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Socio-technical evolution of Decentralized Energy Systems: A critical review and implications for urban planning and policy

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A B S T R A C T

The growth of Decentralized Energy Systems (DES) signals a new frontier in urban energy planning and design of local energy systems. As affordability of renewable energy technologies (RET) increases, cities and urban regions become the venues, not only for energy consumption but also for generation and distribution, which calls for systemic and paradigmatic change in local energy infrastructure. The decentralizing transitions of urban energy systems, particularly solar photovoltaic and thermal technologies, require a comprehensive assessment of their sociotechnical co-evolution – how technologies and social responses evolve together and how their co-evolution affects urban planning and energy policies. So far, urban planning literature has mainly focused on the impact of physical urban forms on efficiency of energy consumption, overlooking how the dynamics of new energy technologies and associated social responses affect local systems of energy infrastructure, the built environments and their residents. This paper provides an interdisciplinary review on the co-evolving technical and social dynamics of DES focusing on Distributed Generation (DG), MicroGrids (MG), and Smart MicroGrids (SMG), in order to draw insights for their integration in urban planning and policy, in particular reference to climate change mitigation and adaptation planning.

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1. Introduction

Centralized approaches to energy production, delivery and consumption constituted the original framework for provision of modern energy services. With the invention of high voltage AC power in late 19th century, electricity could to be transmitted over large distances through electric cables [1,2]. Mass production, delivery and consumption of energy were expanded, stretched across the country through one nation-wide grid, designed as if to convey electricity perpetually to the energy-hungry masses of residential, commercial and industrial consumers. Although the sheer ingenuity of the centralized energy paradigm underpinned unprecedented growth in the 20th century – with 'electrification' named its greatest invention [3] – the signs of its decay in the 21st century are increasingly evident. In an assessment by the American Society of Civil Engineers [4], energy infrastructure received a dismal D+. In addition, increasing resource conflicts tied to fossil fuels, depletion of the fossil fuel reserves, and anthropogenic climate change offer ample reasons for designing an alternate energy system that enables weaning off of carbon-intensive fossil fuels in meeting the world's current and future energy needs.

The alternate approach is decentralized; it is predicated on recognition of the finiteness of fossil fuels and their carbon-intensive character, deteriorating energy infrastructure and growing demand for energy. Decentralized Energy Systems (DES) suggest a paradigm shift in the way energy is produced, delivered and consumed. DES conceived on the basis of Renewable Energy Technologies (RET) offer a clean and inherently resilient approach towards reaching sustainable development goals. Literature notes four characteristic advantages of such DES over centralized energy systems: the ability to offer low to zero-carbon emissions [5–7], offset capital-intensive investments for network upgrades [8–10], impart local energy independence and network security [11–13], and motivate social capital and cohesion [14–16]. As RET becomes more affordable and penetrate the energy markets, cities become the place for celebrating these benefits of DES.

As DES contribute to environmental, economic and social aspects of urban sustainability, they are viewed from different perspectives in literature. This is mainly because energy systems research is itself located at the disciplinary boundaries of social science and technology studies. This becomes especially true in the case of DES, where the physical proximities between local energy technologies and social structures are reduced [13,17–20]. Existing literature on this subject mainly takes a technocratic approach, investigating optimal placement of DES [21–25] and their integration into building and transport infrastructures [26–34]. On the other hand, social perspectives on DES are concerned with spatial and temporal diffusion of DES across urban regions [35–37] and their influence on consumer behavior and response [38–43]. Lastly, interdisciplinary socio-technical research on DES is focused on examining the mutual impacts of social and technical aspects of DES in co-creating social and commercial value [44–50] and exploring the potential for their realization through commercial organization models for new local energy infrastructure [51–55]. These topics of study locate the research on DES squarely in the domain of interdisciplinary socio-technical research.

The transition to DES requires a more comprehensive assessment on how new energy technologies and social responses evolve together in cities and how we link their sociotechnical co-evolution to urban planning and policies. So far, there remains a disconnection in literature across highly technical (engineering based), social (social science based) and applied (planning and policy based) studies. Most urban planning literature has focused on the association between urban forms on transport and building energy consumption [56–60], while the technical, social and institutional impact of DES on urban planning and policy received little attention. Recently planning literature calls for planners to engage with emerging energy technologies [61], link land use regulations with renewable energy generation [62] and pursue collaborative planning for promoting clean energy [45,63]. Still, little attempt has been made to incorporate new DES such as MicroGrids and Smart Grids into planning and emphasize their role in climate change and collaborative planning.

In this review, we advance this research orientation further by bringing the co-evolving social and technical perspectives of DES to bear on urban planning and policy. We accomplish this by pulling together different strands of research from the existing literature, identifying corresponding parallel arguments and drawing insights for planning of local energy systems. We then use these insights to point further avenues for urban planning and policy with a particular focus on climate change mitigation and adaptation, given the rising importance and urgency of climate change planning, and the direct contribution of DES towards reducing greenhouse gas emission and increasing resilience of local energy infrastructure. Such implications to planning and policy can vary significantly depending on geography and socio-economic condition of each country; this paper sheds light on best practices and literature from the U.S. and Europe to identify the implications for local energy planning in North American and European cities, particularly in the U.S.

Here, we focus our attention on three specific decentralized energy technology configurations, namely Distributed Generation (DG), MicroGrids (MG), and Smart MicroGrids (SMG). Considering these three configurations under the umbrella term of DES, we provide a general overview of the literature landscape. Auxiliary devices for storage and co-generation as well as electric vehicles (EVs), for purposes of organization, are assumed to be included within the ecosystem of technologies that each configuration creates in its wake. Reflecting the predominant focus of DES literature on solar PV and solar thermal in urban areas, most examples in this paper naturally address urban application of on-site solar energy generation and distribution; however, the general framework can be applied to other RET such as on-site micro wind generation and biomass as their urban applications become more

