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Resilience framework and metrics for energy master planning of communities

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ABSTRACT

Changes in the nature, intensity, and frequency of climate-related extreme events have imposed a higher risk of failure on energy systems, especially those at the community level. Furthermore, the evolving energy demand patterns and transition towards renewable and localised energy supply can affect energy system resilience. How can an energy system be planned and reconfigured to address these challenges without compromising the system's resilience against chronic stresses and extreme events? Unlike energy system reliability, resilience is neither a common nor an explicit consideration in energy master planning at the community level. In addition, there is no universally agreed-upon method or metrics for measuring or estimating resilience and defining mitigation strategies. This paper introduces a multi-layered energy resilience framework and set of metrics for energy master planning of communities, including the new generation of district energy systems. The potential system disturbances and their short and long-term impacts on various components of the energy system are discussed for commonly expected and extreme events. Three layers of energy resilience are discussed: engineering-designed resilience, operational resilience, and community-societal resilience. A starting set of energy resilience metrics to support engineering design and energy master planning for communities is identified. Implications for future research and practice are noted.

1. Introduction

Climate change has imposed uncertainty upon energy systems through extreme events mainly caused by climate-related threats, which are expected to increase in severity and frequency [1]. Conventional energy systems are not designed to withstand these extreme conditions. Article 7 of the Paris agreement explicitly asks the committed parties to put in place policies and frameworks to improve their "adaptation" and "resilience" to climate change [2]. Sweeping actions are needed across the energy supply and value chains at various scales to achieve this adaptation and resilience.

Energy demand and supply are changing faster than ever before. Energy systems are moving from conventional centralised systems towards more sustainable and decentralised community-level energy systems [3–6], with district energy systems being especially key in this transition [7]. Both climate change and the transition to community-level systems are affecting the resilience and reliability of energy systems, as well as impacting various stakeholders (e.g. individuals, businesses, local and federal governments), for example see Refs. [8,9]. Therefore, the energy performance of modern community-level systems should be well-understood, especially in terms of energy resilience. However, a universally agreed-upon method or set of metrics for measuring or estimating resilience and defining mitigation strategies at community-level energy systems seems to be lacking.

In this paper, we initially focus on the performance of the community-level system to commonly expected events (e.g. component failures and overgrown vegetation) and the energy resilience of the system to extreme events, including those exacerbated by climate change. The community-level system

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Table 1
Summary of resilience definitions.

System	Proposed definition and characteristics	Reference
Ecological	"…a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationship between populations or state variables".	[20]
Socio-ecological	The capacity of that system to bounce back and to retain its function, structure, and feedbacks after the disruption.	[15]
Infrastructure and economic	"…the ability to efficiently reduce both the magnitude and duration of the deviation from targeted system performance level" where the system consists of interconnected entities with a collective and measurable purpose.	[25]
Community	The concept of resilience is the same as the concept of risk management and is an operational characteristic of the system.	[26]

considered in this paper is a new generation of district energy system [10,11] representing the new generation of decentralised local energy systems. The system consists of mixed-use (including both thermal and electrical energy uses), co-located buildings that own generation units and are connected to both internal energy networks and national energy grids. A single owner/organisation is responsible for making decisions and investments related to the system.

Resilience as a concept has gained much attention in recent years [12,13]. Researchers have defined resilience in various disciplines and systems such as ecosystem resilience [14,15], infrastructure resilience (e.g. power, energy, water and transport) [16–18], seismic resilience [19], ecological resilience [20], economic resilience [21], and community and societal resilience [22,23]. The word *resilience* or in Latin *resilio* "refers to the ability of an object to rebound or return to its original shape or position after being stressed" [24]. A summary of resilience definition in the literature is outlined in Table 1. Although there are slight variations in the definitions in different fields, the basic concepts are similar and most of them can be adapted for broader applications. Resilience can be defined based on the performance of the system as a whole, as well as the performance of individual components. This paper focuses on system resilience.

