Resilience of Community Energy Systems and Multidimensional Transformations: Resilient Behaviors, Functions and Scale

Adrian Jimenez, Institute of Physics, University of Oldenburg (corresponding author)
adrian.jimenez@uol.de
Tel: +49 (0) 441 798 3212
Institute of Physics
University of Oldenburg
Carl-von-Ossietzky-Straße 9-11
D-26129 Oldenburg
Herena Torio, Institute of Physics, University of Oldenburg

Abstract

To be part of the required multidimensional transformations and cross-cutting solutions, the development of energy systems and the transitions towards renewable energy (RE) sources should be interconnected with local needs and conditions, and cannot be merely based on technical and economic decisions. Such transitions should be able to consider the present and future needs of communities and neighborhoods in the lower organization level (distribution grid) and involve their interest and agency in the decision making process. Several communities in Germany are interested in developing local RE systems to fulfill their needs, utilize local resources, contribute to reduce climate change and add local value. Therefore, there is a need of assessment methodologies to evaluate the impact of RE systems alternatives and their capacity to fulfill the community needs and foster this transition.

Consisting of functions to be fulfilled, services to be supplied and the integration of several RE technologies working in fluctuating conditions, local RE systems are a result of the integration of multiple dimensions. A holistic assessment with a system approach should be multidisciplinary.

Future energy systems will need to operate under changing conditions, such as: varying demand from the social and technical perspectives, including changes in social habits and sectors coupling; and fluctuating production and climate change impacts from the environmental dimension. Resilience theories study the capacity of systems to cope with changes, while maintaining some system elements (e.g. functions and structure). This is achieved by the systems through resilient behaviors: toleration and restoration, which absorb disturbances and restore the system; and adaptation and transformation, which enhance the system capacity to tolerate disturbances, recover and avoid their negative effects. Despite multiple understandings of transformation and adaptation, they include the creative and innovative capacity of complex adaptive systems. Including the ability to enhance system tolerance, renewal, reorganization and capacity of transformation.

The objective of this paper is to explore the integration of multiple dimensions in energy systems to perform resilience assessments. It suggest Community Energy as a central scale of observation with high potential to foster adaptability and transformability in energy systems. This paper argues, first, about the multi-dimensionality of energy systems and introduces Community Energy (CE) systems as one suitable framework for analyzing the meaning of adaptability and transformability in multiple dimensions of community energy systems. It is followed by an introduction to resilience theory with a strong focus on resilient system behaviors. Finally, it explores energy system scales, and the potential effect of their dynamics and range of impact. Thereby the present paper highlight the potentials of CE to contribute to the development of resilient energy systems and to reach multidimensional transformations.

1. Introduction

Energy systems and the services they provide are interdependent with technical, social, economic and environmental dimensions (Santoyo-Castelazo & Azapagic, 2014). This interdependence is key to develop multidimensional transformations that search solutions for socio-ecological problems. Community energy (CE) has the potential to play an active role in the development of multidimensional solutions (Hewitt, et al., 2019) (Huybrechts & Mertens, 2014), due to its local approach and possibilities to integrate alternative objectives and paradigms.

Energy systems operate under dynamic environments with internal and external disturbances, which increase when multiple dimensions are considered, such as with CE systems. Energy systems must be able to fulfill their functions, even if they are affected by disturbances and changes that are unknown in this moment, including the ones derived from the energy transition (Jesse, Heinrichs, & Kuckshinrichs, 2019). Assessment and design tools utilizing perspectives from resilience theory can help to prepare and understand the capacity of systems to cope with changes, adapt and transform while maintaining the systems functions. These tools could support in the development of resilient energy systems able to fulfil their functions under changing conditions and disturbances.

This paper analyses the possibilities to integrate resilience perspectives within energy and CE systems. In the following sections, the multidimensional impacts of energy systems is explored, as well as the potential of CE to integrate multiple dimensions. Afterwards, a deeper analysis of the concept of resilience is done, in order to search for possibilities to integrate multiple dimensions within CE as functions and disturbances. Finally, it analyses three energy system scale, while exploiting the potentials of CE to foster adaptive and transformative capacities in the energy system.