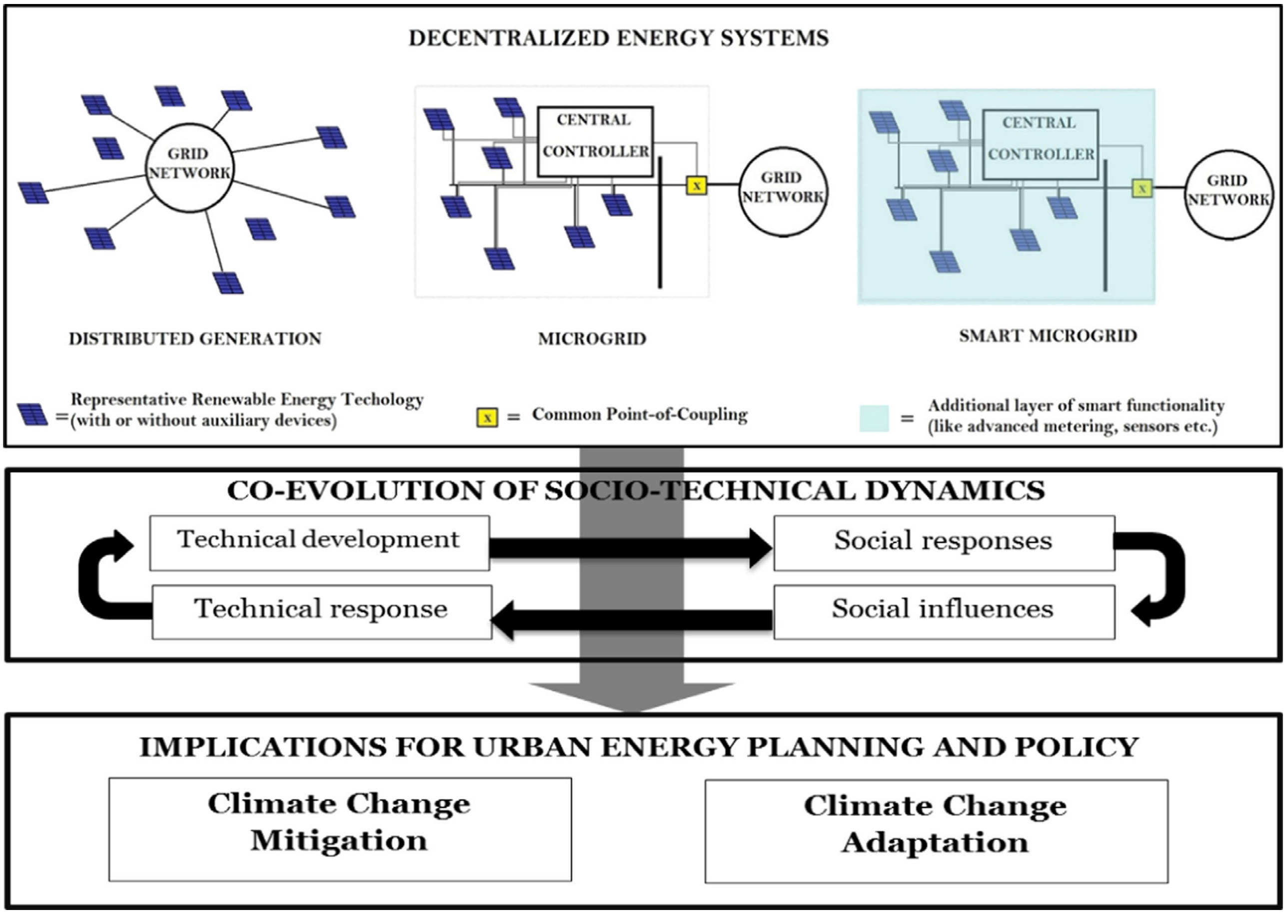

Fig. 1. DES Configurations and schematic structure of the paper.

common. Fig. 1 illustrates the schematic structure of the article as well as the configurations considered for review.

The definition of each of the three DES configurations considered in this paper is as follows:

1.1. Distributed Generation

Distributed Generation (DG) is defined as an electric power system that is either connected within the distribution networks or on the consumer side [64]. Individual installations of RET characterize the distributed nature of clean energy generation. Therefore, DG has come to predominantly be associated with renewable energy generation [10]. In the case of urban geographies, major scholarship discusses solar energy based RET like solar PV and solar thermal, most likely due to the relative ease of installation, operation and maintenance in urban settings. From a systems view, any RET operating either independently (off-grid) or in connection with the grid and serving specific energy needs at their site of installation is described as *Distributed Generation*.

1.2. Microgrids

The U.S. Department of Energy (DoE) defines *Microgrid* as "a group of interconnected loads and distributed energy resources (DER) within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid and can connect and disconnect from the grid, operate in grid-connected or island mode" [65, p. 7]. The image depicted by this definition denotes a neighborhood or community level expanse of *Microgrids*. In fact, the funding opportunity announcement by DoE, from which the definition originates, proposes achieving community-defined objectives for electricity system resiliency through this DES configuration [65].

1.3. Smart MicroGrids

The additional layer of intelligent functionality on *Microgrids*, enabling real-time and transactive (2-way) information and energy flows between consumers and providers characterizes a *Smart MicroGrid* (SMG). Note that this is different from 'Smart Grid' which refers to the network upgrades to the entire power grid system using digital processing and transactive communication technologies [66]. As such, while Smart Grid denotes a grid-wide network improvement, *Smart MicroGrids* are urban scale counterparts and, as some authors suggest, key components of future Smart Grids [67–69]. In fact, the DoE's Smart Grid initiative considers *Microgrids* as basic units of the future Smart Grid [12].

In the following section, we review these different technology configurations – DG, MG and SMG – from the literature and depict their evolving socio-technical sophistication. First, we consider the technical advantages and drawbacks of DG, MG and SMG configurations as discussed in literature, alongside the social perspectives relating to each. The review describes the contributions to technical sophistication of DES as each technology configuration improves over previous ones, although not in a linear fashion. The selection of literature for this review is thus informed and guided by the aim of drawing out parallel arguments that exist across different perspectives in particular reference to DG, MG and SMG, and at a scale that is distinctly urban. This helps explain how improvements in technology and their social implications co-evolve, summarized in Section 3. Lastly, the relevance of DES at the local scale is considered through a broad discussion of their implications for urban planning and policy in Section 4. This discussion in conducted in specific reference to climate change mitigation and adaptation based on the arguments drawn out. Finally, in Section 5, we conclude by underscoring further research avenues and directions.