In order to conceptualise the definition of resilience and to quantitatively measure it, the resilience triangle was first proposed by the Multidisciplinary Centre for Earthquake Engineering Research as part of a framework for measuring the seismic resilience of a community [19]. This concept has been extended to the resilience trapezoid by categorising the performance response into three main stages; namely the disaster prevention (or system disruption/preparation) stage, the damage propagation (or disrupted state or adaptation/respond) stage, and the system recovery (or restorative) stage [27–30]. Panteli, Mancarella [31] demonstrated time-dependent infrastructure resilience and operational resilience in the resilience trapezoid in a methodical manner. Various studies have employed these concepts to develop qualitative and quantitative resilience assessments [12]. Sandia National Laboratories has proposed a general framework for both local and national energy infrastructure which includes a seven-step resilience assessment process to define resilience goals, define system and resilience metrics, characterise threats, determine the level of disruption, define and apply system models, calculate consequences, and evaluate resilience improvements [32]. Studies show by considering the resilience in planning, system resilience can be significantly increased [33]. A more comprehensive set of resilience metrics and impacts such as infrastructure and operational resilience, monetary value of resilience, and societal burden, that have been employed in other systems and approaches show a major influence in decision-making for planning and operation of energy systems [31,34,35].

In isolated communities (e.g. an indigenous community or a military outpost), energy system resilience is critical because residents have no, or very limited, access to the main energy grid. Other areas such as hospitals or university campuses have a high population density and critical services may strongly depend on energy system performance. In both cases, disruption in energy systems can cause severe impacts to communities and trigger long durations of profound socioeconomic impacts [9]. These impacts can be life-threatening to some communities. Therefore, in designing and planning these communities, explicitly considering system resilience and reliability measures is a necessity.

This paper proposes a novel energy resilience framework consisting of a layered set of metrics which allow for structured planning and assessment of energy resilience at the community scale. This study contributes to the literature in three main ways; firstly, a novel way for addressing the energy resilience of community systems is introduced by defining three dimensions of energy resilience and their interrelations. Secondly, a set of energy resilience metrics is identified that can guide the engineering design and energy master planning of both greenfield and brownfield developments based on this new framework. Finally, resilience planning steps are introduced and demonstrated as a flowchart which shows how the resilience framework can be employed in the planning, design and operation of community systems to enhance their energy resilience. The paper is organised as follows. The acute and chronic climatic hazards and their short and long-term impacts on energy system are discussed in Section 2. In Section 3, the definition of reliability, energy resilience and related metrics are reviewed critically. In Section 4, a layered set of energy resilience metrics (including engineering-designed resilience, operational resilience and community-societal resilience) is presented and thoroughly discussed. Section 5 presents the energy resilience planning steps, provides a discussion on the findings and an assessment of the implications of the resilience framework in relevant case studies. Finally, Section 6 presents concluding remarks and recommendations for future work.

1.1. Hazard types and impact on community-level energy systems

As shown in Fig. 1, meteorological events, hydrological events, geographical events and climatological events have been increasing throughout the world. The magnitude and frequency of extreme events are expected to increase even further in the following years [1].

Understanding the hazards is crucial for resilient design and preparation against extreme events. Although various hazards may manifest differently, they can all be categorised based on their impact, frequency, return period, geographical probability, event duration, and warning time. In Fig. 2, hazards are categorised based on their duration and warning time. Acute threats include sudden hazards such as hurricane, tornado, bushfire, earthquake, pandemic[1] or cyber-attacks[2]; and chronic stresses include slow and

[1] Pandemic can affect the energy supply and value chains in different ways, for example changes in the energy demand profile, lack of staff, regional and economic lockdowns and more.

[2] Cyber-attacks sometimes might have forewarning depending on the actors involved.