2. Multi-dimensionality in energy systems analysis

Energy systems, besides supplying societies with energy, are interdependent with the social, economic and environmental dimensions (Huybrechts & Mertens, 2014). For example, economic capacity is tightly related with energy availability and demand (Steinberger & Roberts, 2010). Simultaneously, there are multiple social, technical an environmental problems that must be tackled if societies aim to live in a fair and sustainable manner, which operate safely within the earth limits. Multiple approaches define and tackle this problems, such as Sustainability and Socio-Technical Transitions (Markard, Raven, & Truffer, 2012), Socio Ecological Transformations (SET) (Fischer-Kowalski & Rotmans, 2009) and Degrowth (Kallis, 2011). Several political plans and agreements, such as the Sustainable Development Goals (SDG) (UN, 2015) and the Climate Change Paris Agreements (UNFCCC, 2015) establish goals to be reached in that processes.

One of the strongest and most attended impacts of energy systems is climate change. Energy systems are in the center of climate change discussion, as 95% of anthropogenic CO2 emissions (excluding land use emissions) are linked to the energy sector, and global trends show that energy and fossil fuels demand will continue increasing (WBGU, 2011, S. 54). The urgency of mitigating climate change has broad scientific, political and social consensus. Therefore, multiple countries have agreed in the Paris Agreement to keep the global temperature rise below 2° C (Agreement, 2015) and the EU has plans to be climate-neutral by 2050 (EuropeanUnion, 2020). One of the main points of attention is the transformation of the energy systems from relying on fossil fuels to renewable energy sources.

As energy systems are so broadly interconnected with other social, technical and environmental issues, transformations within them are required as part of more general and multidimensional transformations and cross-cutting solutions. Following (Sommer & Welzer, 2014, S. 66) “an energy transition without social and cultural transformation could increase the destruction power of unsustainable social and economic systems if an unlimited availability of renewable energy in an expansive economy (rebound effect) and cultural model remove barriers to resource intensive living and mobility styles, accelerating the degradation of soil and sea”. Thus, a transformation towards sustainable energy systems needs to address these different dimensions. To be part of multidimensional solutions, the development of energy systems and the transitions towards renewable energy (RE) cannot be merely based on technical and economic decisions. Instead, energy systems should address environmental aspects, interconnected local needs and conditions, the present and future needs of communities, as well as their interest and agency in decision-making processes.

Interdisciplinary work is required to achieve and foster such multidimensional transformations. Despite being highly desired, the integration of multiple dimensions increases the complexity of system analysis, as each dimension

(Social, Ecological and Technological) have different operation dynamics and theories from different disciplines.

Socio-technical systems and socio-ecological systems have perspectives that integrate respectively two dimensions within their conceptualization of the system. A socio-technical perspective studies the development of technology and its social interdependencies. It puts “technological and social practices of human needs at the centre of its analysis” (Smith & Stirling, 2008). Transition management uses such perspectives, searching for a transition towards more sustainable socio-technical systems in the long term. A social-ecological perspective focuses on the environmental impacts of the systems and the social processes and dynamics influencing them (e.g. governance, centrality). Adaptive management searches the maintenance of social-ecological system functions, avoiding large-scale collapse. As they have different scopes, the success of one does not mean the success of the other (Smith & Stirling, 2008).

From the perspective of infrastructure (Grabowski, et al., 2017) propose a deeper interdisciplinary and intersectional dialogue. They present a deeper analysis of infrastructure dimensions, seeing those as irreducible Socio-Eco-Technical systems. They propose that such perspective would allow a simultaneous analysis of impacts and structures or processes influencing them. This approach includes infrastructure governance to address the social dimension and infrastructure lifecycle analyses for characterizing the ecological one, allowing the integration of the three dimensions.

This work searches for possibilities to analyze and enhance resilience of energy systems through Community Energy Systems. Specifically for possibilities of analyzing energy systems resilience integrating multiple dimensions, where each of them operate with its own elements, dynamics and objectives, but are part of one system.

3. Community Energy (CE)

Community energy can be a useful object of analysis for the aim of this work, as CE Systems are able to capture social needs and enable the society to take active and local participation in socio ecological transformations. CE have already played a fundamental role to accelerate the German and the Danish transition toward renewable energies (Debor, 2014) (Wierling, et al., 2018).

