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Unpacking the complexity of community microgrids: A review of institutions' roles for development of microgrids

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ABSTRACT

Community microgrids implemented in existing electricity grids can meet both development targets set out in the Paris agreement: 1. mitigate greenhouse gas emissions through increased implementation of renewable energy sources, and 2. to adapt to climate related disturbances and risk of catastrophes. Community microgrids are, however, complex to implement and institutional change is needed to reach their full potential. The purpose of this article is to review existing literature and analyze institutional developments influencing the growth of community microgrids. The literature describes a concentration of microgrid activities in specific regions: USA, EU, Asia and Australia. Varying reasons for implementing community microgrids were found in the different regions but similar institutional developments occurred, albeit with differing emphasis due to contextual specificities. Formal directions do however influence informal institutions even though their aims differ. Power utilities stand out as a critical actor and both formal and informal institutions put pressure on utilities to update their traditional business models. This article illustrates how informal and formal institutions play a significant role in the growth of community microgrids in existing electricity grids and provide interesting examples which can be utilized by policymakers. Microgrid development is still in a formative phase and further institutional change in the form of updated regulations is needed.

1. Introduction

The COP 21 meeting in 2015 resulted in a global agreement to tackle climate change, known as the Paris agreement. Two overall development actions were defined: the mitigation of greenhouse gas emissions into the atmosphere, and adaptation measures to meet climate change related disturbances [1]. Mitigation actions include replacing fossil energy with renewable energy. Adaptation actions include creating resilient infrastructures which will withstand in the event of extreme weather and disasters. In recent decades deployment of renewable energy technologies has increased extensively, with solar PV being the fastest growing technology [2].

Renewable energy varies with weather and time of day and as a result requires balancing to provide a reliable supply of electricity. There are different alternatives for balancing, one being locally implemented microgrids (MGs) which store and control the distribution of electricity and balancing effects [3]. Other alternatives include large-scale storage facilities and additional grid connections (cross-national) with enhanced grid capacity. These alternatives would be able to integrate more variable generation sources but would not affect local resiliency. MGs, on the other hand, can facilitate integration of more renewable energy as well as create local energy resiliency since they can operate in isolation from the larger grid and thereby respond to both development actions stated in the Paris agreement.

Historically, MGs have been implemented in remote areas as cost effective alternatives or the only alternative to a connection with the nearest larger grid. Further, to create energy infrastructure where none previously existed, such as in parts of developing countries, this is often done by building MGs. In recent decades as the use of renewable energy has expanded, MGs are increasingly also being implemented in existing electricity grids. These implementations are especially interesting from an institutional perspective, since the MGs compete with the traditional infrastructure based on large-scale power plants with long transmission and distribution lines to consumers. In addition, the organization and

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ownership of the grid infrastructure will be affected, and different types of implementations exist. Recently, MGs are often implemented at campuses or specific security areas such as military bases while MGs implemented in residential and mixed communities are rarer [4]. Still MGs suit the expanding implementation of renewable energy in those areas and could provide more control to e.g. urban communities. This implementation can be described as community MGs [5].

MGs implemented in existing electricity grids offer potential benefits but since they are in a formative development phase, they necessitate structural and institutional change to attain scale [6]. Transformations of energy systems involve both technical and social aspects with the latter including how users experience value from the new system and how they behave and respond to it [7]. In addition, the way related actors and networks are structured influences the development of the system, especially in the decentralized pathway [8] Research has further shown that social acceptance is key for energy system transformations [9–11]. Development of socio-technical systems can be analyzed with the help of theories on sustainability transitions [12]. Here social aspects are sometimes referred to as informal institutions in a technological field [13]. Formal institutions include laws and regulations which shape the implementation space of the technological field. Thus, change might be needed in both informal and formal institutions for community MGs to develop and diffuse.

Previous studies on the development of MGs are often technically oriented such as optimization simulations, e.g. Refs. [14,15] or specific technology simulations, e.g. Ref. [16]. Some studies have reviewed general issues, including institutions, around MGs [17–19]. However, these studies often lack the focus on social aspects and informal institutions, and on MGs being implemented in communities. Some case studies on community MGs do exist however, and these bring about specificities for certain cases, but lack the overall analysis on general drivers for community MGs and general institutional issues.

The aim of this article is therefore to review current literature to identify factors which contribute to the successful growth of community MGs implemented in existing electricity grids focusing particularly on the role of informal and formal institutions. The study addresses the following research questions: i) *Under what conditions do community microgrids develop? ii) What role do informal and formal institutions have on this development?* The focus is on the implementation of community MGs in existing electricity grids.

This article is structured as follows: Section 2 presents definitions of microgrids and community microgrids. Section 3 presents the conceptual framework used for the review and Section 4 the method. The results are presented in Section 5 followed by discussion and conclusions in Section 6.

2. Definition of microgrid and community microgrid

MGs have existed since the beginning of electrification in society. In the last hundred years, MGs can be found in remote locations serving smaller populations [3]. Rationales for MGs in history have been to cost effectively provide electricity in locations where transmission lines have been impossible or too costly to build. In recent decades new rationales have evolved and implementation is no longer limited to remote locations. A MG can be conceptualized by using the five critical functions presented by Abu-Shark et al. [20]: the nature of connection with the main utility, precise energy and power balance within the MG, energy storage, demand management, and seasonal match between generation and load. Fig. 1 presents a conceptual picture of a MG incorporating the critical functions. In addition, Appendices A-C provide further information of the included technologies in a MG.

There are various interpretations of what the concept of “community microgrid” means. Therefore, the two terms, “microgrid” and “community” will first be defined separately, then put together in order to show how this concept is used for the purposes of this article.

One of the most frequently used definitions of a MG is presented by the USA Department of Energy (DOE): *‘A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode. A remote microgrid is a variation of a microgrid that operates in islanded conditions.’* [33]. This technical definition clearly describes the functionality of a MG and can also be used to delimit the MG concept from e.g. a solar PV plus battery installation.

The term community can be derived from the concept of “community energy” which is frequently used to describe energy projects which are connected to specific communities. Walker and Devine-Wright [34] make a useful contribution to the definition of community energy, by suggesting two dimensions of community in relation with renewable energy projects: ‘*First, a process dimension, concerned with who a project is developed and run by, who is involved and has influence. Second, an outcome dimension concerned with how the outcomes of a project are spatially and socially distributed—in other words, who the project is for; who it is that benefits particularly in economic or social terms.’* Both these dimensions are not concerned with the technology itself, instead they focus on the social parts of the concept of community energy. Different community energy projects can end up being more locally owned by the community itself, or being more locally benefitting, and there are examples of both separated extremes or both combined.

Hana [35] describes three meanings of the term community found in community energy literature: community as stakeholder, community as space/place, and community of shared interest or vision. The first definition can apply since communities themselves can operate and implement the MG and thus act as a stakeholder, i.e. Walker and Devine-Wright’s first dimension on local ownership [34]. The community can also be a specific area defined in e.g. the utility’s electricity grids where a utility-owned MG is implemented and described as a community MG. Therefore, the ownership of the MG might differ from the community itself, a utility, or other private or public companies. However, for the third meaning it becomes apparent that community MGs can differ from general community energy projects. Since MGs physically are located in a specific area, communities as shared interest or vision does not apply to this article[1]. In a physical community MG the second outcome dimension by Walker and Devine-Wright [34] will therefore always be fulfilled, at least to the extent that the community is electrically served by the MG.

There have been some attempts to provide a specific definition of community MGs, see e.g. Gui, Diesendorf [5], which provide some specific features such as residential loads. In their definition, the community MG can however be isolated from the grid. Therefore, we choose to use our own definition for the purpose of this article.

Based on the definition from DOE [33], with an addition from the discussion provided by Walker and Devine-Wright [34] the following definition for community MGs will be used in this article: ‘*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 island-mode. Moreover, a community microgrid is connected with its community through physical placement and can be owned by said community or other part.’*

In addition, for the purpose of this article, only community MGs which primarily include renewable energy sources, but can include back-up generation from fossil sources, will be addressed.