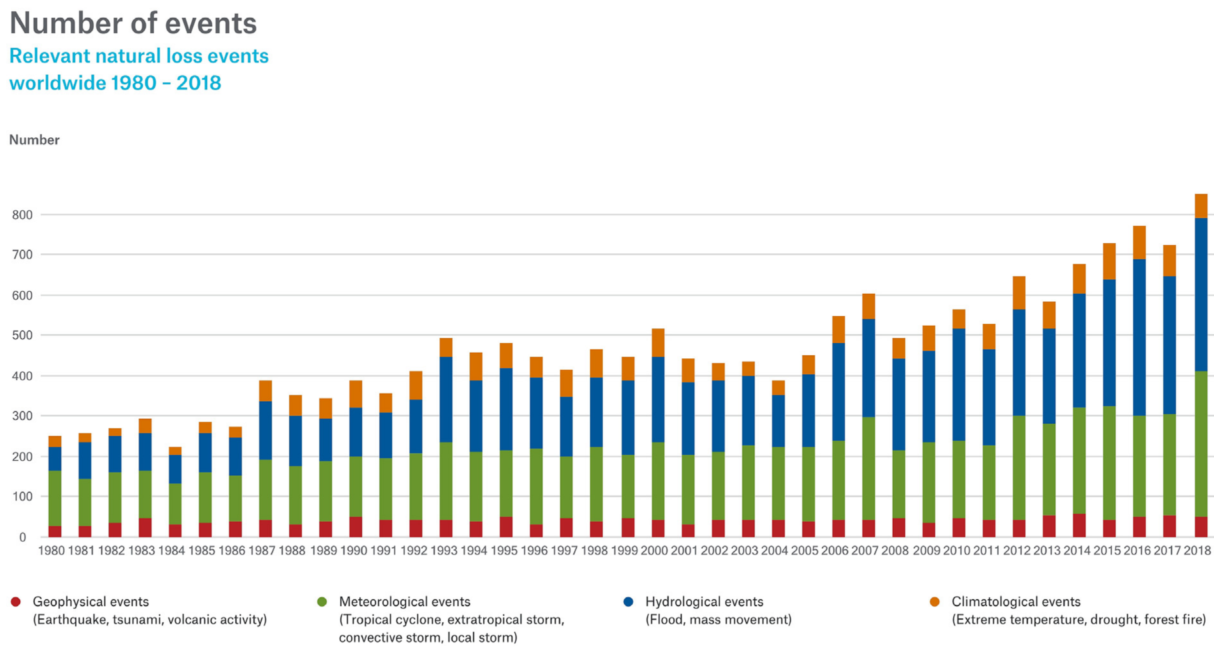

Fig. 1. The trend of climate events obtained from NatCatSERVICE [36].

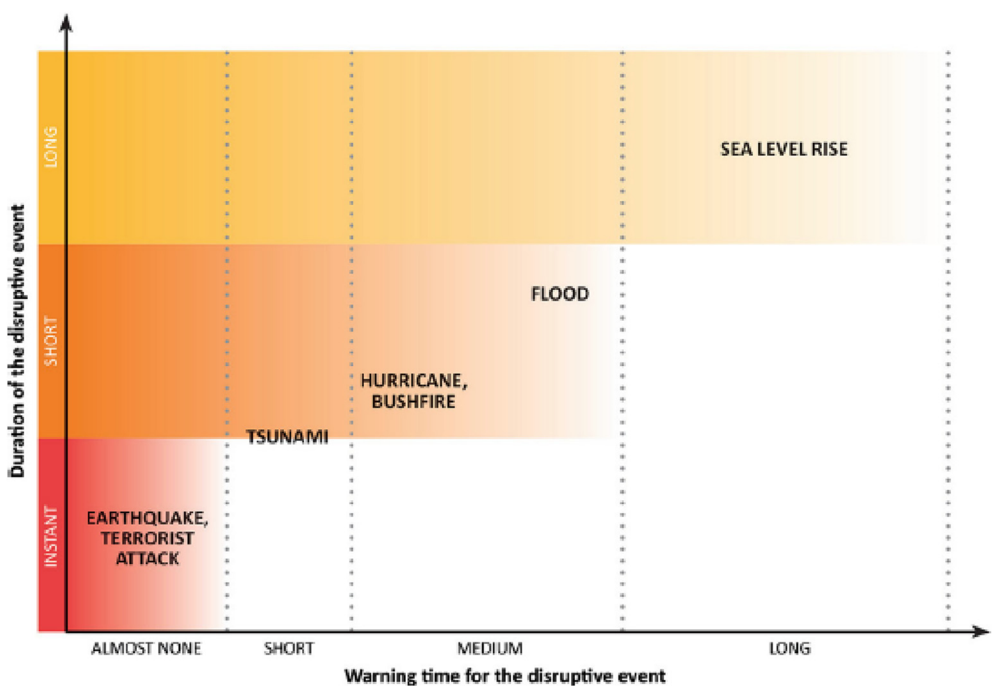

Fig. 2. Various types of hazards based on their duration and warning time obtained from [38].

mostly cyclical hazards such as drought, chronic flooding, sea-level rise and increases in ambient temperature. Hughes [37] indicates that disruption events can be categorised based on the impacts on the energy entity that results in declining availability, affordability, or acceptability of energy metrics. Under some circumstances, the combination of extreme events (multiple hazards) might create a high impact threat with distinct characteristics. Extreme events can lead to prolonged and severe failures that threaten lives, political landscapes, and businesses. Therefore, these threats should be identified and their potential impact on energy system components should be investigated.