It does not exist a unique definition of CE. (Brummer, 2018) considers that all activities dealing with energy systems and the involvement of a community can be considered Community Energy. Examples of CE systems are projects related to generation and consumption of energy within rural (Yadoo & Cruickshank, 2010) or urban conditions, such as solar and wind plants, electrification, district heating and energy efficiency. Thus, CE often includes the use of renewable energies, sustainable technologies, and operation models that increase the community participation and democratic control. A direct participation of governments and big business structures is normally absent (Brummer, 2018).

Communities get involved in activities related with energy systems due to multiple reasons, such as supplying energy to a community, or improving and taking part in environmental, political and financial issues related to energy systems (Sagebiel, Müller, & Rommel, 2014) (Katre, Tozzi, & Bhattacharyya, 2019). These communities are normally formed by people with shared interests that live ether in the same area, or in different geographic locations (Musall & Kuik, 2011). Each of them with different impacts on processes and outcomes (Tarhan, 2015).

The goals and structures of CE enable potentials to develop multiple benefits, not only for the community involved, but also in general to the society. (Brummer, 2018) classifies CE benefits in seven categories:

- *economic benefits*, improving social inclusion and employment;
- *education and acceptance*, creating trust and examples;
- *participation,* increasing political participation and supporting behavioral change;
- *climate protection and sustainability,* influencing lifestyles and energy-climate awareness;
- *community building and self-realization*, improving and empowering communities;
- *renewable energy generation targets*, with direct participation as change agent, supporting transformation processes;
- *innovation*, technological and within societal norms.

Brummer also identified six barrier categories that impede the formation and resilience of CE projects:

- *Organizational issues, legal framework and planning requirements*, related with costs and regulations;
- *Discrimination against big companies*, related with the market structure, legal frameworks;
- *Lack of institutional and political support*;
- *Skepticism and opposition*;
- *Lack of resources, expertise and resilience*, related with capital, low resilience (legal changes and business risks), uncertain Feed in tariffs, costs;
- *Saturation* effect related with members and projects.

There are multiple barriers that CE projects must overcome to be successful, which are dependent on multiple internal and external changing conditions. However, CE has also shown multiple properties that make it suitable for supporting multi-dimensional transformations at a local level. CE need to be able to overcome these barriers continuously in order to provide its services and impact transformations in the long term.

These barriers and possible solutions could be found through resilience assessment methodologies. Such methodologies could also aid to assess properties or conditions, which would give CE systems the capacities to overcome them. Such methodologies can support CE members and policy makers. The following section explores deeply the concept of resilience and its applicability towards CE and multidimensional transformations.

4. Resilience Theory

The aim of developing reliable, sustainable and economic energy systems is present both in regions that are developing energy infrastructure to supply basic needs, and in regions with high levels of industrialization. It is socially desirable that energy systems are able to fulfill their *functions* while operating under dynamic environments with internal and external changes (such as variable load and energy resources, natural disasters, prices, social expectations, etc.). To achieve this, energy systems should be able to cope with known and unknown *disturbances*, which might create stresses and disruptions. Resilience theory is a common approach to analyze the reaction of systems to disturbances.

There are multiple approaches to resilience, derived from different disciplines. As each perspective derives in multiple theories and methodologies, there are not universal definitions for resilience concepts. Resilience approaches are increasingly being used both with a descriptive-analytical perspective that aims to understand or identify the dynamics of systems, and a normative-interventionist perspective that aims to control or govern systems to guarantee the fulfilment of its functions (Hamborg, Meya, Eisenack, & Raabe, 2020) (Folke, 2006).

Holling distinguishes two resilience perspectives according to their understanding towards the stability of a system. The first one, engineering resilience, looks at “stability near an equilibrium state” and “focuses on efficiency, constancy and predictability”. It searches for a fail-safe design. The second one, ecosystem resilience (first called ecological resilience), looks at conditions “far from any equilibrium steady state” and “instabilities can flip the system into” another stability domain. It “focuses on persistence, change and unpredictability” (Holling C. S., 1996), and searches for a safe-fail design. Ecosystem resilience is the resilience of complex adaptive systems (CAS), which are able to learn, adapt (Jesse, Heinrichs, & Kuckshinrichs, 2019) or transform.