[1] Virtual microgrids also exist in the literature, but commonly described as a way of controlling a normal grid in certain areas often with smart infrastructure; however, these virtual microgrids lack the potential to be self-sufficient or enter into island mode.

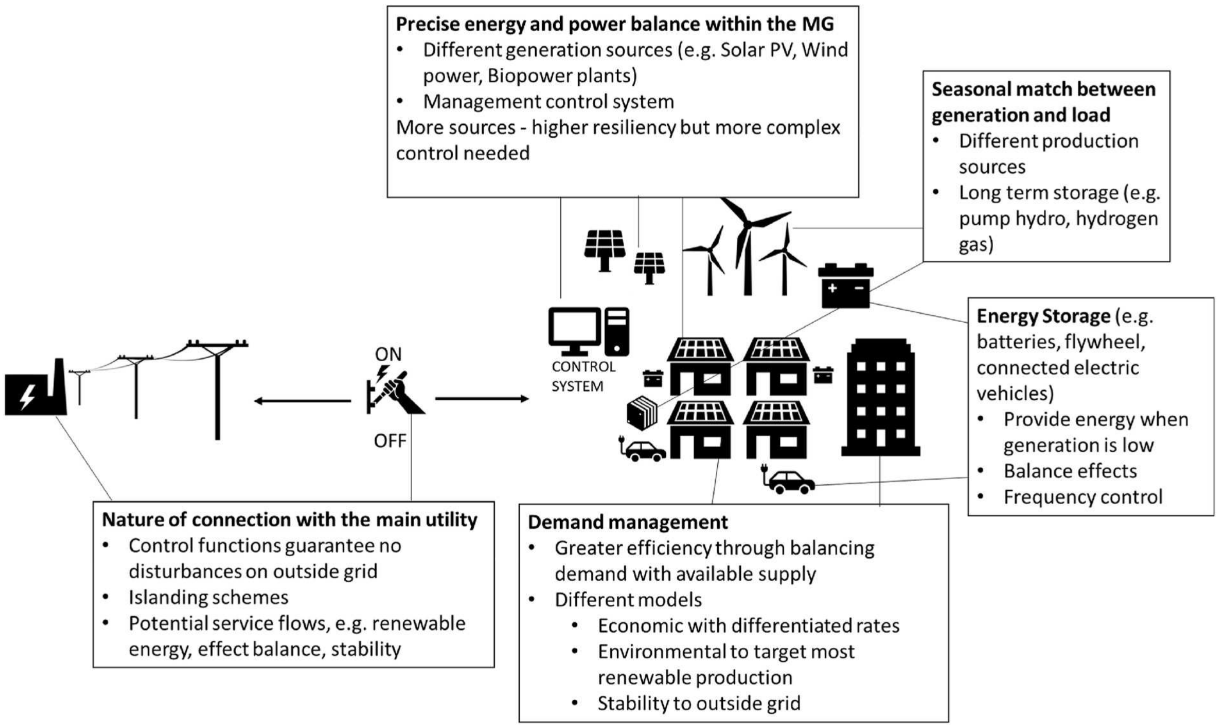

Fig. 1. Conceptual picture of MG with critical functions [20–32]].

3. Conceptual framework

The conceptual framework for the literature review departs from the theoretical field of sustainable transitions which has grown rapidly in recent decades [12] and gathers researchers from different backgrounds such as economics, sociology, history, economic geography and engineering. Within the field several theoretical approaches have been developed in parallel: Strategic Niche Management (SNM) [36,37], Multi-Level Perspective [7,38–40], Transition Management [41,42] and Technological Innovation System (TIS) ([13,43,44]. Most of these frameworks focus on the interplay between an innovative technology which is under development (e.g in a niche) and the current system of practices and technologies in a specific sector (i.e. the regime). Although being differently composed, there are similarities between the different frameworks (see e.g. Refs. [45,46]). Especially, the importance of different actors and the institutional setting are recurrent themes in the various frameworks. Institutions are drawn from institutional theory and can be both formal such as rules and regulations, and informal such as attitudes, guiding principles and values [47]. They are also specifically interesting in the context of community MGs where the community dimensions bring forward non-traditional roles and actor groups, as well as institutional settings [48,49].

In the SNM literature, the niche is described as a protective space in which new technologies can develop protected from current selection environment [37,50]. The belief is that these new technologies need support for their development before being able to compete on equal terms with current technologies in practice (or perhaps replace them). The niche includes processes of shielding, nurturing and empowerment, always in relation with the current regime.

A TIS similarly focus on the niche technology and is defined as: '*set of networks of actors and institutions that jointly interact in a specific technological field and contribute to the generation, diffusion and utilization of variants of a new technology and/or a new product*' [45 p. 611]. The systemic perspective implies that the elements of the TIS are interdependent and develop various forms of synergies such as collective assets which different actors can utilize but could not produce if working in isolation [51].

The theoretical roots for both the TIS and SNM frameworks come from evolutionary and institutional economics [52,53] with institutions and interactive learning as central aspects [54]. In SNM, certain acts of articulating expectations on the niche technology and the building of social networks with niche advocates, contain both proactive actors and institutional development. In research on energy transition these new articulated expectations are shown by both Markard et al. [55] and Wittmayer et al. [48] when they describe how advocacy coalitions changed shared values and beliefs when renewables became the new mainstream. Thus, the focus on institutions and aligned actors is important in both TIS and SNM theory and will also be the focus of this article.

3.1. Actors and networks

Actors are included along the whole value chain: technology vendors, consumers, consultants, universities, research institutes, public bodies, influential interest organizations, venture capitalists, standards-setting organizations, etc. [13]. Actors form networks, both formal and informal, which are also important for the niche. Many different types of networks can contribute to strengthen the niche. Formal networks, such as the Transitions Network in England [56], are formed in order to strengthen the field of community energy. Other types of networks emerge informally, for example along a value chain or in the link between industry and universities. Apart from the target to solve technical challenges, networks can form around the task of forming a market or influencing institutions.

In recent literature the importance of civil society and social movements have been recognized [12]. Social movements '*are networks of individuals and organizations that have the goal of changing established institutions in the state, private sector and/or civil society*', whereas civil society organizations do not necessarily have the goal of social change [12]. For the development and diffusion of novel technology these type of actors and networks can have different roles: they can become a source of resistance, strengthening current regime(s) or support the novel technology and related niche. An example of the latter is to form advocacy coalitions in support of policies which foster technological development and diffusion [55]. Another example is civil society organizations which provide a protected space for social innovation such as practices, consumer and producer behavior [57], which are often needed for diffusion of technology and transitions. For the development of innovation which involves community-based initiatives these types of actors can play a particularly important role [9]. For example, Bauwens and Devine-Wright [58] show that community energy members have a more positive attitude toward renewables in general and this is important to foster a socially acceptable energy transition.

3.2. Institutions

Institutions can be seen as the incentive structure of society or the '*rules of the game'* which shape human interactions. Institutions can be formal (such as regulations, laws and constitutions) and informal (such as attitudes, norms, values and beliefs) and their enforcement characteristics [59]. For the development and diffusion of a niche technology there is often a need to align institutions to the technology [60].

Markard et al. [55] describe the institutional dynamics related to a technology and a niche in terms of technology legitimacy. They identify three processes which can contribute to change. First, institutions may be formed and built up within the niche. In early phases of technological development institutions related to the technology are often adapted to existing institutions in order to create legitimacy [61]. Second, institutions can form and change in the context of the niche which both can strengthen and weaken the legitimacy of it. Third, the formation and change of institutions can occur in the relationship between the niche and the context. However, this relationship might change as a consequence of framing (e.g. Ref. [62]), the process of selecting and connecting structures in the context which is important for the technology. For example, in the case of biogas technology in Germany it was first framed as a solution to problems in agriculture, but over time this changed and the technology built strong institutional ties with the energy sector [55].

From an institutional perspective, a transformation of the energy system is often viewed in policy as a matter of technology and costs [63]. While energy systems always have included a social part, the decentralization of energy systems creates an even greater focus on these social parts; community involvement, socialization and democratization of the energy system will affect the development (Ibid). From community energy literature, it is shown that communities value their social welfare highly and that community driven initiatives, apart from lowering their energy costs, seek to maximize the social benefits for the community [56]. These changes can sometimes be described as part of a "deep transition" where social change is changing the previously industrialized regime [64].