Energy systems are formed from interdependent components and may be weather-dependent. The current energy systems have been designed based on previous climate-related assumptions, where climate-induced energy supply and demand variations were based on historical assumptions. The impacts of increasing intensity and frequency of extreme events caused by climate change on different components of the energy supply chain are discussed in several studies [39–43]. The generic short and long-term impacts of the typical climatic hazards on various aspects of energy systems are summarised in Table 2. However, the quantification of these impacts is challenging due to high uncertainties in the models and inputs [44]. Community-level energy systems are a part of the national and regional energy systems. Often, the impact of the extreme events on the larger energy system also has inevitable consequences on the community system.

One of the main chronic threats on energy systems today is an increase in ambient temperature due to global warming which directly results in lower efficiency of electricity generation for both conventional fossil fuels and new renewable sources. Higher temperatures also raise cooling needs and lower the efficiency of mechanical cooling systems (less effective natural ventilation). Pagliano, Carlucci [45] have demonstrated that in the future there will be an increase in cooling needs, and it is necessary to consider resilience as a factor in the long-term planning and design of buildings. In addition to direct impacts, extreme events also have cascading consequences for all stakeholders, such as access to clean water and provision of acceptable indoor air quality. Although estimating these multi-dimensional impacts is not easy, public and private organisations have started to categorise these impacts and employ strategies in the planning and design of energy system components. The City of Melbourne [46], for example, provides design guidelines for the climate-resilient design of new buildings and redevelopment of existing buildings. Similar resilience strategies and design guidelines are established in the cities of Los Angeles and New York [47,48].

The goal is for local energy generation in communities to be designed to be more resilient, efficient, and sustainable, e.g. the fourth generation of district heating systems [10,52], with a low frequency and duration of outages in critical systems. It helps that these systems are located near the energy demands that they serve. Energy delivery distance is usually short and reduces the risks and losses of energy transmission. These systems tend to be more rigorous due to the direct economic impacts on the system owner. However, changes in climate and its associated risk will not only change the planning and design of energy infrastructures but also their operation and maintenance.

In energy master planning at the community level; such as in a municipal district heating and cooling system, an isolated indigenous community, or a hospital campus; the impacts of disruptive climate-related events should be considered in early stages of the design and planning of the location's energy system to increase resilience. To understand the potential opportunities and challenges of reliability and resilience in energy master planning, these concepts are elaborately discussed in the following section.

2. 3. Towards a more resilient community-level energy system

The changing nature of energy systems as they transition towards clean and decentralised energy sources, and the risks imposed by climate change on both the energy supply and the energy demand, require more resilient energy systems. Resilience metrics should be explicitly incorporated into the energy master planning process to complement the existing reliability approaches, especially at the community level.

2.1. Robustness and reliability

The term robustness can sometimes be confused with resilience but a more explicit definition of the former is "the ability of the system to withstand a given level (of disruption)" [53]. The Department of Energy (DOE) in the US defines reliability in the electricity grid context as "the ability of the system or its components to withstand instability, uncontrolled events, cascading failures, or unanticipated loss of system components" [54]. Reliability focuses on energy systems being able to provide service during disruptions which occur frequently. A reliable system and system components offer long-term and robust performance in their intended function. Reliability can be defined both in terms of system performance and individual system component performance. The focus here is on system level robustness and reliability.

The reliability of systems is usually expressed as a coefficient in design, which usually covers short-term measures such as emergency systems and energy reduction measures [4]. For example, In Australia, the reliability standard in the electrical system is equal to %0.002 of the unserved energy of the total energy demand in each region per year [55] for all expected events.

The robustness and reliability of the system are pre-disruption characteristics of a system [56]. However, climate change and the transition to clean energy systems limit the robustness and reliability of the systems. The changing conditions require a dynamic response to the combined impacts of climate risks with both short and long-term planning and enhancement measures. Although a

Table 2
Short and long-term impacts of climate-related events on different items of the energy system.