2. Socio-technical evolution of Decentralized Energy Systems

2.1. Distributed Generation

2.1.1. Growth of Distributed Generation

Although there is some agreement on what DG means, it should be noted that ambiguities persist; differences in specifics like sizing, expanse of service areas, interconnection mode with the utility grid etc., continue to be negotiated (see [64] for details). Nevertheless, DG technologies like solar PV and solar thermal have numerous benefits. With cost reductions, these technologies are achieving grid parity in locations where retail electricity costs are extremely high, for instance in Hawaii and California [70]. The site-specificity of DG installations allows system designs and generation capacities to be optimized to individual user's energy needs, allowing critical improvements in power quality, reliability and reductions in emissions [8–71]. Due to rapid cost reductions in solar PV and solar thermal technologies, some of the early predictions seemed to envision them as having an independent, and mainly off-the-grid future [6,72], while others suggested the co-existence of centralized and decentralized systems [11,73]. In any case, DG, especially solar PV, has continued to grow rapidly across cities, finding market with individual homeowners and commercial entities [74].

2.1.2. Motivations of DG consumers

The market growth for residential solar technologies like solar PV and solar thermal was investigated through the study of consumer purchase decisions. In a 1981 study of over 600 mail surveys in the State of Maine, the authors found the existence of 'enthusiastic non-adopters' of solar thermal technologies – consumers who despite being interested had not purchased them [75]. These consumers were later denoted as the 'early majority', based on the diffusion of innovation theory, when higher financial capacity and greater level of awareness were found as the main determinants for furthering uptake [38,41,54]. More importantly, the formation of social networks among consumer groups based on ownership of solar PV and solar thermal technologies [41], as well as the influence of 'prime movers' or 'local mediators', also suggested by diffusion theory, are instrumental to the advancement of the market for these technologies [54].

2.1.3. Challenges of increasing DG deployment

Off-grid deployment of DG based on solar and wind, however, can only offer intermittent energy supply. Although energy storage technologies have matured enough to possibly alleviate this issue, costs are still prohibitively high for residential deployment [76]. On the other hand, grid-connected DG offers continuous and reliable supply while offsetting as much retail energy demand as on-site renewable energy generation [77]. As such, grid-connections to DG installations overcome the challenges of intermittent energy generation, with the utility grid essentially acting as a large storage facility [78]. But the increase in demand-side deployment of DG exposes the utility grid to the impacts of distributed variability of DG installations that operate individually in connection with the grid [79,80]. Therefore, while the intermittence of DG installations is overcome through grid interconnections, grid-tied operation itself requires rigorous standard interconnection rules to manage the variability introduced by these technologies.

In addition to federal standards for DG interconnection (IEEE 1547 and UL 1741), similar processes and rules have been implemented in a variety of forms in a number of states [81]. Institutionally, as the number of utility customers who generate their own energy – often referred to as *prosumers* – increases, so do the requests for processing their interconnection requests with the utility grid [82]. Furthermore, the entry of private utility companies into the local renewable energy market requires regulatory provisions to preserve competition and monitor fairness of retail electricity prices. These institutional requirements accompanying increased DG units within a utility's service area, representing the first phase of renewable energy integration, cause higher processing times, costs and technical rigor of allowed interconnections, and may negatively impact normal service standards and capacity [82].

2.2. Microgrids

2.2.1. Improvement in technical sophistication over isolated DG installations

Microgrids are technical configurations that represent the optimum approach – one where centralized and decentralized systems of energy production exist simultaneously [50,83,84]. They offer the opportunity to integrate spatially dispersed DG units into local energy networks that are grid-tied through a single point of interconnection called the common point-of-coupling. Microgrids are noted as having a clear advantage over individual DG installations in the literature in that they enhance the overall controllability of DG units within the larger grid network. For instance, Driesen and Katiraei [85] identify efficiency, reliability and autonomy as advantages of a microgrid-based approach to renewable energy integration. Zoka et al. [86] note the economic advantage of enabling optimal operation of DG within a microgrid as opposed to their uncoordinated independent operation by individual consumers. Lasseter [87] considers microgrids as a 'subsystem' to the grid network containing DG units and associated loads with the capability to operate in isolation from the utility grid, as well as in parallel to it. These technical features of microgrids indicate an improvement in technical sophistication over isolated DG installations.

2.2.2. Modes and methods of efficient microgrid operation

Microgrids can be operated to maximize the export of energy generated by the constituent DG installations or to co-manage the distribution network with the utility grid [88,89]. Based on the approach adopted, microgrids can become net producers of energy by reducing demand from constituent consumers through energy efficiency measures, or promote overall system reliability and flexibility through grid-coordinated operation, or they can do both [80]. In any case, interconnection standards clarify the preferred operation approaches whilst in connection with the utility grid. Also, in both cases, microgrids retain the ability to disconnect from the grid when disturbances occur – either on the grid network side or in the microgrid. This feature protects the utility grid from untoward fluctuations in energy flow between the microgrid, either when switching from off-grid to grid-tied modes or due to variability of energy generation [84,90]. Through diversity of DG installations like Combined Heat and Power (CHP), in addition to intermittent solar PV and solar thermal systems, variability of energy generation can, to some extent, be reduced, thereby improving the overall microgrid operation [78,90].

2.2.3. Community Microgrids and consumer–utility relationships

The diffusion of isolated DG installations increases the possibility of forming neighborhood-scale microgrids by tying proximate systems together, which in turn impinges on current consumer–utility relationships [46]. In recent diffusion studies, inclusion of spatiotemporal variables indicates a positive influence of 'neighbor effects' on the uptake of solar PV installations [35], suggesting a stronger role of communities than of informational and financial incentives [16,45]. These results indicate the heightened influence of peers, by virtue of social and community relationships, to further energy democratization – and at some point – to organize and create local interest groups around this common issue. In light of these social implications of DG diffusion and the technical necessity of their grid-tied operation as explained above, the vertically-integrated format of utility-based energy services is brought into question [70,91,92]. A number of alternate models for organizing evolving consumer–utility relationships exist and signify a continuum with individual or consumer ownership and control on one extreme and remote control of such systems by a private or public energy company on the other. A small sampling of different models in Table 1 indicates the emerging relationships in the local energy sector, where prosumers become an intrinsic part of the system, and whose active participation is facilitated by private and public stakeholders.

