community energy is widely used to describe energy-related communities and projects they develop and operate. However, the concept of community SMG, as in social communities engaging in and running SMG projects, needs more elaboration as only a few studies have attempted to define it [115]. Two dimensions of community energy are suggested in the literature [116]. First, it is important to address who develops and runs community energy projects (i.e., the process dimension). Second, it is important to consider who is influenced by these project outcomes (i.e., the outcome dimension).

Hana [117] discerned three commonly used terms that determine the meaning of community energy: (i) community as stakeholders, which refers to significant stakeholders in decisions and the implementation of energy initiatives; (ii) community as a space or place, which relates to space where collective action happens; and (iii) as a shared interest or vision, which is about groups of people with shared interests and visions. Linking these dimensions to SMGs, the following can be derived: social and economic dimensions of SMGs can be seen as the core focus in defining community SMG regardless of technologies used in SMGs.

Warneryd [126] provides the most suitable definition of MG community as: "A community microgrid is technically a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries which acts as a single controllable entity with respect to the grid. A community microgrid can connect or disconnect from the grid to enable it to operate in both grid-connected or islanded mode. Moreover, a community microgrid is connected with its community through physical placement and can be owned by the said community or other parts". However, this definition does not reflect the features and benefits of SGs to communities. A community SMG can deliver carbon savings, increased grid stability and cost savings for the stakeholders. According to the International Energy Agency (IEA), these potentials can be unleashed by advanced digital technologies to monitor and manage the transport of electricity from all generation sources and storage devices to meet varying electricity demand. Therefore, in community SMG, interaction and the coordination of energy consumption between stakeholders is of key importance.

We contribute to the above definition of MG by drawing attention to the smartness of community and coordinated actions with the following:

"A community SMG is a self-sufficient energy network with groups of interconnected loads and distributed energy resources within clearly defined electrical boundaries. This community works based on information sharing and communication technologies, locally distributed renewables and demand-side resources. It should be cooperated to pursue system reliability, resilience and stability, to maximise market values, and minimise costs and environmental impacts".

We recognise two possible research avenues to study acceptance of SMGs in communities. First, by addressing ownership and involvement, and second by addressing community members' identity and behaviours.

5.4. Ownership and involvement

Implementing any energy project, including the use of SMG technology involves actors and ownership issues [109]. Ownership and involvement can result in the strong conviction of community members that the project serves their interests and offers benefits [115]. However, there is a need for more insight into the reasons and opportunities that foster communities' involvement and how involvement is encouraged.

To this purpose, community values should be considered. Historically, reliability and efficiency have been the central values in energy sectors. More recently, environmental sustainability concerns have gained importance [108]. Although energy produced from RESs addresses sustainability to a large extent, it endangers the supply and consumption balance. SMGs have the potential to make a considerable contribution to resolving this conflict, but some values in SMGs are only achieved at the expense of others [88]. For example, deploying monitoring and controlling devices might cause conflicts between values, like security and accountability of technology on the one hand, and privacy and democratisation on the other. Moreover, violated values cannot be compensated unless SMGs allow the community to be part of the decision-making process or to establish trust between the local community and project developers. Without 'sense of ownership', trust and involvement in decision-making cannot be taken for granted [119].

Community energy initiatives vary in terms of organisational structure. For example, they have different legal forms including public–private partnerships (PPPs), cooperatives and limited liability companies and some are even in municipal ownership. In practice, three local energy governance models can be discerned: 'remunicipalisation', 'revolution' and 'participative governance' [120]. Remunicipalisation refers to an increased role of municipalities in taking control of energy companies and energy infrastructures. Examples in Germany and France show that political parties are becoming more involved in local energy markets. Similarly, as showcased using the devolution model, local authorities and city councils have taken on the responsibility of supporting energy communities. This model, which is frequently observed in Scandinavian countries, eases the information flow and interaction between governments and local citizens. Although the models have certain benefits, they can neither increase the number of citizen-led energy projects or transfer national governments' power and opportunities to local energy producers [120]. In other EU countries including Germany, the Netherlands and Belgium, participative governance approaches are being used in which citizens are allowed to inform climate and energy policies (e.g., by involving in discussion forums and participative budgeting process). This leads citizen empowerment through partnerships and cooperatives (e.g., renewable energy cooperatives; REScoops) but also via housing associations [120].