3.3. Development of innovative technology over time

Successful development and diffusion of an innovative technology can be described as a series of phases: formative, growth and saturation phases, often illustrated with an s-shaped curve [65]. In the different phases technological development and diffusion face different challenges and therefore different processes in the socio-technical system/niche might be more or less important. For example, in the formative phase focus is often on research, development and demonstration as well as diffusion in niche markets; while in the growth phase focus is on diffusion in large market segments and mass markets. The technology in focus for this paper, MGs, is in the formative phase. This phase is characterized by long time scales (typically 2-3 decades) [66] and high uncertainty regarding technology, markets and institutions [36,67]. Furthermore, there is often experimentation [68] and several competing designs [69] in this phase.

4. Methods

Based on a literature review, this article investigates under what conditions community MGs implemented in existing electricity grids develop. To identify and analyze conditions in the literature, a conceptual framework which draws on theories from sustainability transitions is used. The data sources primarily comprised existing scientific literature; however, as explained below, it was later complemented with e.g., 'grey' literature and media coverage.

The departure point for this article was to review scientific articles on the topic of community MGs implemented in existing electricity grids. The selection process began by searching in the Scopus database using the key terms 'microgrids' OR 'local energy systems' for the years 2000–2018. Articles were examined on the basis of their abstracts, making a qualitative assessment and including only abstracts which focused on MGs *and* social and/or institutional aspects. Strictly technical articles were thus not included. In some articles, terms such as 'community energy' were used instead of 'microgrids', but if the content was clearly related to MGs, these articles were included in the review. Additional relevant articles were included through backward and forward citations. The selection of articles was thus iterated a few times, finally resulting in a total of 28 scientific articles included in the review. However, as community MGs are still in an early formative phase, some regions and specific cases were at the time of the review more well-covered in scientific publications, whereas others lacked extensive coverage or more in-depth reports. As a result, the included literature is naturally patchy, which is important to keep in mind. In addition, as MG development is highly dynamic and scientific publications are often lagging due to e.g., publishing processes, the most recent development of community MGs in all regions was not available. To obtain a more complete understanding of conditions, additional sources such as non-scientific reports, policy documents, actor's webpages and MG news media were accessed, following pointed cases or regions in the scientific literature, to create a more up-to-date picture.

While reviewing the literature, certain regions or countries stood out due to the concentration of activities around community MGs in those areas. Four dominant regions were identified – the USA, the European Union (EU), Asia and Australia. Literature-wise, these regions differed from each other, where both the USA and the EU are more frequently documented in scientific articles and offer more in-depth studies, whereas Asia and Australia appear to be less covered in the reviewed literature. In addition, the included scientific literature had a broad range of research methods and theoretical departure points which impacted the results from each region. For example, the literature from the EU region included more existing case studies of implemented community MGs, and these provided more in-depth findings of how MG deployments affect the community. Another example is in Asia, where the literature lacked a bottom up perspective, and focus was on existing formal institutions and actors. In the next section the results are presented to correspond to these dominant regions.

5. Results

This section begins with a brief overview of MGs in the world and specific examples of community MGs in existing electricity grids. Thereafter, results from respective regions are presented following the parameters *actors* and *institutions* followed by an outlook of future development, except in the Asia region where none could be found in the included literature.

5.1. Overview of community MGs in existing electricity grids

MGs are rare today, but in recent years a growing market has emerged. Navigant research produces quarterly statistic updates on MGs globally; the 4th quarter of 2018 lists 2258 MG projects in the world [70]. Many are located in developing countries; another study lists 122

MG projects in the developed world [27]. In addition, Navigant research predict that the MG market will increase to a total value of $30.9 billion by 2027 [71]. Community MGs hold a small share of the total MGs in the developed world, and Fig. 2 and Table 1 provide examples of existing community MGs following the definition presented above.

5.2. USA

According to recent statistics, the number of power outages in the USA has steadily increased over the last ten years [77]. Several sources report that the electricity grid in the USA needs a major update to function satisfactory in the future [78–81]. Recent MG developments in the USA are therefore to a large extent driven by the need to address aging electricity grids, costly power outages and increased awareness over vulnerability during extreme weather events [79]. The idea of resiliency has specifically gained importance in the aftermath of the storm Sandy which hit northeastern USA and the Caribbean in 2012 [82]. States which frequently experience disasters are more likely to adopt MGs [83]. In the New York State's MG prize competition, it is specifically defined that MGs should be able to separate from the larger grid to provide power to customers in the event of any extreme weather events or emergencies [84].

Many states in the USA have ambitious targets for the transition to renewable energy production mainly from solar PV and wind energy [85,86]. With an increase in these variable resources, MGs are seen as one of the most effective methods to integrate these and at the same time provide grid operators with more control [87].

5.2.1. Actors and networks

State and federal actors are influential for MG development and play several roles such as policy providers [17], funding instances [78] and to some degree market demanders [88]. Most community MG initiatives are indeed driven by those actors [78] linking to the overall drivers of renewable energy integration and resilient infrastructure. Other influential actors are local utilities responsible for the existing grid where the MG is implemented [89]. Sometimes local utilities can themselves initiate a community MG for different reasons, e.g. to meet increased demand without having to invest in traditional substations. In addition, several technology providers are present where integration of different technologies and MG control through management systems are crucial for system operability [23]. Technology providers often work closely with research institutes and universities to develop and test systems and technologies [90]. Thus, knowledge-based actors also influence community MG development. Communities which use and sometimes own the MG set the design default according to their demands [91]. Further, supporting organizations for MG development work with the communities themselves, as well as policy and state actors who are also present (e.g. Climable.org). Financial investors are also beginning to be present in the MG market (see e.g. microgridinvest.com) often with an "energy-as-a-service" (EaaS) business model [92]. See Appendix D for examples of actors in each region.

As MGs are complex installations, different actors are required in the planning, implementation and operational stages. Collaboration is crucial and several "lessons learned" from project implementations indicate that unified targets and strong leadership are keys to success [24,93]. The Blue Lake Rancheria (BLR) MG provides an illustrative example of actor inclusion and collaboration aspects. The California Energy Commission funded the MG through its electric program investment charge (EPIC). Schatz energy research center (SERC) at Humboldt State University was the primary contractor with engineering responsibility. The local utility PG&E gave essential support to the MG

Table 1
Name, location and content in existing community MGs [17,23,24,72–76].

Name of community MG	Place	Technologies	Starting year
Blue Lake Rancheria	USA	PV, biomass gasifier, batteries	2016
Fort Collins	USA	PV, CHP, fuel cell, back-up diesel, thermal storage	N/A
Borrego Springs	USA	PV, Diesel, community batteries and home storage	N/A
Bronzeville	USA	PV, CHP, back-up, batteries,	2018
Brooklyn	USA	PV, batteries, Smart meters	
Reynolds Landing	USA	PV, Wind, batteries	2017
Simris MG	Sweden	PV, wind turbine, back-up biodiesel, batteries, smart meters, DR system	2017
Aardehuizen	Netherlands	PV, Battery	2015
Feldheim	Germany	PV, Wind turbines, Biogas, Biomass plant, Battery	2011–2016
AM Steinweg	Germany	PV, CHP, Battery	2005
Mannheim Wallstadt	Germany	PV, flywheel, CHP, Battery	2006
Sendai	Japan	PV, Fuel cell, Back-up diesel, battery	2005
White Gum Valley	Australia	PV, Battery	2015

Fig. 2. Community MGs in existing electricity grids.

concept at the proposal stage and during the first three years, including selling the grid infrastructure to the BLR. This purchase needed approval from the California Public Utilities Commission and was supported by PG&E. Idaho National Laboratory and Siemens introduced the project idea to SERC and tested the hardware before installation and live operation. Siemens provided the management system, Tesla provided storage batteries, and REC Solar provided PV panels. In addition, the consultant GHD, Robert Colburn electric and Kernen construction company were involved in the design and implementation of the MG [94].

5.2.2. Institutions

Institutions have in recent years begun to promote MG development directly. Legislative examples and narratives from policy makers as well as community groups and utilities are slowly being reshaped to highlight the experienced benefits from MGs.