As new frames of institutional and operational partnerships among a broader group of stakeholders coalesce into standard models around participative and community focused outcomes, lessons for best practices and risk management can be derived. Table 1 indicates emerging ownership and operation models, which entail advantages and drawbacks that need attention in subsequent improvements. The consumer control model signifies residential and commercial ownership of RET – particularly solar PV and solar thermal in the urban environment – and is encouraged under conducive regulatory and political conditions [93]. This model enhances consumer autonomy and peer-to-peer influence on RET uptake [35,94]. It however runs into issues pertaining to uneven diffusion of RET, which find currency mainly among financially capable energy consumers. The community ownership model, while rightly purported as highly appropriate for the local scale, faces the question of what constitutes a 'community' [16,94], while the case for Community Choice Aggregate (CCA) model can only be made for municipal energy utilities, thereby limiting its scope [95]. On the other hand, the scope is broadened in the case of Sustainable Energy Utility (SEU), where the local public energy utility is administratively controlled by a third party non-profit entity instead of a municipal government, and which subcontracts private energy companies to fulfill local energy needs [96]. Here, because the procurement decisions of energy services depend on community's choices [97], this discretion in some states may offset RET advancement [93]. Finally, while the leasing model has introduced consumer involvement in traditional utility competition without shifting the underlying paradigm [98], the company control represents a mere extension of traditional utility players into the RET landscape [54,99].

2.3. Smart MicroGrids

2.3.1. Smart MicroGrids: building blocks of Smart Grid

A key difference between Microgrids and Smart Grids is the scale of technology-driven optimization. Microgrids denote a more efficient distribution-scale optimization as described earlier, and Smart Grid represents a large-scale transmission network upgrade through information and communication technologies (ICTs) [88]. While the smart grid vision is predicated on progressively upgrading the entire grid network, implementation of microgrids with ICT enabled energy management capabilities denotes the decentralized version of achieving the same vision – from the ground up. According to Asmus [88], not only is the latter approach more economic and efficient, it offers the much needed innovation in distribution network applications. Several authors also identify the value of a coupled or multi-microgrid concept towards achieving the smart grid vision of energy systems transformation. For instance, the improved operation and management capabilities from a multi-microgrid (MMG) design facilitates higher integration levels of microgrids, and hence RET, into the grid network [105]. The MMG concept is further linked to the smart grid vision; smart grid implementation is simplified by breaking it down into distribution scale implementation and optimization of grid-coordinated MicroGrids [68]. Furthermore, this decentralized version of smart grid implementation helps acknowledge multi-source, multi-product and multi-agent based systems where several energy sources, several locally specific end uses and multiple stakeholders are involved [106–108].

2.3.2. Technology-enabled innovation at the distribution scale

Although consumer involvement through captive (for self-use) or participative (for cooperative production and consumption) energy generation is independent of additional ICT implementation, Smart MicroGrids prove to be intelligent versions of 'dumb' MicroGrids [88]. As such, the degree of smartness of micrograds is greatly supplemented by incorporating ICT, which increase the system interoperability with proximate microgrids as well as with

Table 1
Emerging social and commercial organization models for local energy systems.

Model	Ownership	Operation	Technology	Examples
Consumer control	Consumer	Consumer	Solar PV	Bayonne School, New York [100]
Community control	Local community	User-led collaborative operation of individually or commonly-owned infrastructure	Solar PV	Brooklyn, New York [101]
Energy cooperatives* (community control with legally binding responsibilities)	Group of consumers	User-led operation, management and control of commonly-owned infrastructure (with or without support from the utility)	Solar PV	Germany [102,103] and Sweden [52]
Community choice aggregate	Municipal utility	Contracting of energy and electricity services to private companies	Wind, solar and biomass	California [95]
Third-party administrative control	Publicly owned	Competitive contracting and performance incentives to private energy company by third-party nonprofit entity	Solar PV	Delaware [96,97]
Leasing (intermediate control)	Energy company	Coordinated between consumer and energy company	Solar PV	Baden- Württemberg, Germany [102]
Company control	Energy company	Remote control by energy company	Solar PV	Hunters Point, San Francisco [104]

the larger grid network. For instance, dynamic pricing systems enabled by smart meters encourage (or discourage) consumption to shift overall peak demand as desired [109]. Installing smart home appliances, which communicate with the distribution network via sensors, allows automatic response to these dynamic price signals [110]. As these automated energy networks become commercially viable, the possibilities of integrating plug-in hybrid electric vehicles (PHEVs) and other innovative devices increase [27,28,34,111–113]. Additional technical functionality, therefore, increases the number of smart sensing and optimization tools at the disposal of local energy system operators to facilitate demand-side participation [46].

2.3.3. Technology-enabled consumer participation and consumption psychology

As smart technologies permeate the energy sector, the rise in demand-side participation entails opening-up of communication channels between energy consumers and the energy utility [114]. The two-way exchange of energy and information through smart metering infrastructure, dynamic price signals and networked operation of household appliances and electric vehicles (EVs) requires a heightened understanding of technology implications on consumer response and behavioral patterns [43,49,115]. As more smart devices become 'proven technologies' their commercialization is affected by end user perceptions, suggesting a deeper study of socio-psychological and philosophical aspects of energy consumption behaviors [42,45,46,48,116,117]. These research implications also inform policy questions on the sources of capital investments in smart technologies [40], and appropriate consumer technology standards that retain site and context-specificity of designs given the influence of climatic and consumer characteristics on energy consumption [39]. These in turn inform the commercial and societal consequences of new energy technologies as they relate to sustainable energy consumption [118,119].