Favourable outcomes of local community energy models are being jeopardised because relevant national structures like political support, financial requirements and clear rules to govern community energy activities are not in place. From a socio-political perspective, there is a lack of clear support and commitment. To this end, voluntary commitments have the potential to accelerate this process. The Covenant of Mayors is an example of a voluntary movement that the European Commission launched to support local energy authorities in 2008. By adopting this scheme, local authorities across the EU voluntarily commit themselves to promoting energy efficiency and implementation of RESs in their local jurisdictions [120]. However, similar movements are hard to find.

In practice, local community groups typically encounter financial barriers that endanger local energy projects. While upfront subsidies are available for many projects, they usually come with strict limitations, for example in terms of time. Nonetheless, a need for financial instruments remains necessary to support start-ups in local energy communities. A relevant example is the German KFW Bank that provides loans with preferential rates for local energy initiatives [121].

Finally, the importance of regulatory and legal frameworks with regard to the operation of community energy should be mentioned. In particular, terms and conditions for accessing the national electric grid should be clarified. In Ireland, for example, local communities are reporting uncertainties about connection of SMGs to the electrical grid as a major problem. And procedures to connect local energy projects that involve RESs are costly for small-scale energy communities [120].

5.5. Identity and behaviour of community members

The identity of geographical locations determines how members interpret values that are relevant to SMGs. Identity can vary depending on, among other things, social norms, income rates, the desire to adopt innovations and invest in them, and the type of enterprise involved [90].

Involvement of community members in SMG projects requires investments that vary according to the financial means available. End users with high income are expected to enjoy the benefits of SMGs more than others. Analysis of SMG demonstration projects with demand response programmes reveals that low-income households reap fewer benefits [127].

Moreover, members differ significantly in the amount of space they can offer RESs [128]. In addition to householders, other local stakeholders, such as schools, are important for community identity because they can provide more rooftop surfaces to install PV panels. Other examples pertain to hospitals and military bases where the importance of resiliency and the reliability of power require an independent operating power system for emergencies. They may also consider attuning their load profile with other stakeholders' consumption patterns [119]. The identity of a community is also influenced by the nature of the enterprises. The adoption of SMGs technology is meaningfully higher in communities where tourism is the main source of income [119].

Community identity is also linked to behavioural barriers and this is often explained by the aid of demand response [125]. Sometimes customers are reluctant to change their behaviour even when clear benefits are offered and the need for adoption is clear. This related to the notion of 'bounded rationality', for example with costumers resisting the adoption of controlling devices for consumption optimisation [3]. This is understandable from the standpoint of customers seeking utility maximisation. Penetration of demand response technology means loss of control over devices and costumers' comfort. Unpleasant experiences for the customer from poorly designed technologies may exacerbate the situation [122]. Another example of bounded rationality is linked to flexibility providers who sometimes avoid increasing flexibility and profit by installing storage devices. This can be interpreted by the risk involved in the development of the business because they feel it challenging to leave their comfort zone, and they are happy with the current profit [109].

Although community energy members' economic situations and identity are inevitable consequences of the class differences in society, some actions can mitigate it. For example, free access for all community members to information about SMG projects on the one hand and the active participation of end users in the decision-making process on the other are considered important to alleviating inequity [128].

5.6. Institutional barriers

5.6.1. Path dependency and lock-in

The 'rules of the game' in electric systems have historically been developed to support the incumbent centralised power system [128]. The existing pattern of rules, in the first place, consists of physical infrastructures of power systems that have materialised in a path-dependent paradigm, leading to a situation of 'lock-in' and inertia to change among incumbents. Accompanying change is challenging for incumbents because it is considered to violate the current way of working, and is not in line with current belief systems. Lock-in also applies to the use of information and data in the electric system's infrastructure. Metering routines, data collection methods and data provision for consumers are examples.