As multidimensional CAS, energy systems dynamics can be seen as the interaction of multiple self-organized subsystems at different time and space scales, which derive in emergent and interdependent dynamics. These subsystems can have elements at different dimensions, such as social, technical and ecological. CAS have neither linear, nor totally predictable dynamics, and cannot be fully controlled by traditional control interventions. Resilience of CAS is achieved through system abilities to cope with disturbances, learning mechanisms and self-organization (without intent) that govern system dynamics (Walker, Hollin, Carpenter, & Kinzig, 2004). These abilities are not necessarily found in individual elements of the system and can include intentional and unintentional human interventions, related with foresight and intentionality (Gunderson & Holling, 2002, S. 99). They are derived from system internal properties and mechanisms that interact with the system dynamics to procure the maintenance of the functions of a system.

While studying the dynamics of socio-ecological systems, (Gunderson & Holling, 2002) created the term Panarchy to represent the “nested nature of temporal dynamics and spatial structures” and complex dynamics. The Panarchy is formed by self-organized adaptive cycles of different time (fast-slow) and space (small-large) scale, nested one within the other and interlinked in a whole. In the Panarchy, the scale of observation (intermediate) interacts with smaller, faster scales that are more likely to implement innovations; and bigger and slower scales preserve past successful elements. During times of change in the intermediate scale, each of them has, respectively, the effect of revolt (innovate, create, learn) and remember (conserve, continuity), which guide its adaptive and evolutionary nature. Each level then transform with transfers between scales.

Resilient Behaviors – What Makes Systems Resilient?

A system is resilient through system abilities to cope with disturbances, system learning mechanisms and system self-organization (with and without intent) that govern its dynamics (Walker, Hollin, Carpenter, & Kinzig, 2004). (Hamborg, Meya, Eisenack, & Raabe, 2019) classify these system abilities as four resilient behaviors: 1) toleration and 2) restoration, which absorbs disturbances and restore the system functions, making it robust; and 3) adaptation and 4) transformation, being these last two preventive resilient behaviors that enhance the system capacity to tolerate future disturbances, recover and avoid their negative effects.

Resilient behaviors are part of system abilities derived from internal properties and mechanisms that interact with the system dynamics to procure the maintenance of the functions of a system. Each dimension of the system has its own dynamics and resilient behaviors, which are not necessarily generated or represented by individual elements of the system.

There is a lot of research focused on toleration and restoration, the resilient behaviors that create the system buffer capacity to absorb disturbance and allow persistence (Folke, 2006). This perspective mainly corresponds to (Holling C. S., 1996) engineering resilience, which describes the ability of a system to return quickly to its equilibrium point after a shock or disruption. Engineering resilience is useful to evaluate the effect of quantifiable known disturbances on the technical dimension of systems, but not so much for unknown disturbances or to represent aspects from social dimensions (Jesse, Heinrichs, & Kuckshinrichs, 2019).

There is less research on adaptation and transformation, behaviors related to the renewal, reorganization and development of system capacities, in which disturbance gives a resilient system the opportunity to create new things, innovate and develop (Folke, 2006). These capacities are more related with ecological resilience (Holling C. S., 1996). This is the resilience approach oriented to Complex Adaptive Systems (CAS), which focuses on persistence, change and unpredictability. It analyses systems far from an equilibrium state and has multiple stability domains. Ecological resilience analyses the ability of a system to benefit from changes and react to unknown disturbances, including the unknown unknowns (Chandler, 2014). Ecological resilience usually includes the technical and social dimensions as equally important and can be used to integrate multiple dimensions of energy systems. Applications include crisis recovery and preparation (Erker, Stangl, & Stoeglehner, 2017) and resilience of transitions for energy systems (Binder, Mühlemeier, & Wyss, 2017).