3. Interdisciplinary discussion of socio-technical dynamics

The discussion of DES technology configurations offers two general insights. First, it shows the evolution of DES from DG to MG to SMG, with each subsequent configuration overcoming the shortcomings in the previous one. It should be noted, however, that this continuum of technical sophistication does not suggest the practicality of one technical configuration over another, and does not detract from the technical, financial and institutional contexts which dictate their relative feasibility and applicability. Nevertheless, framing the literature on DES in this manner allows other technology configurations – like virtual power plants, hybrid energy systems etc., not considered in the review – to be organized on this continuum to assist an interdisciplinary understanding of the impacts of and from technological improvements. Second, the discussion considers in parallel the social and institutional implications of DES technology evolution. This conveys the underpinning interdisciplinary discourses pertaining to local energy systems and presents the evolution of social and institutional perspectives of DES.

The technical and social dynamics of DES are summarized in the interaction map are shown in Fig. 2. The technical and social perspectives on each technology configuration – before intervention and thereafter – are described in terms of their causes and effects. The *pre-intervention technical and social dynamics* represent the causes that justify the realization of each technology configuration – introduced in the map as an *intervention* whereas the *post-intervention social and technical dynamics* outline their implications that lead to further improvements in technological sophistication.

In summary, increasing affordability of RET increases their cost competiveness and encourages their uptake as awareness among the general population continues to rise (arrow 1). This increase in the uptake of RET like solar PV and solar thermal systems renders Distributed Generation as a valid technical intervention (arrow 2) for local energy infrastructure. Through DG, consumers avail the opportunity to produce their own energy and become prosumers (arrow 3). As prosumers increase, so does the challenge of two-way energy management on the grid due to intermittence of RET (arrow 4), leading to a preference for aggregated grid-tied operation of local energy systems via a common point-of-coupling (arrow 5, *continued*). Together with this technical advantage for aggregated operation of proximate DG units (arrow 6), and cost competitiveness of RET (arrow 'a'), the impacts of 'neighbor effects' on increase in proximate systems help MicroGrids become feasible interventions for local energy infrastructure (arrow 7). The involvement of groups of prosumers within the local energy system through MicroGrids (arrow 'b'), requires new models of social and commercial organization around Community MicroGrids (arrow 8). As such, the success of these models is determined by the social contracts and commercial arrangements between end users and energy utilities, as well as the need for improved energy management on the grid (arrow 'c'). These social and commercial requirements are supported by new technologies like smart meters and accompanying changes in rate structures (arrow 9). This in turn indicates the potential for further improvement in distribution-scale energy management (arrow 10, *continued*) – especially with the preference for aggregated operation of dispersed DG units (arrow 'd'). The application of smart technologies at the distribution-scale renders cross-sectorial connectivity and helps improve user–utility relationships (arrow 11). Such improvements through smart technologies convey the benefits of Smart MicroGrids as a technical configuration implemented at the distribution-scale (arrow 12). Smart MicroGrids entails conferring new roles and responsibilities to end users through new commercial organization models (arrow 'e'), and especially as RET uptake increases and smart technologies become more affordable (arrow 13). The developments in smart technologies, which facilitate realization of these new models of engagement between users and utilities, render the multi-MicroGrid concept feasible (arrow 14) – as a precursor to the larger Smart Grid vision being sought by the Federal government.

The following parallel arguments are elicited from the interdisciplinary interactions across DES technologies as illustrated in Fig. 2.

- Intermittent energy generation of isolated DG installations and the rise in retail energy prices both indicate the need for grid-tied operation of RET through local energy utilities.
  From a technical perspective, grid-tied operation reduces the intermittence of renewable energy generation through interconnections with the utility grid.
  From a social perspective, grid-tied operation imparts further agency to energy consumers who become renewable energy producers (prosumers), as they simultaneously offset their retail energy demand by supplying energy to the grid.
- Aggregated operation of spatially dispersed DG installations and the positive impact of social networks on the uptake of RET both indicate the need for community-oriented local energy development strategies.
  From a technical perspective, community-oriented energy planning encourages aggregation of isolated DG installations into grid-tied community MG.
  From a social perspective, community-oriented energy planning allows for participative energy generation where energy utilities, without losing their revenue base, can engage with