Wolsink [101] has discerned five categories of rules of the game that can lead to lock-in in community energy, i.e., (1) government policies and interventions, legal frameworks, government organisations in departments, ministries and agencies; (2) dominant technologies, including standardisation; (3) organisational routines and relations; (4) industry standards and specialisations; and (5) societal expectations and preferences

Considering this categorisation, some scholars (e.g., [129]) have analysed institutional lock-in using a decision-making process perspective, whereas others have used an institutional economic perspective (e.g., [115]).

5.6.2. Institutional economic barriers

By adopting the New Institutional Economics (NIE) framework, Minghui et al. [115] analysed government institutions and the structure of transactions in energy communities.

They hold that an institution's reconfiguration should be performed through transaction alignment and economising on associated transaction costs. After examining the relevant terms of applying SMG to community energy, such as ownership, governance and features of the contracts among parties, it has been suggested that the technical assets involved in SMG projects are often associated with idiosyncrasy, low frequency and uncertainties that have profound implications in the adoption of new governance structure, investment and ownership.

Investment in SMG assets is considered idiosyncratic mainly because they concern specialised equipment and can rarely be deployed to other uses or find alternative consumers outside the SMG. With the current institutional arrangements, investors view SMG assets as a sunk investment. Transactions in SMG projects are infrequent because stakeholders are not inclined to maintain long term relationships. Moreover, actors show opportunistic behaviour misuse the situation without worrying about their reputation [115].

5.6.3. Complexity of decision-making

The difficulty of decision-making regarding SMGs derives from assigning new responsibilities and the redistribution of power among electricity market actors. This may occur when designing institutional rules while using a participatory approach, instead of top-down policy making, to give a proactive role to community members, and stakeholders [131].

Researchers have developed theoretical frameworks as guiding tools that can eventually be used for system analysts and policymakers. An example of this is the Institutional Analysis and Development (IAD) framework that is used to analyse institutional settings [134].

To this end, Lammers and Hoppe [130] tried to establish 'which institutional conditions enable or disable decision-making processes regarding the introduction of smart energy systems' by applying the IAD framework to four SG projects in the Netherlands, and analysing institutional condition (e.g., rules in use) empirically. The results show that existing rules are not appropriate for SG development for a number of reasons. First, local community members, particularly householders, are usually not aware of plans for developing energy projects in their district. The disengagement of end users is consequently perceived as a barrier, particularly in the development and implementation stages of projects. Second, the formal and informal positions of the actors are not communicated in projects, and no specific project actor plays a key role in developing SG projects. This is also reflected in poor cooperation between actors and consortium members who take on a passive observer role in projects. These passive roles are also associated with legal barriers, which deter DSOs and property owners like housing associations from making any investment in projects. Additionally, despite providing subsidies for projects disagreement between project consortium members on sharing costs and benefits serves as a disabling condition. Following these insights the authors suggest that institutional conditions, including decision-making, should be evaluated in the early stages of project development to avoid setting over-ambitious and unattainable goals [130].

5.7. Summary of social and institutional barriers

In brief, barriers to the social acceptance of SMGs and local institutions are as follows. First, there is a need to acknowledge systemic, complex and polycentric character of SMGs. An SMG can be viewed as a CPR. Therefore, managing and implementing SMGs requires concerted collective action, not only action by an individual initiator or agent. When planning SMG projects, attention is required regarding the local situational context in which SMGs are to be implemented. This includes attention to addressing local acceptance of SMG technology. Acceptance, however, comes in many forms, i.e., community acceptance, socio-political acceptance and market acceptance, and involves more than just the persuasion of a number of local residents.

Next, the planning of SMGs in local projects needs to focus on institutional conditions and rules. This pertains to interaction, involvement and coordination between stakeholders concerning the management of energy flows. These conditions are, however, hardly ever met in practice. More insight into the reasons and opportunities that foster communities' and stakeholders' involvement and how involvement materialises is needed.

6. Interaction between barriers

The barriers discerned in the previous sections are based on extensive academic laboratory conditions, demonstration pilots (for technical barriers), theoretical and empirical studies (i.e. regarding regulatory and social barriers). To enrich the results, taking a holistic viewpoint is required to combine the findings from the literature study with actual case implementation studies. Analysis of real case experiments is critical because laboratory conditions are removed and the interaction between problems can be observed.