Adaptability and Transformability

Despite existing differences in the understanding of adaptability and transformability by multiple resilience perspectives, in general, these terms include the creative and innovative capacity of complex adaptive systems: from altering system thresholds to enhance system tolerance or bypass disturbances; to creating new systems and opportunities under undesirable or untenable conditions. They cover the system capacity of transformation, renewal, reorganization and development, which is required for sustainability discourse and to speed up desired transformations (Folke, 2006).

Although adaptability and transformability are recognized as fundamental for resilience theory, the definitions of these terms are still vague, and both of them are among the less mentioned keywords in resilience papers analyzed by (Jesse, Heinrichs, & Kuckshinrichs, 2019), together with socio-technical systems. A deeper understanding and integration of these concepts within resilience theory would help to understand preventive resilient capacities of energy systems, such as their ability to react to changes, renew and learn from them; to identify which features enable systems to change towards desirable directions and speeds and avoid undesirable ones.

(Hamborg, Meya, Eisenack, & Raabe, 2019) define adaptation as a preventive behaviour that enhances the system's capacity "to tolerate disturbances or recover from negative effects" (tolerance or restorability). Transformation is also a preventive behaviour, but it "enhances a system's capacity to tolerate a particular disturbance entirely".

(Walker, Hollin, Carpenter, & Kinzig, 2004) recognize that the distinction is not totally defined and is subject to interpretation. For SES, adaptability is seen as the intentional "capacity of actors in the system to influence resilience" or build resilience through collective action (Folke, 2006). Adaptability operate within the existing dynamics of a system, for example: moving thresholds; "moving the current state (or trajectory) of the system away from or closer to the threshold"; changing the difficulty to reach a threshold; or altering the interaction across scales. Transformability is seen as "the capacity to create a fundamentally new system when ecological, economic, or social structures make the existing system untenable", or when reconfiguration of the existing system is extremely difficult and is necessary to do it with new introduced or emergent variables. It alters fundamentally the nature of a system and its scale.

As seen, complex adaptive systems are self-organized systems, which can be modified and transformed with intent and without it (Walker, Hollin, Carpenter, & Kinzig, 2004). Both, self-organization and intent are dependent in the system elements and dynamics within each dimension. Systems with a social dimension, such as social ecological systems, have human actors with intent. "Human cognitive abilities provide the ability for developing forward expectations that should allow human-dominated systems to respond not just to the present and the past, but to the future as well" (Gunderson & Holling, 2002, S. 35). Social-ecological systems emphasize transformation to improve, instead of adapting to the actual conditions. This is done through adaptive governance, which relies on the collaboration of stakeholders at different scales (Folke, 2006).

(Walker, Hollin, Carpenter, & Kinzig, 2004) suggest that system attributes that promote adaptability and transformability have an overlap (e.g. "diverse and high levels of natural and built capital"). Besides, "attributes required for transformability will emphasize novelty, diversity, and organization in human capital—diversity of functional types (kinds of education, expertise, and occupations); trust, strengths, and variety in institutions; speeds and kinds of cross-scale communication, both within the Panarchy and between other systems elsewhere".

Lock-in Behavior

Lock-in behaviors are ambivalent for resilience assessment. A system is locked-in when it, or some of its elements, do not react to external changes (known or unknown disturbances). While this might be desired for elements expected to be resilient, it can also derive in a system without the capacity to react to fundamental change, potentially affecting the resilience of the full system or of some elements. An example, in the context of climate change and renewable energies transition, are energy systems that keep technologies that do not provide anymore the required response to challenges (such as coal power plants, with strong lobby capacity and structural dependence, but low operational flexibility and high greenhouse gases emissions). These individual technologies lead to a locked-in system because they imply patterns and institutions that do not allow desired changes to happen at the pace necessary or at all (Goldthau, 2014).

System Functions and Structure – Resilience of What?

While it has been mentioned that resilience is the capacity of a system to cope with disturbances, it has not been clearly said what should be maintained (i.e. "resilience of what?"). Answering that question leads to identifying the "resilience object" and implies a detailed definition of the properties to be maintained. Identifying the "resilient object" in an open and transparent manner is of fundamental importance, as it makes the normativity of analysis obvious and strongly influences strategies for resilient transformations within the system. While analyzing the resilience multidimensional systems, it might be required to distinguish the resilience object for each dimension. Whether it is the structure, function (or even a transition and dynamics) depends on the elements considered within the system and the goal of the analysis.