Items	Short-term Impacts	Long-term impacts	Reference
Centralised energy generation (both renewable and non-renewable)	Physical damages cause higher failure/disruption risk, risk of cascading failure	Efficiency reduction, capacity reduction, higher generation variability, extended disruption period, higher water consumption, relocation of current plants	[41,43,44,49,50]
Local energy generation (e.g. district energy systems and microgrids)	Physical damages cause higher failure/disruption risk, risk of cascading failure	Efficiency reduction, capacity reduction, high uncertainty in generation forecast, extended disruption period, higher water consumption	[43,49]
Transmission and distribution (e.g. pipelines, poles and wires)	Higher risk of failure/disruption, risk of cascading failure	Capacity reduction, efficiency reduction, accelerated aging, relocation of the current networks, longer disruption period	[40,43,49]
Energy storage (e.g. batteries, thermal storage and hydro)	Higher risk of failure/disruption	Efficiency reduction, water scarcity may affect investments	[49]
Energy use (e.g. commercial and residential uses)	Higher risk of disruption	Increase in peak load, increase in energy demand, change in demand profile, higher demand for air conditioning systems, high uncertainty in demand forecast	[41,42,49]
Operation and maintenance	Higher risk of operational disruptions, increase in components replacement frequency	High uncertainty in generation forecast, increase in unscheduled maintenance, reduction in capacity factor, new operation strategies	[42]
Socioeconomics	Higher uncertainty in investments, higher social burden, increase in physical injuries and trauma	Health risks, higher social and political pressures, technological changes and new markets, cross-sectoral competition (e.g. food, water and energy), increase in energy prices	[50,51]

variety of scenarios are considered in estimating the reliability of the future energy systems (e.g. electricity system in Australia [57]), the response to extreme climate events seems to be lacking in these scenarios. Panteli and Mancarella [24] argue that reliability and resilience have different characteristics in a power system context. These concepts need to be harmonised with the broader engineering literature and other industry sectors. In addition, the evolving risks require more explicit metrics, as well as comprehensive approaches, policies, and regulations that can guarantee the resilience of the energy system and its ability to provide valuable services to communities and other industry sectors.

2.2. Energy resilience

Although there are various definitions of system resilience in the literature, the resilience of modern composite energy systems requires more research [58], especially at the community level including the new generation of district and smart energy systems. The resilience of energy systems can be defined based on the characteristics of these systems and the nature of the disruptive events (e.g. a system can be resilient to a heatwave but not to an ice storm). For example, DOE defines the resilience of the electrical grid as "the ability of a system or its components to adapt to changing conditions and withstand and rapidly recover from disruptions" (opposed to "security[3]" which is to "withstand attacks") [54]. There are six components of resilience, namely "the ability of an entity — asset, organisation, community, region — to anticipate, resist, absorb, respond to, adapt to, and recover from a disturbance" [60]. Sharifi and Yamagata [18] argue that a sustainable energy system (i.e. satisfying four dimensions of availability, accessibility, affordability and acceptability) should be comprised of preparation, absorption, recovery and adaptation abilities.

In order to provide more resilience to increasingly complex and interconnected (energy) systems and tackle the uncertainties, costs, and challenges in the nature of these systems subject to extreme events, Linkov, Bridges [61] highlighted the need for clear definitions, metrics, and evaluation methods for resilience development. Furthermore, the performance criteria that include these metrics need to be formulated more in probabilistic terms to account for risks and likelihoods of disruption. In the Sandia National Laboratory report for the 2015 Quadrennial Energy Review, the authors note that resilience metrics should consider threat, likelihood, and consequence and thus because common reliability metrics do not possess these attributes, they are "orthogonal in purpose and discrimination capability to resilience metrics" [32,62]. Resilience metrics encompass all disruptions that have different levels of uncertainties, with particular attentiveness to high-impact, low-frequency events [29]. But in addressing system resilience, both qualitative and quantitative performance criteria and metrics are required.

Quantitative, time-dependent resilience metrics are introduced for power system resilience to measure how fast and how low the resilience drops, how long the system remains in the degraded state, and how quickly it recovers [31]. Sharifi and Yamagata [18] proposed energy resilience criteria in the design and planning of urban areas. Roege, Collier [63] suggested a matrix for energy resilience which is applicable to all kinds of energy-related systems based on four actions (prepare, absorb, recover and adapt) and in four domains (physical, information, cognitive and social). Although these metrics from the literature are not focused solely on energy resilience, they can be tailored for community-level system energy resilience evaluation.