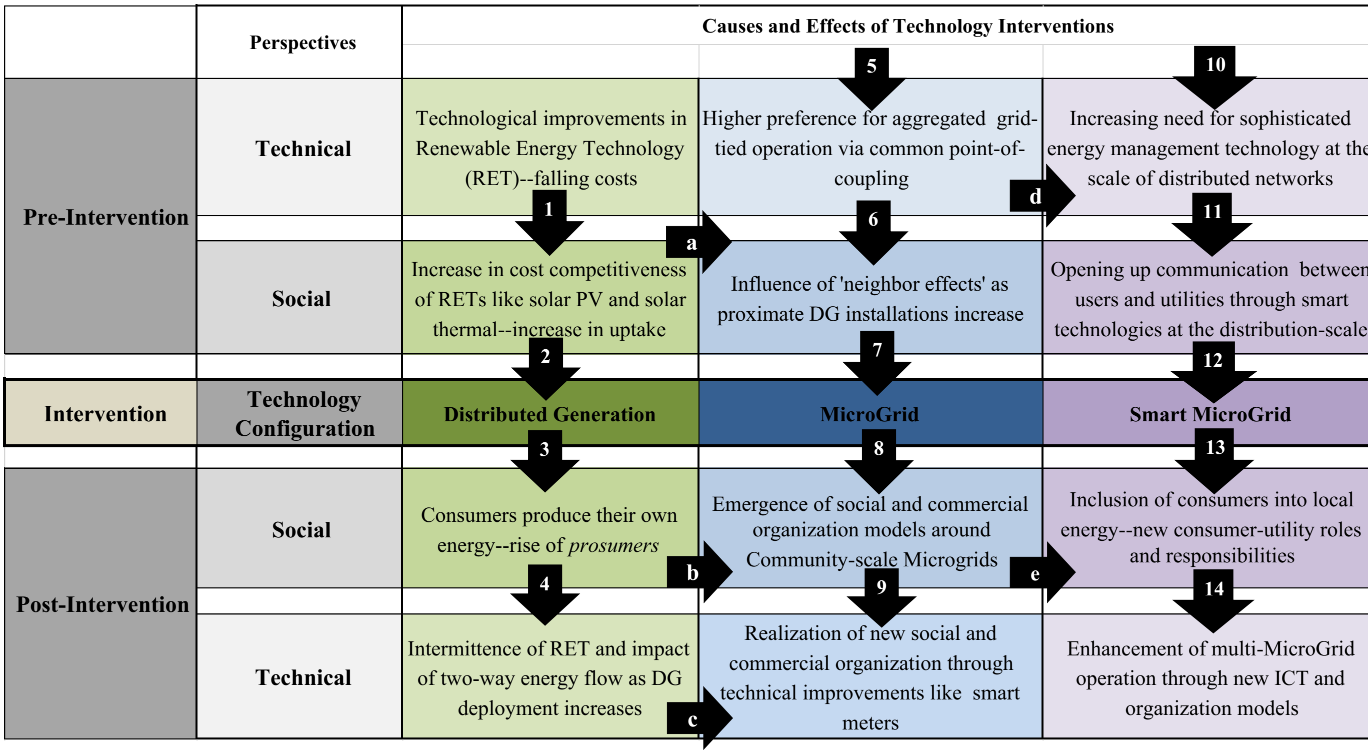

Fig. 2. Interaction map showing technical and social dynamics of decentralized energy systems.

groups of empowered *prosumers* rather than individual passive customers.

- Desired improvements in cross-scale coordination of energy networks (i.e., distribution and transmission networks) and in consumer–utility engagement both indicate the need for incorporating ICT in community MG.

  From a technical standpoint, smart technologies like sensors improve the performance efficiency and controllability of the distribution networks, while optimizing them for large-scale smart grid compatibility.

  From a social perspective, devices like smart meters, enabling two-way communication between end users and utility, convert passive customers into informed participants in energy generation and management, thereby helping curtail unsustainable energy consumption patterns.

In the next section, these parallel arguments are brought to bear on urban planning and local energy policy.

4. Implications for urban planning and policy

At the outset, it is easy to see that as DES continue to gain traction with decreasing costs of RET, cities become the locations of their diffusion, implicating urban planning and policy. The parallel arguments posited above from a sociotechnical view of the literature are considered in terms of their potential implications on urban regions. The following general observations can be made:

- The emergence of grid-tied and community-owned energy generation systems, which entails expansion in the role of consumers in a traditionally private or public sector, offers opportunities to advance participative formats of energy governance [118]. These formats channelize consumer conscious energy conservation, encourage self-regulatory practices, and retain the role of utilities, but as facilitators of community-led energy transitions.
- The criticality of consumers in the process of energy systems transformation [48,50] offers opportunities to empower communities, through education, training, and by providing avenues for social organization around energy-related concerns and concepts [118,120]. These steps require de-commodification of energy [46,121] and institutionalization of consumer participation in local energy generation and management [102].
- Well managed local energy systems transformation implicates other local infrastructure services like water, housing and transportation, as well as regional energy planning, contributing to the dependability of the grid by eliciting ground-up engagement in energy generation and management. Distribution-scale energy generation and management also helps realize local and regional synergies for sustainable and resilient urban development (see [92] for examples).

In light of these observations, the role of planning for climate change mitigation to abate carbon emissions and for climate change adaptation to promote urban resilience is worth discussing. Table 2 summarizes the planning and policy goals and actions that local governments and planners can take towards climate change mitigation and adaptation based on the following discussion.

4.1. Energy planning for climate change mitigation

On-site renewable energy generation has tremendous carbon abatement potential critical for reconceiving energy intensive sectors like buildings and transport. However, energy planning is rarely an isolated endeavor and entails complex linkages to other public services [61]. This invokes the need for integrated spatial and social planning that reconciles the structural underpinnings of different urban infrastructures – from transport to housing to energy – in order to explicate hidden synergies [118,121]. This, in

Table 2
Policy and planning goals and actions for climate change mitigation and adaptation.

Actions for mitigation	Actions for adaptation
Promote integrated system approaches for housing, transport, water, and waste management projects • Incentivize zero-net energy/integrated systems communities utilizing renewable energy and cogeneration technologies with compatible EV and battery technologies (e.g. Hammarby Model, Sweden) [131,132,161–163] • Develop data-driven assessment metrics to track the performance towards achieving desired goals (e.g. GHG emission reductions, optimal material flows, inputs and outcomes of energy and resources, and livability) [131,135] • Resolve solar access related housing conflicts through climate responsive urban design [59,62]	*Improve adaptive capacity of existing infrastructure* • Enhance network redundancy through grid-interconnections [147,164] • Retrofit existing housing stock to install RET and improve energy efficiency [150,151] • Reduce regulatory barriers (e.g. zoning and housing regulations, costs for contracts and transactions) for RET installations and weatherization projects [149]
Promote community-led and inclusive energy planning in community development projects • Ensure formation of a community vision, organizations and programs around local energy issues [13,118,120] • Integrate community-scale MG into new and retrofitting housing and campus design projects [52]	*Prioritize vulnerable populations for social resilience* • Incentivize energy efficiency and weatherization for vulnerable populations (e.g. low-income residents especially tenants, elderly, children etc.) through voluntary on-bill financing [149,154] • Incentivize RET for low-income consumers (e.g. California solar initiative's single family affordable solar homes program and thermal low-income programs/solar water heating) [155,156]
Integrate smart innovations into existing infrastructure, planning and decision making towards climate change mitigation and adaptation • Implement smart metering and clarify sources of investment for advanced communication technologies [39,131,165] • Reduce grid-interconnection processing times and modify energy rate structures [82,166] • Realize multi-microgrid concept using seamless connectivity [90]	*Promote cross-scale resilience from community to nation* • Incentivize community-scale MG projects to improve energy self-sufficiency, especially in preparation for disasters [101] • Align objectives in local energy planning with state and federal smart grid and disaster planning [167,168] • Institutionalize polycentric decision-making structures in local energy projects [169]

part, is afforded by institutional restructure [45,122] and also by land use, physical planning and urban design [59,62,123].