(Walker, Holling, Carpenter, & Kinzig, 2004) understand resilience of social ecological systems as "the capacity of systems to deal with shocks or disturbances and reorganize" while maintaining the system functions, structure and identity.

In contrast, resilience analysis of socio technical systems focuses on maintaining the system functions. Energy systems are human made systems that provide services and functions to a society. From the perspective of infrastructure systems, resilience is the "ability to withstand and recover from severe stress and extreme events without losing its ability to provide the services it is designed to deliver" (Gößling-Reisemann, 2016). Structural changes are only the focus of these analyses if they impede or counteract the maintenance of system functions. For example, transition management goal is to "achieve structural (socio-technical) transformations that improve performance in the desired sustainability functions. The aim is thus resilience with respect to these functions and those socio-technical structures that are judged best to deliver them and emphatically not with the countervailing incumbent structures themselves" (Smith & Stirling, 2008).

Functions of Energy Systems

While looking at energy system functions and services, the most basic service in the technical dimension is the 1) supply of energy at an 2) affordable price (Sharifi & Yamagata, 2015). Its functions depend on the time and space scale of observation, which already interrelate the social and technical dimensions. For an electricity system, from a technical dimension, supply of energy could be defined as continuity of service and power quality. Continuity of service in some grids means power available 99% of the time, while in others during specific timeslots during the day. Power quality, consist in keeping voltage and frequency levels (among others) values within the limits specified in the grid nominal values and tolerances (e.g. 50/60 hertz for frequency and 110/220 Volts for voltage). The definition of the second part of the service, affordable price, has more variability, since affordability strongly depends on the amount of energy required and the economic capacity of the user.

The mentioned functions show the influence of normativity and the influence of local conditions in the selection and definition of energy systems functions. Functions are not inherent and completely fixed parts of energy systems, but are influenced by human decisions with normative perspectives. Moreover, we have seen that it is common for CE projects to be developed in places where the service of supply of energy is already fulfilled, and the goal of developing CE systems is to provide the same services together with extra benefits to the community, sometimes even at higher price (Sagebiel, Müller, & Rommel, 2014).

Scale of Observation

In this section, we analyze advantages of selecting CE as the scale of observation in order to support an overall resilience of energy systems. The analysis is inspired by (Gunderson & Holling, 2002, S. 63) Panarchy scales, which state that scale of observation influences the possible actions and explanations of phenomena.

While analyzing a system, the scale of observation influence the speed and impact range of the dynamics in which the system interact. In order to design resilient energy systems with multiple dimensions, the scale of observation should allow a meaningful integration of dimensions, in which the system can experiment and interact. It should also provide with the conditions to contain and develop learning capabilities that let them adapt and transform when required.

The present analysis has some conceptual differences with the one of Panarchy, such as considering systems that are not strictly nested in the scales, and an analysis focused on dynamic and impact range differences. It considers three scales time/scale within energy systems, looking at 1) Individual Household Energy Systems as a smaller scale, 2) Utility or Regional Energy Systems as a bigger scale and 3) Community Energy system as the scale of observation, with an intermediate scale.

Small Scale - Individual (Household) Energy Systems

Individual (household) energy systems are in the smallest side of the scale, and so is its range of impact, which is limited to one household or small facility. A system designed to be implemented at this level would normally maximize the benefits in a household, and its implementation depends on each household interests, economic capacity, available space and energy consumption.

Individual systems can have a simpler decision-making process. From other perspective, multiple individual systems could derive in higher overall environmental impacts (than a system providing the same service but installed in a higher scale) due to the installation of duplicated infrastructure (for example smaller inverters or batteries for decentralized and small photovoltaic systems). Its small scale derives in fast moving dynamics, with small impacts and high capacity to experiment.

Bigger Scale – Utility or Regional Energy Systems

Utility, regional or larger energy systems are in the bigger scale. Systems designed at this level require high investment, and therefore their development is limited to big companies or governments. Large-scale infrastructure requires big amount of space and time, and its design usually optimizes efficiency and cost. The magnitude of the systems and the limited capacity for the public to influence the process derives often in conflicts due to the use of land, or undesired not attended local effects. Some examples are the environmental, political and social issues derived from coalmines, big hydropower plants and big wind farms. Its large scale derives in slow moving dynamics, with high impacts, low capacity to experiment and high capacity to conserve memory of past successful developments.