Resilience assessment methods can be divided into quantitative and qualitative methods. Hosseini, Barker [12] classified the quantitative methods into general measures including dynamic and static probabilistic and deterministic approaches, and structural-based models including optimisation, simulation, and fuzzy logic models. They also categorised qualitative methods into conceptual frameworks and semi-quantitative indices. Vugrin, Warren [25] have reviewed various resilience assessment frameworks such as assessment frameworks for human-social systems resilience, probability-based resilience, and economic resilience (static and dynamic), and they suggest a system resilience framework that can be applied to various types of critical infrastructure and key resources. Their proposed system resilience framework consists of (1) the definition of system resilience, (2) qualitative assessment of system resilience (based on resilience cost depending on the systemic impact and total recovery effort), and (3) quantitative assessment of features (based on absorptive capacity, adaptive capacity, and restorative capacity) that determine system resilience [25]. A summary of resilience metrics, and qualitative and quantitative resilience evaluation methods, is given in Table 3. It can be seen that although there are several metrics and evaluation methods for specific events, there is no consensus on method or metrics for measuring energy resilience, and defining the mitigation and enhancement strategies, especially during the energy master planning. Various aspects of resilience are considered individually and with a narrow focus which restricts opportunities in other dimensions of resilience e.g. infrastructure, operational and social. Although these qualitative and quantitative methods and metrics can lead to measurement of a particular resilience measure, they do not provide a consistent approach for measuring the overall resilience of the system for the purpose of energy resilience planning.

In energy master planning process, prescriptive and performance approaches (and associated metrics) can be employed in resilience assessment and enhancement. Prescriptive-based resilience approach considers the acceptable or required resilience solutions and limits, while the performance-based resilience approaches use quantifiable metrics to measure the resilience of the system performance. The performance-based approach includes the system-based or attribute-based metrics such as level of redundancy, number of backup transformers and number of highly trained staff. Resilience planning for critical infrastructure should be based on the critical services required to support the community rather than the physical condition of infrastructure only [68].

The system performance metrics can be divided into the consequence-based (e.g. environmental, social, economic and the national security) metrics and service-based (e.g. electricity, heating, cooling and water) metrics. Sometimes the resilience performance of each service should be measured in each critical nodes of the energy system. Each of these nodes might have different resilience requirements. The performance-based metrics can be employed in energy master planning to estimate the impacts of the system disruption or unusual system service performance in terms of environmental, social and economic consequences. These consequences are sometimes inter-related—for instance, assessing the social impacts might be required to be able to assess the economic impacts. In the next sections, a resilience framework including a layered set of metrics is presented which allow for structured planning and assessment of energy resilience at the community scale.

[3] Energy security can be also defined as "uninterrupted availability of energy resources at an affordable price" [59] IEA. Energy Security, URL: https://www.iea.org/topics/energy-security. 2018. Energy security concept, which includes balancing of energy supply and demand, is usually considered at national and/or regional scales.

Table 3
Resilience metrics and evaluation methods revised [58] and extended.

Type	Metrics	Evaluation Methods
Qualitative evaluation	- Resiliency indices [60] - Functional redundancy [63]	- Checklists and questionnaires [60] - Matrix scoring system [63] - Analytic hierarchy process (AHP) [64]
Quantitative evaluation	- Time-dependent metrics for the resilience of power networks based on slopes and area of resilience trapezoid [31] - Probability distribution of economic costs [32] - Area under the curve between targeted performance and real performance [19,56] - Ratio of the area between real performance curve to targeted performance curve during a year [30] - Probability of network performing its intended functions [65] - Time to restoration following a failure [66] - Performance-based resilience index [67]	- Energy flow based system performance modelling methods under different scenarios [32,56] - Graph-theory based system performance and complex system modelling methods [27,30] - Graph-theory and probabilistic method [65] - Spatial power outage duration model [66] - Benefit-cost analysis [67]