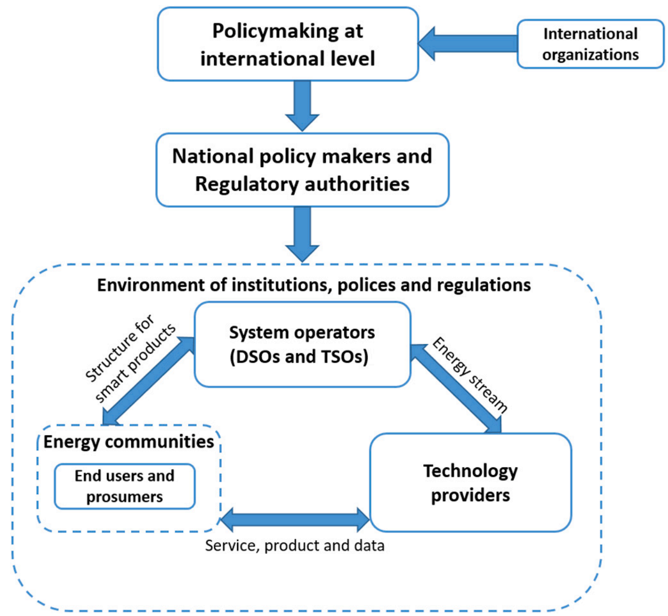

Fig. 7. Holistic picture of interaction between actors.

As depicted in Fig. 7, the interplay between actors has a hierarchical order starting from policymakers (e.g., at the UN or EU level). This level is responsible for setting targets and guidance. Internationally, global organisations, such as technology development organisations or knowledge development organisations, like the International Smart Grid Action Network (ISGAN), can influence energy policies by providing reports and data. After regional authorities adopt the policies at national level, there are interactions between technology providers, customers and system operators (e.g., DSOs and TSOs) that determine the extent to which the rules and policies are materialised [17].

In MG pilot projects (central) grid-connected or islanded modes are usually considered for regulatory reasons. This, however, ignores dual-mode switching. Similarly, most SMG pilot projects are restricted to small neighbourhoods with a low number of buildings or households. Therefore, controllers and protection schemes can be easily configured because there is only a small proportion of power grids within experimental project's boundary. In the Boralex project, in Canada [136], system operators confined the negative impact of SMG on the grid through standards and grid codes. Notably, in demonstration pilots such as Sendai Microgrid in Japan, DSOs imposed regulations against protection related issues in terms of anti-islanding [137].

Although most of the proposed solution discussed in Section 3.3 emphasised islanding detection at the PCC, in practice, inappropriate anti-islanding techniques applied to SMGs can lead to putting an unintentional islanded mode of some DG units inside SMGs into operation. This can lead to a negative effect in terms of neighbouring loads. This turns out to be most problematic in islanded mode cases when DG units inside SMGs use similar islanding detection systems [31].

On the other hand, system operators apply Low-Voltage Ride-through Capability (LVRT) requirements for generators to stay connected during a short period under-voltage conditions in the grid to prevent widespread loss of generation. However, analysing various LVRT experiments [138] reveals that time requirements of LVRT can vary between 150 ms and 1.5 s. This can be problematic because both anti-island mechanisms and seamless islanding detection methods usually act faster (310 ms and 10 ms, respectively).

In addition, SMGs ideally control the voltage range and frequency at PCC by adjusting the reactive and active power levels. However, system operators, for example, Am Steinweg MG in Germany, are reluctant to trade power with SMGs because it requires modification of a protection scheme at the distribution system [139].

In interaction between regulations, energy suppliers, and technical barriers in SMGs, the nature of the incentives for suppliers is problematic in practice. In brief, some financial incentives, such as time-invariant FIT, encourage DG units to work at a maximum operational capacity. Asmus et al. [140] show the implication that the initial SMG business model will turn into a DG business model. Therefore, other services such as the control functionalities of the SMGs to support islanded mode or energy management options will no longer be implemented.