Intermediate Scale – Community Energy Systems (Scale of observation)

CE systems lie between individual and utility scale systems. This is a broad range, which could go from multiple households in a building, to neighborhood and city scale. The impact range of CE depends in the size of the community, although (Brummer, 2018) reports the risk of losing community support by growing too big. The design of CE systems can aggregate resources (e.g. space, capital) and needs (e.g. energy demand) of its members, potentially avoiding unnecessary duplicated infrastructure, sharing risks and benefits. CE, with multiple objectives (such as environmental and social impacts in the community instead of mainly profit), can bring multiple changes and benefits for local needs of the community. It can also increase participation through operation models, such as energy cooperatives, and introduce different paradigms. The dynamics derived from the medium scale give them the high potential for experimenting, with the possibility of having faster reactions for local changes, learning capacity and high modularity.

CE potential to integrate multiple dimensions and transformations at a local level match with the benefits and effects mentioned by (Brummer, 2018). Specifically, for each dimension:

- Social: sharing risks, integrating local needs and economic benefits; increase of participation, education and acceptance; community building and self-realization; social innovation brings the capacity to introduce different paradigms and react to local changes.
- Ecological: introducing local conditions, reducing unnecessary use of resources that impact climate protection and sustainability.

- Technical: learning and experimentation capacity, modularity and technological innovation; capacity to have faster reaction for local changes; renewable energy generation targets.

Thus, a scale of observation that puts Community Energy Systems in the center can provide broad flexibility for experimentation and develop innovation capacity. Including the possibility to integrate multiple services from a local perspective and impact in the community. These properties could derive in the development of dynamics that favor multidimensional transformations, and enhance the overall resilience of energy systems.

5. Conclusion

Future energy systems should be resilient and able to cope with disruptions and changes. This could be better achieved by systems with adequate resilient behaviors: toleration and restoration, but particularly through adaptation and transformation, which give systems the capacity to react to changes, renew and learn.

The system definition, its dimensions, functions and structures, strongly determines the results of resilience assessment methodologies. They are not general and inherent of all energy systems. Therefore, the definition of system functions or any other elements to be maintained in each system dimension should be the first step of a resilience assessment, which has a strongly normative aspect and should be made transparent.

Lock-in behaviors are ambivalent for resilience assessment. While this might be desired for elements expected to be resilient, it can also derive in a system without the capacity to react to fundamental change, potentially affecting the resilience of the full system or of some elements.

The high interconnection of energy systems with other human systems makes them an important part of multiple transformations required in the technical, social and ecological dimensions. To achieve that, these dimensions could be incorporated to develop interdisciplinary assessment methodologies of resilience of energy systems. The increased system complexity deserve special attention, particularly due to the existence of different theories to explain system dynamics and their respective resilient objects.

Energy systems are self-organized complex adaptive systems, which are modified and transformed with intent and without intent, depending on the dimension elements and dynamics. Social systems have intent, due to human actors with the ability to react to the present, past and future expectations. Therefore, it is relevant to analyze how self-organization is reached and which elements provide the system with resilient behaviours within each dimension.

To integrate multiple dimensions effectively, and support the creation of adaptive and transformative resilient behaviors, the right scale of observation has to be selected. It should be one that allows the integration of multiple dimensions, and which has capacity to experiment fast and slow dynamics of energy systems.

Community Energy (CE) is a promising scale to observe and enhance energy systems resilience, due to their potential to integrate multiple dimensions, derived from their scale and community interests and agency. They have broad action range and intermediate dynamics in time and scale. CE has also shown potential to foster transformability and adaptability. Besides, CE projects are often developed in places where the service of supply of energy is already fulfilled, and their goal is to provide extra benefits to the community.

Further research is required to develop adequate assessment methodologies that allow the integration of multiple dimensions from an interdisciplinary perspective, as well as to understand the origin and dynamics of their resilient behaviors.

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