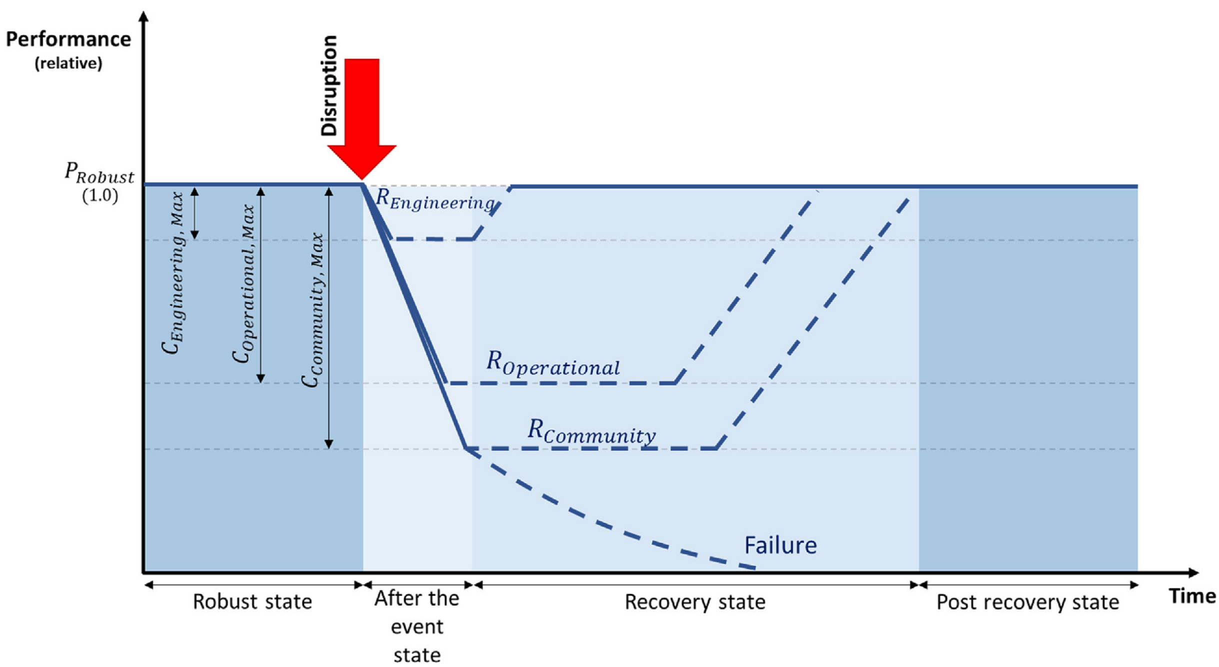

Fig. 3. Conceptual multi-phase energy resilience trapezoid, revised based on [31].

2.3. Energy resilience metrics at the community level

In order to establish effective metrics to evaluate the energy resilience of community-level energy systems, this section focuses on performance-based resilience metrics at the system level. A resilience framework is introduced, including a set of metrics that are crucial in the process of decision-making and energy master planning for communities. The present resilience framework utilizes the resilience trapezoid concept to measure (qualitatively and quantitively) the resilience performance of a community-level energy system, proposing a consistent treatment of resilience metrics, dimensions, and phases. This framework is a guide to resilience planning and provides many opportunities for specific resilience enhancement. These resilience metrics, dimensions, and phases are defined and presented individually. The next section discusses how the presented metrics can work together and be integrated into the resilience planning process during energy master planning to enhance the energy resilience of the community.

The multi-phase energy resilience trapezoid is re-conceptualised in the diagram shown in Fig. 3, with different layers. In the robust state, the energy system is working at nearly 100% (or providing reliable energy supply). In the case that an external event causes a noticeable disruption beyond what the system is able to handle, the system's ability to avoid permanent failure and bounce back is illustrated with three layers of resilience, working in progression or concurrently, that emphasises on three dimensions of system resilience performance.

The first layer of resilience is built-in or "engineering-designed resilience" ($R_{Engineering}$). In this approach, the overall energy system assets may be designed in such a way that normal services can be restored after a short disruption, without human intervention. In some sense, this may be seen as an extension of a system designed for reliability and redundancy. But it also provides the opportunity for other or new innovative solutions (e.g. self-healing systems) that are activated when the primary system fails.

The next layer is "operational resilience" ($R_{Operational}$), which is the set of technological and organisational measures that can be employed when the disruption exceeds the capacity of engineering-designed resilience. This also includes the processes of decision-making — from the team or organisation level, up to the whole energy sector in a region— that are necessary to contain

Table 4
Summary of energy resilience layers for community-level energy master planning.

	Engineering resilience	Operational resilience	Community resilience
Definition	Physical assets and engineering-designed measures	Set of technological and organisational measures	Cooperation and contributions of customers and other community stakeholders
Example attributes	Redundancy, separation	Rerouting, reorganisation	Awareness, cooperation, trust
Example enhancement measures	Self-healing systems, resistant systems storage systems, energy-self-sufficiency	Demand side management, smart operation, ready supply of critical components	Adaptive thermal comfort, voluntary mass energy-use reduction, mass relocation

damage or preserve a certain level of service, and later to fully restore services.