4.1.1. Integrated system approaches in spatial planning

It is known that a resident in a large, single-family detached house in a suburb uses more energy for heating, cooling and traveling than its counterpart living in a smaller multi-family attached unit in urban cores [57,59,124]. DES brings a new perspective to the energy-urban form relationship. Suburban single-family houses provide larger rooftop areas for solar collectors per capita than multi-family houses [62], which contributes to compensating for the larger carbon footprint of suburban residents. Energy democratization, therefore, is bound to generate spatial impacts affecting physical forms of cities [125,126]. Note that urban spatial structure and energy infrastructure have a two-way relationship [125], evident in the urban spatial expansion in 19th century alongside the extension of infrastructure networks, including energy [127], as well as the role of urban form in reducing energy consumption [59,128].

Focusing on trade-offs between energy demand and urban density, recent literature examines whether solar neighborhoods with different density levels can meet their energy demand for buildings and transport – a task that is highly location-specific [123]. O'Brien and Kennedy [129] report that low-density neighborhood could not meet their energy demand through solar energy systems under current technology options; however, they can when applying extremely high-efficient vehicles and solar collectors. Byrd et al. [128] also argue that low-density suburbs could be efficient for on-site solar energy generation, which reduces peak electricity demand and also generates enough electricity to meet daily transport needs – assuming the use of electric vehicles. It should be noted that these studies did not fully assess all the costs associated with suburban development like infrastructure construction and maintenance, public health and farmland loss etc. More comprehensive, empirical research on life-cycle assessment of net energy balances in different urban forms would help planners and policy makers develop systematic DES and energy conservation strategies through both adjusting built environments and adopting new technologies in the long term.

Beyond optimal urban forms for enhancing net energy performance, spatial planning must address the question of optimizing metabolic flows of energy and resources and integrating decision-making processes across different public services like housing, transport, water and waste for capturing horizontal synergies. For example, cogeneration of electricity, heating and cooling requires optimal mix of uses, usually multi-building systems, for achieving load diversity, system efficiency and economic feasibility [61,130]. The Hammarby model from Hammarby Sjöstad, Stockholm in Sweden, provides a striking example of an integrated system approach that considered metabolic flows of energy, water and wastes at an urban district level [131,132]. Additionally, the *trias energetica* concept identifies sustainable integrated urban design principles for the built environment [123]. This approach may be expanded to include increasing energy efficiency through tree placements [133,134], reducing energy losses by recovering waste heat for residential heating [123], and enabling renewable energy integration through building integrated PV systems, solar facades and electric vehicles [27,111]. Tracking complex metabolic flows and operational performances of integrated infrastructure systems has been challenging; such systems require the development of data-driven, systematic assessment metrics to measure their operational performance towards achieving desired goals (e.g. GHG emission reductions, optimization of material flows, and effects of energy resources on livability) [131,135].

Planners and local governments can play a key role in resolving conflicts in DES implementation on the ground through planning tools and technology adoption. Given most local energy interventions are based on solar energy, providing solar access is primary for maximizing energy generation. As more rooftop solar PVs and solar thermal systems are installed, planners face challenges in minimizing conflicts among neighbors through solar easements to protect solar access [136]. Planning tools encompass not only zoning ordinances (e.g. height restrictions and setback requirements) for building structures but also coordination with tree ordinances [62,133].

4.1.2. Socially inclusive, community-led energy planning

Planning and policy should support socially inclusive, community-led local energy planning that is driven by a shared vision for community organization, and local education and outreach activities [118,120]. In addition to enabling a good fit between DES and the community [16], the rise of co-providers or *prosumers* of energy services requires institutionalizing consumer participation [102], as well as assigning new roles and responsibilities to streamline multi-stakeholder engagement [121]. In doing so, planners are required to offset potential asymmetric social–economic gains in the community due to unequal financial capacities and variable space constraints for some households – potentially restricting ownership of energy generating assets like rooftop solar PV systems [137]. Therefore, the institutional and technological improvements for mitigating carbon emissions from urban infrastructure services – particularly the energy sector – are significantly more effective when collaborative and inclusive cross-sectorial synergies are operationalized through local energy planning.

Incorporating MG into new and retrofitted housing and campus projects is exemplary of community-scale energy planning. Encouragingly, a number of real world examples highlight the economic and technical feasibility of MGs as sustainable and resilient energy infrastructure [138]. MG deployments have continued to increase worldwide, with majority of them located in North America occupying 44% of the global market share [139]. The deployments in US include campus MGs in UC Irvine [140], and Illinois Institute of Technology [141], as well as community MGs in Brooklyn [101] and Hunters Point [104] among several others. Intended for purposes ranging from research and education in case of campus MGs, to creating resilient, efficient and clean energy infrastructure in case of community MGs, the applications are widespread and increasing in number.

4.1.3. Integrate smart innovations into existing infrastructure planning

Smart metering and sensing technologies can afford cross-sectorial connectivity, especially between buildings and transport [27,28,61,111]. These technologies enable opening up of the previously obscured communication channels between utilities and consumers [39,110,114,121] and between smart homes [142], encouraging energy conservation, participative energy management, and thus affecting norms like billing and payment structures. MGs and SMGs affect the built environment and the urban form influences their design and implementation. Depending on their geography, MGs help cities reduce their dependence on energy generated outside their jurisdictions and hence its exurban carbon footprint [143]. In turn, the size and expanse of MGs depend on the city's physical form as well as the regulatory definitions of urban neighborhoods [130].

4.2. Energy planning for climate change adaptation

As the threat of natural disasters continues to increase, mitigation, while necessary, is no longer sufficient. Climate change adaptation overlaps to a considerable extent with mitigation actions taken to reduce carbon emissions. It further includes strategies that build urban resilience – a concept that has roots in the social–ecological resilience theory [144,145]. From a social–ecological perspective, resilience rebuts assumptions of stability and predictability of complex systems like urban energy systems. Here, resilience is given to acknowledge the existence of multiple states of stability, which in terms of design translates to redundancy, connectivity, and diversity [146,147].

4.2.1. Improve adaptive capacity of existing infrastructure

Retrofitting existing housing stock to enable complementarity between energy efficiency improvements and renewable energy deployments plays a critical role in enhancing adaptive capacity against rising temperature extremes [123]. With evidence for more local support for energy efficiency than RET projects [148], it would be advisable to draw on policy lessons for increasing energy efficiency towards RET uptake, which face similar, if not the same challenges like capital and transaction costs, zoning and housing ordinances, and quality verification [149].