5.2.2.1. Formal. MGs have in recent decades benefited from specific legislation and business models which promote MG related technologies such as solar and wind. Examples include the renewable portfolio standard (RPS) which the majority of states have adopted and the solar power purchase agreement (SPPA) model which began in California and later spread to several states [19,95]. A specific MG funding program was launched in Connecticut in 2012 [96], mainly to provide resiliency to critical infrastructure [97]. Other states have later followed, the most cited one being the NY prize competition [78]. Here, 83 feasibility studies for different locations in New York were conducted in stage 1 and 11 were awarded in stage 2 [84].

Several states have taken important steps to change current utility business logic. Two general utility policies are of significance to conditions for MGs: decoupling policies and performance-based regulation (PBR). With decoupling policies, the traditional revenue model based on increased sales is abolished and instead utilities are compensated independent of sales volumes [98]. Currently 19 states have decoupling policies for utilities. PBR requires utilities to provide an affordable, reliable and clean power system, independent of specific infrastructure investments which was the case before PBR. Several states have investigated PBR and in April 2018 Hawaii became the first state to implement a PBR law, SB 2939 [99].

Although specific utility regulations aimed directly at MGs currently are uncommon, some initial examples do exist. Again, Hawaii state leads the way and SB number 2933 [100] extends the public utility commission to include a MG service tariff. This tariff shall give reasonable compensation for any services provided from the MG to the connected grid. It is thereby acknowledged that MGs can provide flexibility to the connected grid, which can be valuable for grid operators in times of peak demand or production. Fair compensation for these services would increase the return on investment for MGs, providing certainty to market development. California state followed and in September 2018 a MG bill, SB1399 [101], was approved increasing certainty for investors while fine-tuning the discussion regarding formal MG regulation. Some believe that this bill could pave the way for other states similar to the SPPAs which originated in California [102]. At present other states have pending proposals for specific MG regulations [103,104].

The IEEE1547 standard is also implemented in Hawaii through rule 14H and in California through rule 21, however not yet the latest revision [105,106]. The FERC ruling of 755 and 784 state that fast responding services to the grid should be rewarded fairly [18], and could also potentially affect MGs.

5.2.2.2. Informal. Several examples of proactive USA utilities say that their attitudes toward their own role and business model are changing. In Chicago the utility ComEd is creating the Bronzeville community MG close to the existing IIT MG to understand how clustered MGs can increase resiliency and robustness of the grid [72,107]. Prior to this, ComEd developed a resilience metric to be used to detect critical areas in the city; the Bronzeville area was identified as best suited to offer efficient resilience [108]. Bronzeville and IIT MGs provide unique data and will be important in the continued development of the MG market. Further, the utility Arizona Public Service Electric Company is utilizing MGs to strengthen the current grid and thereby replace traditional grid updates [109].

Positive MG narratives from proactive states are also being formed. According to the “Roadmap for commercializing microgrids in California” MGs can facilitate the state’s goals of: increased use of renewable power generation, GHG reduction, supporting distributed energy resources goals, promoting energy efficiency goals, supporting deployment storage goals and supporting transport electrification goals [87].

Within the demand side with communities as well as technology providers, the concept of local energy markets is also gaining interest. In Brooklyn, NY, a peer to peer (P2P) market based on Blockchain technology is being piloted. Utilizing owner control over MG assets creates a shift from the traditional electricity retail market to an independent consumer-based market [110].

5.2.3. Future developments

MGs in urban developments are investigated in a few articles. Adil and Ko [111] provide a sociotechnical development path for urban energy planning going from distributed resources to MGs and finally smart interconnected MGs. This development path can guide urban planners and create stronger resilience in urban energy infrastructure. Kelly-Pitou et al. [112] address resilience benefits of community MGs by providing an assessment over vulnerable areas in Pittsburgh. Emphasizing the “immediate resilience” in terms of environmental and social goals provides a more secure framework for return on investment. As resilience is the target with urban community MGs, this should be reflected in a higher domain than just a business problem. Instead, state or federal interest in resilience development could potentially provide budgets for MG developments. Donahue [113] investigated 13 cities and how new developments can integrate MGs to decrease strain on the larger grid in increasingly dense areas. Donahue showed that MGs can actually increase the value of residential developments and are thus generally preferable to increase return on investment.

Advocates of energy democracy see the centralized traditional structure as a key barrier to democratizing the energy system and hence community MGs; democratized models of grid management offer a desirable new structure [114]. Climable, a Boston-based NGO which strives to increase energy democracy and climate justice, views community MGs as the key to achieve this. Therefore, they offer support to communities interested in developing MGs, e.g. through their resilient urban neighborhoods project [115]. Giotitsas et al. [116] show how MGs can drive the development of a “commons-based peer production” system; electricity access is thus a societal common instead of being treated as a consumer good in a capitalist market.

In parallel, different business models are being developed, and Dynamic Energy Networks (DEN) have the goal to offer EaaS to different customers, using clean energy MGs [117]. The value proposition is reliable, secure and sustainable electricity without the upfront costs. According to Microgrid knowledge, 25% of current MGs in the USA are using this business model [118].

However, the costs of MGs in the USA are still high and except for a few examples, such as the Stone Edge Farm MG which is privately funded [119], the majority of MGs are partly state funded. It is a consequence of the lack of regulations for MG value compensations; this is beginning to change but they were not in place for already installed MGs.

5.3. EU

EU has a community-oriented approach and the EU commission itself as well as nations such as Germany and the Netherlands have policies to promote community energy in various ways [120]. According to Koirala et al. [121] there were more than 2800 energy communities in Europe in 2016. This has implications for community MGs and the rationale for MG development is in part a means to create strong self-sustaining communities [122]. Several European countries have ambitious targets to decarbonize the energy sector, and incentives and policies have increased renewable energy production (mostly wind and solar PV) heavily [123]. With existing difficulties to balance the grid in e.g. Germany, community MGs offer a local solution [124,125]. Smart grids are focused within research programs, and MGs are an enabling design for smart applications [111]. The German village Feldheim claims to be the only grid-independent village in the developed world with 100% renewable sources [126].

5.3.1. Actors and networks

Many existing MGs are connected to EU research programs [27]. Thus, the EU commission and its research departments are important actors for MG development. Further, some communities themselves have been active in initiating MG projects e.g. Feldheim in Germany and Aardhuizen in the Netherlands [127,128]. Utilities are involved in community MG development in the EU, so far with varying approaches. There are examples of utilities which are proactive in one market, but resistant in another [129,130]. Regulatory frameworks and resisting utilities have sometimes led to the establishment of a new utility company solely operating one MG [131]. Although similar technology providers exist throughout the entire developed world, local companies are sometimes responsible for system operations in the community MG.

The Feldheim case illustrates how this community MG was a grassroots initiative and how they involved the necessary actors to fulfil the installation [131]. In 1995 the village agreed to invest one turbine in a wind farm making them co-owners of the farm. The other owner was Energiequelle which added several turbines in the park, especially after the energy renewable sources act was passed and attractive incentives for renewable energy were launched. At the same time, the newly elected mayor in the municipality was dedicated to increase renewable energy production. Next Energiequelle bought land area and installed a PV plant, and together with the village agricultural co-op invested in a bio-plant for the community's bio resources. The next step was to create the MG. Here the utility Eon was asked to collaborate but resisted to support the project. Therefore, the village created a parallel grid in the community which Energiequelle officially operates. Later a large battery from LG and management system from Enercon were added to the MG making the village truly independent (ibid).

5.3.2. Institutions

EU was early in transforming their electricity systems away from fossil sources to integrating renewable energy production on a large scale. Despite this, the whole of Europe only accounts for 9% of the global MG market [132]. Grassroots movements are common, forming a base for institutional development around MGs which can be observed in EU directives; however there are differences between countries, for example to what extent community energy has been promoted and implemented historically [133]. This can likely have an effect on how EU directives are transferred to national legislations.