Considering end users, analysis of a number of projects implemented in European counties [13] reveals practical reasons why adopting smart technologies and promoting DSM programmes are not routine practice yet. With current electric systems, the value of DSM is neglected by utilities. Common practice for solving the congestion problem is generating capacity and system reinforcement. DSM becomes a possibility only in some system segments with costly network reinforcements. On the other hand, current analysis shows that the operational complexity of dealing with DSM is relatively high for system operators. Some experiments [141] also show that the current network structures could not support multiple applications like AMI, ADA and automated demand response (ADR).

7. Conclusion

The present study was conducted in response to the need for a holistic and comprehensive overview of the barriers to SMG development and their interaction. This paper contributes to the body of literature on SMG innovation, notably by using a multidisciplinary socio-technical approach that considers all the relevant stakeholders, including technology designers, market actors, RES providers, system operators and consumers. This study identifies the barriers, and addresses them separately, and in terms of interaction.

In terms of the interaction of possible technologies and the interests of system operators, the coexistence of some technologies such as island detection to protect the grid and anti-islanding to protect some parts of SMGs is inevitable (see Section 3.3). However, there is serious concern that anti-islanding functionality can work adequately with current limited islanding detection methods. Similar problems occur when DSOs cannot apply their desired power control at the PCC because SMG is supposed to be an independent identity.

This issue is interwoven with market conditions and regulatory issues. For instance and as discussed in Sections 6 and 3.1, although hierarchical controllers have been developed and perform for MG, this controlling strategy is still unable to address DSO concerns about handling the provided active power (i.e., to determine who the potential buyer is). And there is also a lack of regulations for reactive power trading in most countries.

The present study found that the main problems for market actors are rooted in the fact that they are not motivated to invest in SMGs because this novel concept comes with many uncertainties and perceived risks. This is related to uncertainties in the value chain and because incentives like price caps are designed based on theoretical assumptions that are far from implementation conditions in reality.

Moreover, social acceptance of SMGs among local communities and end users suffer from a multidimensional problem between technology structures, regulations and institutions. Even though ICT technologies are presumably ready for DSM programmes, the electrical grids are not sufficiently prepared or updated to handle most SMG technologies. There are also incompatible standards that are not specified for different customers and regional areas. As ownership and involvement are considered at the community SMG level, business models cannot engage local communities in projects. Acceptance and the adoption of SMGs by local communities also requires changing end users' views and even behaviours while taking community members' identities, preferences and behavioural profile into account.

8. Suggestions for future research

The unanswered question is how policymakers could intervene to resolve the multidimensional problems discerned in the present study. Since SMGs can be applied or adopted differently according to regional requirements, there is a need for context-based analysis to study the inter-dynamics between institutions, technology and actors. Using an approach that only addresses attempts to solve or mitigate separate barriers falls short and leads to ineffective solutions. A broader systemic perspective of socio-technical innovations is required. Therefore, we suggest applying theoretical approaches and research methods from the Innovation Studies research domain to discern potential interventions to resolve these barriers. This could, for example, be done in line with a study by Negro et al. [142] who addressed the failures of RESs from an innovation perspective. Potentially, such an approach could be extended and applied to SMGs when viewing the latter as an integrated system innovation.

Global governance has recently emerged to facilitate the niche market development and adoption of promising technologies as a way to accelerate climate mitigation efforts. This governance approach is attempting to address the problems that technology providers or market actors cannot solve individually or at a national level because such problems go beyond national borders and require a cross-national response. This refers to collective problems that require experience, policy mobilisation and the inclusion of a wider set of governments and international actors. However, in the operational stage, actors involved in SMG niche market development come into conflict with each other due to, for example, resource scarcity and geopolitical issues. Negotiations, agenda-setting, monitoring, and the enforcement of agreements can resolve conflicts between nation states. This continuing process requires supranational institutions and organisations to manage affairs and accommodate diverse interests. Therefore, we suggest that future studies consider the role and influence of supranational institutions and intergovernmental agreements to address and resolve the barriers related to SMG research and development using international cooperation schemes.

CRediT authorship contribution statement

Farshid Norouzi: Conceptualization, Methodology, Writing – original draft, Investigation. **Thomas Hoppe:** Supervision, Validation, Writing – review & editing, Resources. **Laura Ramirez Elizondo:** Writing – review & editing. **Pavol Bauer:** Coordinator.

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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