These complementarities should also be extended further incorporating energy generation diversity at the distribution (or city-)scale with reducing energy demand and implementing energy efficiency retrofits [150,151]. Redundancy in and interconnectivity of distribution networks improves the network capacity to retain full or partial function when another part of the network fails, and diversity of energy generation units ensures that no single component is over-relied upon. RET-based MG and SMG, as described earlier, demonstrate these characteristics by breaking down the network into smaller, functional, efficient, and thereby more resilient systems [12,68].

4.2.2. Prioritize vulnerable populations for social resilience

Adaptive capacity also relies on social resilience, captured by improving social capital, enhancing inclusivity and trust, and expanding the diversity of resources that the community depends upon [152]. Consideration of social planning for resilience building, in addition to environmental and physical adaptations, is further justified when the relationship between social structures and urban form is scrutinized [153]. In the case of urban energy planning, financial and spatial restrictions on ownership of DG assets is an issue of social planning [118], wherein concerns related to social equity and inclusion in on-going energy transitions should be considered.

Given the increasing risks of extreme weather and climate change, incentivizing RET, energy efficiency and weatherization for vulnerable populations is critical for enhancing social resilience. Low-income residents, especially when they are tenants, incur a high-energy burden, most often without commensurate benefits from housing maintenance and upgrades, and thereby face higher risk from and vulnerability to temperature extremes [154]. In this case, voluntary based financing program that ensure concurrent benefits for landlord and low-income tenants (e.g. on-billing financing) could be more effective than regulatory restructuring approach [149]. As for increasing RET installations, California Solar Initiative's Single Family Affordable Solar Homes (SASH) program and Thermal Low-Income Program/Solar Water Heating provide good examples [155, 156].

4.2.3. Promote cross-scale disaster resilience from community to nation

Resilience, based on social–ecological theory, broadens the normative view of emergency management to enable dealing with slow-acting systemic disturbances like infrastructure deterioration and fuel price hikes, as well as sudden shocks like earthquakes, hurricanes or other catastrophes. Seen this way, current responses to disasters by state and local authorities seem predominantly reactive. On the other hand, resilience planning instills proactivity in disaster and emergency management. Such an approach substantively enhances the four phases of emergency management – mitigation, preparedness, response and recovery – as defined by the Federal Emergency Management Agency (FEMA) [157,158]. DES, particularly MG and SMG, help achieve this enhancement. For example, RET based DES accomplish two purposes; first, they mitigate the root cause of climate change by offsetting carbon emissions, and second, they enhance the adaptive capacity of local energy infrastructure. Therefore, by prioritizing MG deployments after hurricane Sandy, the state of New Jersey is improving the long-term resilience of its energy infrastructure, particularly for critical services like hospitals, emergency response centers and transit [159].

Furthermore, adopting resilience thinking provides impetus for scale-specific energy planning approaches at the neighborhood, local and regional levels, and promotes cognizance of cross-scale interactions [160]. For instance, polycentric development of local energy systems interconnected across an urban region increases regional resilience; disruption of energy services in one disaster-hit city can be recuperated through assistance from neighboring cities. Participative energy systems, for instance through community cooperatives or citizen co-management with private or public utilities or both, have the potential to increase social consciousness and cohesion, resulting in a higher level of social resilience [153].

5. Conclusion

This study provides a useful framework for examining the co-evolving social and technical dynamics – pertaining to Distributed Generation, MicroGrids, and Smart MicroGrids – as a continuum of increasing technical sophistication and smartness supported by extensive literature from various disciplines. Such a view of literature on DES has helped to draw out parallel arguments across interdisciplinary sociotechnical research landscape. Admittedly, the continuum greatly simplifies the process of socio-technical advancement of DES but offers valuable insights for urban energy planning and policies. In this article, the insights obtained have been considered in particular reference to climate change planning, for mitigation as well as adaptation. The observations help consider the potential of urban energy planning and policymaking in guiding the design and development of sustainable energy systems in cities, through collaborative and community-led energy transitions, facilitation of participatory formats of local energy governance, and end user engagement from the ground-up.

The emergence of MGs and SMGs as preferred configurations for local energy infrastructure requires a careful examination of urban aspects – especially physical, institutional and social – which get implicated as energy decentralization and democratization continues. The impacts of urban form on the design and operation of local energy services are as equally important as understanding how new energy technology interventions change the urban spatial structure – particularly when smarter technologies continually enhance human–technology interactions and erode sectorial silos. Therefore, research on urban or suburban low carbon growth, through decentralized technological interventions, inevitably leads to questions on planning strategies that can simultaneously enable urban carbon footprint containment and mitigation, as well as create an integrated, cross-sectorial model of implementation. With critical energy transitions occurring at the urban scale, collaborative, participative and equitable public engagement models become relevant, especially given the likelihood that co-providers of energy services will continue to rise with increase in awareness and plummeting costs of RET.

Essential to this discussion is the resilience of urban energy infrastructure as the threat of climate change related disasters draws near. The increase in deployment of MGs across cities – in university campuses and by local communities – offers local governments and planners the opportunity to consider their integration into a polycentric regional network of coupled SMGs, designed for backwards compatibility with the larger smart grid network. The cross-scale implications of realizing such a MMG concept requires further investigation on aligning local projects with existing regional and national initiatives, several of which focus on resilience, albeit merely as a buzzword. Early efforts to understand and transfer fundamental concepts of resilience for adaptation planning from socio-ecological theory are evident [170–172], but further research is needed to operationalize abstract concepts from this emerging scholarly domain into practical and actionable steps for planning resilient urban energy systems.

As a reflection of the literature reviewed, the article focuses primarily on solar PV and solar thermal applications given their immense urban-scale applicability. However, the framework can be applied to other RET such as wind and biomass as their urban applications evolve. By analyzing best practices and literature from the U.S. and Europe, this article provides insights for urban planning and energy policy in reference to the sociotechnical landscape of DES in North America, mainly the U.S. and Europe. Further research is recommended to extend the utility of this approach to classifying DES and various RET to sociotechnical landscapes in other regions of the world.

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