5.3.2.1. Formal. Many European countries have a history with several renewable energy incentives such as feed-in tariffs, net metering schemes, green certificates and energy origin guarantees [19]. In addition, numerous MG development projects have been run within EU research frameworks, see Appendix E for an overview. However, regulations and legislation still favor traditional structures and change processes are considered slow [134].

The EU commission's "clean energy for all" package includes the renewable energy directive which requires member states to remove all regulatory and administrative barriers to the development of community energy projects (such as community MGs) and regularly assess progress [135]. This is a clear step towards focusing on the consumer or prosumer. MGs are however more complex than only distributed resources, implying that a number of regulations and legislation needs to be redefined to remove barriers for community MGs in Europe. Critical to this development is whether the community is viewed as a utility and regulated accordingly, or if they are exempt from the general utility regulation [18].

In Feldheim, the building of a parallel grid was possible because there was a loophole in the legislation which neither allowed nor prohibited it to be constructed; the decision was taken by the responsible state minister after petitioning from the local mayor [131]. Similar experiences were found in the Aardhuizen eco-village, where Dutch law allowed the creation of a Collectief of Particulier Ondernemerschap (CPO) where residents collectively act as a client for their housing projects [75]. This gave residents full land ownership and hence the possibility to install a community MG. Challenges still remain though and after the success of Feldheim, large utilities in Germany have blocked other attempts by villages to become self-sufficient [130].

Proactive utilities also experience barriers since having a distribution monopoly often means that the utility does not have the possibility to own storage facilities [136].

5.3.2.2. Informal. A community MG is a complex technical system and its success depends on the ability of the community to engage in various social activities around the installation process and operation of the MG [137,138]. The installation process of a community MG has often proceeded over a long time span, such as Feldheim in Germany (1995–2013) [127]. During this time, the community underwent a series of development steps, decision processes, member conflicts, solutions, and increased trust and community confidence [131]. Aardhuizen village concretely used a sociocracy approach to resolve any potential conflicts and disputes following the CPO establishment [75]. This was necessary to advance the installation process and encourage community involvement. According to Kunze and Busch [139] these social processes have been more important than solving technical or financial issues. Often some local members with specific knowledge of energy or electricity systems as well as finance have taken on the role of local experts and provided trust in the greater community [140].

Busch and McCormick [137] identified that '[a] *decisive factor for the development in Feldheim was social capital.*' This was displayed in two aspects: first, the responsible company Energiquelle aimed to contribute to social life in Feldheim, not only implement its solution. Secondly, internal decision making was affected by strong social capital by active community members. The effects of this were several: new jobs, links between energy actors and community, Feldheim energy and local agriculture actors cooperation, common ownership and common responsibility. These effects have been positive for social cohesion and local identity [137] as well as decreasing unemployment rates and keeping economic value locally [140]. Another example of the importance of social capital within the community is the utility-led Simris MG in Sweden. The utility EON first planned this MG in a location just outside the town of Timrå. However, the project met resistance from the local residents. Despite having a dialogue with the residents, EON did not manage to overcome the local resistance, and the project was moved to the town of Simris [141].

5.3.3. Future developments

The coming years can be potentially disruptive for the European MG market. The final action in EU's package "clean energy for all Europeans" [142] was agreement on a new energy market directive in December 2018. In this directive, member countries shall request local utilities to increase efficiency through procuring services such as flexibility and storage [143]. This is seen as an alternative to traditional investments in transmission and distribution infrastructure and could e.

g. potentially allow utilities to operate storage facilities. There are also statements of citizen energy communities in the new directive. Communities shall be able to produce, distribute, consume, aggregate, store and provide flexibility for their members, as well as charge for electric vehicles or provision of other energy services. The purpose according to the directive is that these energy communities shall be able to provide environmental, economic and social benefits to their members or local areas where they are active, rather than operate for economic profit [144].

Further, P2P markets are gaining increased interest. Many MG research projects aim to demonstrate new market concepts for consumer-based business models (eg EMPOWER, P2P SmartEst, Flex-COOP, [see Appendix E for more information]). This is also mentioned in a report from IRENA [145] where the empowerment of the consumer via e.g. P2P is suggested as a solution to the new energy system. Moreover, a focus on direct current (DC) technology in MGs is seen in several development projects (eg DCNextEve, RDC2MT [see Appendix 5 for more information]) for a more efficient integration of DC-based solar PV and wind to utilize with potential DC loads.

5.4. Asia

An overall driver in Asia is *mitigating climate change* by transitioning to clean energy, which is manifested e.g., through national clean energy targets and agendas (e.g., Refs. [146–148]). As the region is diverse, it is difficult to present general drivers for deployment of community MGs, however some commonalities have been found in the literature. One such driver is the strong economic growth in certain areas of the region, leading to a growing population in already densely populated urban contexts. Growing cities in e.g. China [146] mean increasing energy demands which put pressure on existing energy grids, thus requiring alternative solutions such as MGs to increase grid flexibility. In countries such as Singapore where land is very scarce, the majority of the population lives in an urban context and, where other alternative energy sources are lacking [149], MGs are promising because they can be integrated with the existing urban built environment. Another highlighted key driver is to increase *energy resilience* in the event of extreme weather, e.g. the Fukushima nuclear disaster in Japan in 2011 led to a dramatically increased interest in distributed energy generation both in the region and globally (e.g., Ref. [148]). As described in Ref. [148], the Sendai MG demonstration proved remarkably reliable in the aftermath of the Fukushima disaster, and continued to provide power and heat to a local hospital. Another driver, especially in South Korea and Taiwan with competent tech-industry as well as a large production-based industry, is the opportunity to position the national actors in the growing market of smart MGs [150].

5.4.1. Actors and networks

Japan has been the early leader in MG research in Asia, but in recent years South Korea, Singapore and China have been increasingly expanding their MG development [148].

In Japan, the New Energy and Industrial Technology Development Organization (NEDO) is a key actor which has been funding several demonstration projects including the Sendai MG. This was created from a network involving NEDO as funding agency in collaboration with research actors and the City of Sendai local government which were the driving actors in developing and maintaining the MG [148]. This local city support proved particularly valuable in helping to '*sidestep [utility] regulation*' [148].

Both south Korea and Taiwan has a history of government-business driven initiatives. In recent years, these collaborations between private actors and government have been promoting smart MGs, viewing this as a future competitive positioning of domestic actors. Important actors include Ministry for Trade, Industry and Energy (MOTIE) in Korea and Ministry of Economic Affairs (MOEA) in Taiwan. Thus, private actors in these countries, are connected with the government and shaped by strategic initiatives and governmental visions [150].

Numerous state actors in China influence MG development, see Refs. [146,148] and Appendix D for specific examples. In general, most MG initiatives in China are state driven suggesting for instance that MGs are able to enhance grid capacity in already densely populated and yet rapidly growing cities which provides one direction for actors in the domain. Formal, top-down approval of MGs to help integrate renewable energy in dense cities has potential to stimulate fast development.

In Singapore, the government through different ministries has played an important role in formulating strategies and goals for more sustainable development, including clean energy [149]. Among others, it resulted in the Singapore Sustainable Development Blueprint released in 2009, which outlines targets for the next 10–20 years. The Singapore Agency for Science, Technology, and Research (A*STAR) has been involved in MG testing [149].

5.4.2. Institutions

The Asia region includes a diversity of conditions and institutions which makes it difficult to present together; the literature however suggests that most initiatives are top-down driven, especially in China, and lack of bottom-up initiatives in the literature can partly explain a lack of information of informal institutions from the region.

5.4.2.1. Formal. Regarding the Sendai MG in Japan, public utility regulation at first hindered the development of the MG but was then sidestepped with help from the local government which made the MG setup possible[148]. As mentioned above, the City of Sendai was a key actor in the process by proving necessary support. Also highlighted as a major institutional factor was the generous funding from NEDO which made the Sendai MG possible in the first place [148].

In South Korea, one of the most ambitious initiatives to create smart MGs has been the Korea micro energy grid (K-MEG) project [150]. The goal was to develop 'globally adoptable energy solutions' incorporating ICT and distributed resources in a modular customizable way [151]. Electrical MGs were one area, but also heat, gas and PV-based disconnected grids were included in the project [150].

In Taiwan, governmental efforts to decrease carbon emissions led to the establishment of a 'smart grid master plan' in 2012 [150]. Here, the target of increasing domestic actors' competitiveness in smart MG technology is apparent. With various policy tools such as seed funding, standards setting and co-development of technologies, the government influenced several test initiatives, for example MG demonstration projects for buildings and homes [150].

The 12th *Five year plan* in China [152], covering guidelines and policy support for the country's development 2011–2015, contained targets for distributed energy generation including MGs and specifically '*30 new energy microgrid demonstration projects*' [148]. The plan has since been replaced by the 13th *Five-year plan* covering the current time period 2016–2020. This was adopted by the National Energy Administration in 2016 and includes targets such as increasing renewable power and resolving issues around renewable power curtailment [153]. As of 2017, 28 new MG demonstration projects are planned for the upcoming years in China, however not all are community MGs [154]. Given the recent years' growth in renewables in China, it can be argued that 28 planned MGs is a rather modest number. Additional formal institutions of relevance and in place since 2017 are national standards on technical requirements for connecting MGs to the power system, and vice versa [154]. The Chinese State Council released in 2005 and updated in 2009 the "Renewable Energy Law", which is a '*framework policy which lays out the general conditions for renewable energy to become a more important energy source in the Peoples Republic of China*' [155,156]. Chan et al.'s [146] study of a simulation and analysis of MG potential for a community in China point to institutional factors as being crucial to future development. Since the State Grid in China currently allows 6 MW onsite generation, which limits the potential of a MG, future negotiations with the State Grid are needed to overcome these limitations on allowable scale of distributed energy. Other key issues include governmental subsidy/discount rates, which according to Chan et al. are necessary '*for the micro energy grid in China to be financially viable*', as well as tariff structures [159].

According to Wouters [149], Singapore is an interesting case when it comes to MG development because of its ideal conditions. One major reason is its partially unbundled and liberalized electricity market leading to a '*well-regulated and transparent*' energy market which in turn attracts businesses and investment. Other reasons of importance are the fact that '*advanced regulations [are] in place for the local distribution of cooling*' and the fact that MGs are considered a critical element in the national energy strategy [149].

5.4.2.2. Informal. The reviewed literature describes several state-driven initiatives along with formal institutions shaping the development of community MGs in Asia. It can be denoted that the attitudes of state- and state-sanctioned- actors are quite promoting, as can be seen in the development of plans and formal institutional documents. However, we have not found any literature specifically describing attitudes or other informal institutions, therefore there is no further results in informal institutions in Asia.

5.5. Australia

In Australia, a combination of high electricity costs, a sunny climate, and increasingly affordable battery prices even for single households, have strongly stimulated the development of MGs [73]. Furthermore, the country's vast distances and propensity to extreme weather point to MGs being a promising alternative where a centralized grid is not possible or reliable [157]. Together with Asia, Australia as a region has the highest increasing penetration of renewable energy sources, especially solar PV [158].

5.5.1. Actors and networks

Green and Newman [73] report a dramatic general growth in solar PV and battery storage in Australia, encouraging MG development. Governmental actors working for renewable energy include the Renewable Energy Agency (ARENA) which funds renewable energy initiatives (including MGs), and the Department of Resources, Energy and Tourism (DRET) which provides advice and policy support to the government on energy issues [157]. Regulating bodies, including the federal distribution to different Australian states, are led by the Council of Australian Governments Energy Council (COAGEC) [159]. Coordinating strategies for development of the electricity sector are operated by the Australian Energy Market Operator (AEMO). AEMO continually follows the increasing numbers of renewables and investigate alternatives, such as MGs to maintain stability and security of the energy system [160]. On the retailer side, the company Synergy (owned by the Government of Western Australia) is the largest electricity generator and retailer of gas and electricity. Synergy determines electricity prices in the Perth region where '*electricity prices [...] have risen more than 85 per cent since 2008*' [73], which has pushed consumers to consider alternatives such as rooftop solar PV. In terms of private actors, Tesla is also strongly pushing the development of batteries by offering relatively cheap home battery storage systems which encourage MG setups. White Gum Valley (WGV) is one example of a community MG in a Perth suburb currently utilizing ARENA funding to create a demonstrator using solar PV and battery storage in a group housing (strata) context [73,161].

5.5.2. Institutions

5.5.2.1. Formal. In Australia, the "Expanded Renewable Energy Target" legislation from 2009 (which included support for e.g., small-scale solar PV) set the target that at least 20% of the nation's energy was to be supplied by renewables by 2020. However, after a review of the target in 2015, the Australian government changed the target to a less ambitious goal from 41,000–45,000 GW h to 33,000 GW h (due to forecasted decreases in future energy requirements), which signaled a '*reluctance from the government to change the status quo*' [73]. Despite this, renewable energy via rooftop solar PV has increased dramatically in the Perth area of Australia. Through the Renewable Energy Buyback Scheme, households with solar PV can sell '*their surplus renewable electricity back to the energy retailer for a predetermined FiT price*' as well as '*their battery sourced electricity to the grid*' [73]. One on-going development related to community MGs is the deployment of solar PV in group housing. This development is hindered by '*regulatory challenges around managing shared energy infrastructure and the energy it produces, dwellings being rented as well as fairly allocating units of electricity and settling financial payments for purchase of electricity*', which is further explored in the White Gum Valley (WGV) development project in a suburb to Perth [73]. WGV is using funding from ARENA to build up a community MG consisting of solar PV and battery storage to be owned by the residents through a strata company [161].

5.5.2.2. Informal. According to Green and Newman [73], the dramatic increase in installed rooftop solar PV in the Perth region has happened '*without a major government* support *program*' and factors such as cheap batteries and high electricity costs have played a more important role. Cheap solar PV and storage solutions from China and/or Tesla have had a significant impact, and thus play a key institutional role in Australia in making it both possible and desirable for individuals and households to invest in their own alternative energy production to avoid rising electricity prices, creating a bottom-up momentum for MG development. The concept of democratizing the energy system is highlighted in the literature focusing on Australia. Green and Newman [73,161] propose the concept of "citizen utilities" to define how citizens in Australia and globally are likely to become "prosumers", i.e. utilities who produce and trade solar energy. This captures the new logics of community-based distribution systems through MGs and peer-to-peer markets for electricity. White Gum Valley in Western Australia illustrates the transformation from centralized power to citizen-based, which allows new local economies to emerge and democratizes power distribution [73].

5.5.3. Future developments

As Green and Newman [73] report, the development in Australia includes emerging actors and concepts exploring P2P solutions based on Blockchain to enable actors within e.g., a community MG to exchange kWhs in a reliable and secure way. Emerging companies such as Grid Singularity, Solar Coin and Ethereum are mentioned as players involved in driving this development, which can be seen as a next step in a process to find alternative ways to generate and consume energy, away from centralized solutions. Relevant to peer-to-peer solutions, Green and Newman's [161] concept of citizen utilities is a development pushing conventional utilities to "fight", "flight" or "innovate".

6. Discussion and conclusions

This article has reviewed the conditions under which community MGs develop and specifically what role informal and formal institutions have in this development. The results were divided into four regions – USA, European Union, Asia and Australia – given the concentration of literature in these places.

This article partly addresses the open questions proposed by Hirsch et al. [18], in that it reviews the formal institutions which need to be altered or, as Hirsch et al. put it, how existing legal barriers effectively can be surmounted. Moreover, it provides a review of different regions in the world and shows that context matters in this growth. This article demonstrates the need for regulatory updates needed for implementations of more radical forms of community MGs compared to, for example, military or campus MGs which are often exempt from distribution monopoly rules [157].

The need to balance increasing renewables is similar in all regions. In addition to balancing renewables there are different drivers for community MGs in respective regions. In the USA, an aging electricity grid and desire to increase the resilience of cities and critical infrastructure have led to the provision of several MG initiatives. Community MGs are encouraged by state and federal programs with the reservation that they meet overall goals of robustness and resilience. In the EU, more focus is given to the community itself, and increased local autonomy is driving community energy projects where community MGs can be found but do not necessarily occur solely from the community focus. Instead, technical sophistication or market trials are often connected with MG development through EU research programs. In Asia, severe challenges with fast growing mega cities and increased electricity demand motivate infrastructure development and local energy solutions including community MGs in urban contexts. The focus on increasing competitiveness for domestic actors in smart MG markets is also apparent in Asia. Australia differs since prosumer demand for self-sufficiency and decreased dependency on utilities is a driver for community MG development.

Despite different drivers, similar formal institutional developments are found, albeit contextual conditions provide different emphasis throughout the regions. In proactive US states, MG tariffs and performance-based regulations on utilities are being implemented. The EU is currently directing member countries to update their electricity market and renewable energy regulations to allow communities to act as aggregators of renewable generation, flexible loads and storage services to the overall grid, paving the way towards community MGs. In Australia, market and consumer pressure drive institutional developments, emphasizing P2P markets and concepts such as 'citizen utilities'. Asia, specifically China and Japan where MG activities are state-driven, also show increased ambitions to provide a regulatory framework which facilitates local energy systems and MGs.

Although interesting developments are occurring, it can be concluded that the formal institutional barriers to community MGs are still significant. According to Bento et al. [66], this implies that the technological field of MG is in a formative phase which needs some additional institutional change in order to grow. Especially the creation of legitimacy among various actors through institutional developments and the formation of more stable markets are crucial to be able to leave the formative phase and enter the growth phase.

We conclude that governmental directions influence the level of activities within development of informal institutions. In the USA, energy democracy movements are gaining momentum when the government increases community MG initiatives, although this focus is not prioritized by either state or federal government, instead movements are seizing this opportunity. In Australia, low governmental ambition creates greater consumer desire to drive development and diffusion of renewables and become self-sufficient. Since incentives are missing, the community MG initiatives need to present a viable business model and rely on other investors to fulfill their projects. For community energy projects, this has resulted in less benefits to the community compared with other contexts where governmental ambition is higher [162].

Within the community, to be able to stimulate involvement and motivation to implement a MG, we conclude that increased social value is important. This is evident from existing community MGs in the EU and coincides to some extent with the goals of the new EU directive. The process is however challenging and long term since MGs are technically complex and success depends on the implementer's ability to increase the social value of implementing and operating the MG within the community, which in turn will increase social acceptance [10].

One important insight from this study is that the utility stands out as a critical actor whose attitude and level of activity greatly influences community MGs development. Many of the US community MG initiatives are indeed driven by local utilities. In the EU, resistance from utilities is said to have hindered community MGs historically, but recent examples show a change in attitudes and actual implementations, e.g. the utility led Simris MG in Sweden. In Australia, consumers' desire to decrease dependency on utilities puts them in a situation where they need to "fight, flight or innovate" [161]. Thus, it can be concluded that in all regions formal and informal institutional development intensifies pressure on utilities to increase the level of activities with non-traditional electricity infrastructure development and this improves conditions for community MG development.

From the literature, there are also suggestions around future value creation and the linkage between community MGs and the general plans to increase resiliency in cities. There is a trend that including other investments from state authorities on defense and disaster preparedness to community MG development may increase in the future, since initial interest has already begun, and knowledge is being shaped in this field. This is especially apparent in the USA and in Asia.

One limitation of this study is that it draws primarily on scientific publications and additionally pointed grey literature for the analysis which implies leaving out ongoing activities not yet published. One potential negative consequence is reinforcing already established regions and failing to include emerging regions where community MGs are also being explored. Another is that for example some regions seemingly provide more developed attitudes among communities toward MGs in general, but this can be a consequence of the included literature's bias. The results do however provide insights from different parts of the world which can be used as departure points for further research within this field. In this sense, this article provides a clear picture on which regions need further study especially Asia and Australia which at the moment have the lowest number of represented scientific articles given our delimitations. The rapid development of renewable energy in Asia could potentially affect the development of community MGs significantly, and research focused in this specific region would provide useful insights how this potentially can affect the global market. Further, the number of in-depth case studies of community MGs, especially outside of Europe, is low. More research on cases would provide a fuller picture on how this development affects communities and what are the significant factors driving development forward.

Author contributions

The first author has had the main responsibility for structuring the article, reviewing literature and writing the article. The second author has substantially contributed to reviewing the literature and writing of the article. The third author has substantially contributed to the structuring and writing of the article.

CRediT authorship contribution statement

Martin Warneryd: Investigation, Writing - original draft. **Maria Håkansson:** Investigation, Writing - original draft. **Kersti Karltorp:** Writing - original draft, Supervision.

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Appendix A. Interconnection standards

Name of standard	Overall description of standard family	Specific version
IEEE 2030 (2011)	Smart grid interoperability of energy technology and IT operation with the electric power system, end-use application, and loads	Defines communication between the MG and the larger grid. Aims to establish a two-way power flow with communication and control between the MG and the larger grid.
IEEE 1547 (2018)	Technical rules for interconnection of distributed resources into the power system	Early versions required inverters to shut off in the event of grid disturbances. This was changed and from 2011 it was possible for inverters to island and continue to run in the event of disturbances. The latest revision provides for a range of grid services which may be offered by advanced inverters and thereby takes a step closer to a smarter grid where distributed resources are utilized as one active part of the larger grid.

Sources: [1,2]

[1] Lydic B. Smart Inverter Update: New IEEE 1547 Standards and State Implementation Efforts. 2018.
[2] Basso T. IEEE 1547 and 2030 standards for distributed energy resources interconnection and interoperability with the electricity grid. National Renewable Energy Lab.(NREL), Golden, CO (United States); 2014.

Appendix B. Energy production sources within MGs

Technology	Description	Role in MG
Solar PV	Photovoltaic cells produce electricity from photons in the sunlight, inexhaustible and free after installation.	Found in almost all newer MGs. Flexible energy production which is possible to install in already built environments. Production varies with sunlight. Dependent on DC-DC converter and inverter for balanced electricity output.
Wind turbine	Produces electric energy from kinetic energy in a generator driven by wind.	Different sizes and types are possible. Placement, height and size of wind turbine affect economics where larger and taller are more cost effective.
Combined heat and power (CHP)	Combustion plant used for electricity production which also captures heat from the combustion process.	Can utilize locally produced fuels such as biomass or biogas. Needs both electricity and heat infrastructure to be optimally used.
Hydro power	Electricity plant with generator driven by flow of water.	Highly dependent on right natural conditions with flowing water. Varies with seasonal flows, rain, etc. Often a storage reservoir is connected which evens out flows.
Fuel Cell	Power plant producing electricity from chemical processes using a fuel such as hydrogen.	Different sizes and no moving parts make them suitable for installation in urban contexts. Still fairly new and expensive technology.
Back-up generators (fossil energy)	Often diesel or natural gas generators utilized as back up when needed.	Back-up. Dependent on fossil fuels

Sources: [1–3]

[1] Mariam L, Basu M, Conlon MF. Microgrid: Architecture, policy and future trends. Renewable and Sustainable Energy Reviews. 2016; 64:477–89.
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Appendix C. Storage alternatives in MGs

Storage unit	Description	Role in MG
Batteries	Chemical storage through an electrolyte moving back and forth between two electrodes creating a current.	Several different types exist. Some used for bulk storage, some more suitable for smaller storage, high effect and 1000s of charging cycles.
Flywheel	Kinetic energy is stored in a spinning wheel driven by a motor.	Frequency regulation in short time spans.
Pump hydro	An electric pump uses excess power to move water into a reservoir at a higher altitude.	Needs good conditions to be constructed. Used for longer term storage in combination with a small hydro plant.
Thermal storage	Excess electricity is used to heat a substance such as salt or stones to be stored in an insulated container. The heat is then released back through a generator (CHP) and utilized as electricity and heat.	Still in development phase. Could also be used for cost effective seasonal storage.

Sources: [1,2]

[1] Soshinskaya M, Crijns-Graus WH, Guerrero JM, Vasquez JC. Microgrids: Experiences, barriers and success factors. Renewable and Sustainable Energy Reviews. 2014; 40:659–72.
[2] Mariam L, Basu M, Conlon MF. Microgrid: Architecture, policy and future trends. Renewable and Sustainable Energy Reviews. 2016; 64:477–89.

Appendix D. Example of MG actors in the different regions

USA

Examples of state and federal actor	Examples of technology providers	Examples of communities
• Department of Energy (DOE) • Department of Defense (DOD) • Consortium for Electric Reliability Technology Solutions CERTS • New York State & Energy Research (NYSERDA) • California Energy Commission (CEC)	• Siemens (Control and software systems) • Tesla (Batteries) • LO3 Energy (Smart meters)	• Blue Lake Rancheria Tribe • BMG (Brooklyn Community)
Examples of local utilities	**Examples of research actors**	**Examples of NGOs**
• Pacific gas and electricity PG&E (Blue Lake) • ComEd (Chicago) • Con Edison Inc (Brooklyn)	• Illinois institute of technology • Schatz research center	• Clean Coalition • Climable.org

EU

Examples of state and federal actor	Examples of technology providers	Examples of communities
• EU commission • National energy agencies **Examples of local utilities** • Energiequelle (Feldheim) • EON (Simris)	• MVV Energien (Mannheim Wallstadt) • Enercon (Feldheim) **Examples of research actors** • Aalborg university • Fraunhofer • Chalmers	• Feldhiem community • Aardhuizen community **Examples of NGOs**

Asia/Australia

Examples of state and federal actor	Examples of technology providers	Examples of communities
• New Energy and Industrial Technology Development Organization NEDO (Japan) • Ministry of Trade, Industry and Energy MOTIE (Korea) • Ministry of Economic Affairs MOEA (Taiwan) • National Energy Administration NEA (China) • National Development Reform Commission (NDRC) (China) • Ministry of the Environment and Water Resources MEWR (Singapore) • Ministry for National Development (MND) (Singapore) • Ministry of Trade and Industry (Singapore) • Renewable energy Agency ARENA (Australia) • Department of Resources, Energy and Tourism (DRET) (Australia) • Council of Australian Governments Energy Council COAGEC (Australia) • Australian Energy Market Operator AEMO (Australia)	• Samsung • LG • Tesla	• City of Sendai • White Gum Valley
Examples of local utilities • Synergy (Australia)	**Examples of research actors** • Chinese academy of sciences (China) • Curtin University (Australia) • NTT Facilities Research Institute (Japan) • Tohoku Fukushi University	**Examples of NGOs** • Clean Energy Council (Australia)

Sources: [1–7]

[1] Romankiewicz J, Marnay C, Zhou N, Qu M. Lessons from international experience for China's microgrid demonstration program. Energy Policy. 2014; 67:198–208.
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Appendix E. Microgrid related projects funded by the European Commission

Acronym	Title	Program	Start date	End date
DCNextEve	LV DC microgrids for evolved energy communities	H2020-EU.1.3.2.	2016-07-01	2018-06-30
MORE MICROGRIDS	Advanced Architectures and Control Concepts for More Microgrids - MORE MICROGRIDS	FP6-SUSTDEV	2006-01-01	2009-12-31
MICROGRIDS	Large scale integration of micro-generation to low voltage grids (MICROGRIDS)	FP5-EESD	2003-01-01	2005-12-31
GREENERNET	Advanced Flow Battery Energy Storage Systems in a Microgrid Network	H2020-EU.3.	2016-07-01	2018-12-31
RDC2MT	Research, Demonstration, and Commercialisation of DC Microgrid Technologies	H2020-EU.1.3.3.	2017-02-01	2021-01-31
e-GOTHAM	Sustainable-Smart Grid Open System for the Aggregated Control, Monitoring and Management of Energy	FP7-JTI	2012-04-01	2015-09-30
SENSIBLE	Storage-Enabled Sustainable Energy for Buildings and Communities	H2020-EU.3.3.	2015-01-01	2018-06-30
EMPOWER	Local Electricity retail Markets for Prosumer smart grid pOWER services	H2020-EU.3.3.4.	2015-01-01	2018-04-30
DOMINOES	Smart Distribution Grid: a Market Driven Approach for the Next Generation of Advanced Operation Models and Services	H2020-EU.3.3.4.	2017-10-01	2021-03-31
MERLON	Integrated Modular Energy Systems and Local Flexibility Trading for Neural Energy Islands	H2020-EU.3.3.4.	2019-01-01	2021-12-31
PIME'S	CONCERTO communities towards optimal thermal and electrical efficiency of buildings and districts, based on MICROGRIDS	FP7-ENERGY	2009-12-01	2014-11-30
SEESGEN-ICT	Supporting Energy Efficiency in Smart Generation Grids through ICT	CIP		

(continued on next page)

(*continued*)

Acronym	Title	Program	Start date	End date
			2009-06-01	2011-05-31
SHAR-Q	Storage capacity sharing over virtual neighbourhoods of energy ecosystems	H2020-EU.3.3.4.	2016-11-01	2019-10-31
ODYSSEA	OPERATING A NETWORK OF INTEGRATED OBSERVATORY SYSTEMS IN THE MEDITERRANEAN SEA	H2020-EU.3.2.5.	2017-06-01	2021-11-30
DC4Cities	Environmentally sustainable data centres for Smart Cities	FP7-ICT	2013-09-01	2016-02-29
ADAPT	Adaptive Decision support for Agents negotiation in electricity market and smart grid Power Transactions	H2020-EU.1.3.2.	2017-01-01	2018-12-31
REACH	Resource Efficient Automatic Conversion of High-Altitude Wind	H2020-EU.3.	2015-12-01	2019-08-31
P2P-SmarTest	Peer to Peer Smart Energy Distribution Networks (P2P-SmartTest)	H2020-EU.3.3.4.	2015-01-01	2017-12-31
CHESS	Cegasa Portable Hybrid Energy Storage Solution	H2020-EU.3.3.	2016-08-01	2017-01-31
FENIX	Flexible electricity networks to integrate the expected 'energy evolution'	FP6-SUSTDEV	2005-10-01	2009-09-30
FLEXCoop	Democratizing energy markets through the introduction of innovative flexibility-based demand response tools and novel business and market models for energy cooperatives	H2020-EU.3.3.4.	2017-10-01	2020-09-30
VIMSEN	VIMSEN: Virtual Microgrids for Smart Energy Networks	FP7-ICT	2014-02-01	2017-01-31
D-MILS	Distributed MILS for Dependable Information and Communication Infrastructures	FP7-ICT	2012-11-01	2015-10-31
MARE	Mediterranean Activities for Research and Innovation in the Energy sector	FP7-INCO	2013-09-01	2016-02-29
TILOS	Technology Innovation for the Local Scale, Optimum Integration of Battery Energy Storage	H2020-EU.3.3.	2015-02-01	2019-01-31
ERIGrid	European Research Infrastructure supporting Smart Grid Systems Technology Development, Validation and Roll Out	H2020-EU.1.4.1.2.	2015-11-01	2020-04-30
eDREAM	eDREAM - enabling new Demand REsponse Advanced, Market oriented and Secure technologies, solutions and business models	H2020-EU.3.3.4.	2018-01-01	2020-12-31
SpecEMS	Spectral Energy Management System for appliance-level analytics, control, and microgrid renewables trading.	H2020-EU.3.	2019-03-01	2019-08-31
DREAM-GO	Enabling Demand Response for short and real-time Efficient And Market Based smart Grid Operation - An intelligent and real-time simulation approach	H2020-EU.1.3.3.	2015-02-01	2019-01-31
FINSENY	Future INternet for Smart ENergY	FP7-ICT	2011-04-01	2013-04-30
FLEXICIENCY	energy services demonstrations of demand response, FLEXibility and energy effICIENCY based on metering data	H2020-EU.3.3.4.	2015-02-01	2019-01-31
GreenCom	MyGrid; Energy Efficient and Interoperable \nSmart Energy Systems for Local Communities	FP7-ICT	2012-11-01	2016-04-30
e-balance	Balancing energy production and consumption in energy efficient smart neighbourhoods	FP7-ICT	2013-10-01	2017-07-31
ALION	HIGH SPECIFIC ENERGY ALUMINIUM-ION RECHARGEABLE DECENTRALIZED ELECTRICITY GENERATION SOURCES	H2020-EU.2.1.3.4.	2015-06-01	2019-05-31

Source: EU CORDIS Database

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