The next layer is "community (and societal) resilience"[4] ($R_{Community}$), which needs to be invoked as part of the solution when appropriate, especially when engineering resilience and operational resilience alone are not sufficient to address the disruption. This resilience is defined as "community processes that can restore, maintain or enhance community wellbeing in the face of natural disaster or rapid change" [23]. Herein, we extend the definition to include the cooperation, collaboration, or partnership needed between the energy service providers and the demand-side consumers (the "community"). But there is also a broad range of stakeholders within a society, whose cooperation and contributions to manage the disruptions and help bring the service back will be critical. Thus, the community-societal resilience concept can span the range of resilience partners— from the direct energy consumers only, to one that includes some or all of the key stakeholders from the wider society interacting with either or both the supply-side industry actors and the demand-side consumers.

The three main resilience layers are shown with respect to time in Fig. 3. This period of time is divided into four states including the robust state (before the event), shortly after the event state (including event occurrence state), the recovery state, and the post-recovery state. In each resilience layer, the trapezoid size, slopes, sequence, the length of temporal states and the proportion of presented resilience layers mainly depend on the system performance and type of the disruptive event. Shinozuka, Chang [56] called system resilience capacity (C), "system robustness" which is measured as a percentage. Vugrin, Warren [25] confirm that system resilience capacities can be identified depending on the classes of disruptive events. The summary of layers with examples of the system attributes and enhancement measures are presented in Table 4. In the following sub-sections, these layers are discussed further, and an initial set of metrics are identified for each layer.

2.4. Engineering-designed resilience metrics

Engineering-designed resilience enhancement strategies at the asset level, are usually of a physical/protective/mechanical nature, and do not require human intervention to apply. Some example measures are redundant capacities, storage, backup systems, and physical protective measures. Several metrics for engineering-designed resilience (also called infrastructure/asset resilience in some literature) have been proposed. In Fig. 3, the slope and extent of the edges of engineering resilience trapezoid (three pieces) and integral under the curve (area) are example metrics. The maximum engineering-designed resilience capacity ($C_{Engineering,\ Max}$) of the system represents the overall resilience capacity of the assets. Examples of engineering-designed resilience metrics for power networks include [31]:

- The rate of disturbance (number of lines tripped per hour and number of lines tripped)
- The duration of the performance disruption (hours)
- The rate of system recovery (number of lines restored)

Example of engineering-designed resilience metrics in the example of a district heating piping system is the total length of functioning pipelines [69]. Other examples of engineering resilience metrics that can be used in the energy master planning and design of communities are energy (kWh) not served due to assets failure, and asset availability (measured by the amount of time the asset serves its intended purpose divided by the total amount of time the asset was exposed to disruptive conditions). These metrics can be used to estimate the energy resilience of a community system against events with similar probability and intensity.

2.5. Operational resilience metrics

Operational resilience is focused on system level performance and the operational characteristics of the system intended to mitigate the failure risk and to support service recovery. Some examples of enhancement measures are demand response, demand side management (DSM) strategies, prioritising energy use, smart controls, and forecasting. The slope and extent of the edges of the operational resilience trapezoid and integral under the curve are examples of metrics that can be used to measure the operational resilience of the system. The maximum capacity of operational resilience ($C_{Operational,\ Max}$) represents the maximum level of energy resilience that the system can achieve through operational measures. For example, in power networks operational resilience metrics include [31]:

- The rate of disturbance (kW power loss per hour and power capacity loss)
- The duration of the performance disruption (hours)
- The rate of system recovery (kW power restored)

Other examples of operational resilience metrics are energy (kWh) not served due to operation disruption and energy availability (measured by the amount of energy served to end users divided by the total amount energy demanded by those users during disruptive conditions). In the case of district heating pipelines, examples of operational energy resilience are total heated area of connected users and the number of users connected to the piping network [69].

2.6. Community resilience metrics

Community-societal energy resilience accounts for the actions that should be done within the community by some or all of community users to maintain the minimum allowable community-societal services. Mass relocation, effective use of community

[4] The focus here is on the residents and social meaning of the community. It should not be confused with community-level system terminology used throughout the paper which represents the physical boundary of the system.

resources during a disruption, and increasing the bonding, bridging, and linking the social capital [70], are examples of community-societal resilience enhancement measures. The type of these civil actions can be an adaptation or halting of normal actions and can vary depending on the disruptive event and the community wishes [71]. These are especially critical when the minimum engineering-designed and operational resilience limits have failed. Compared to the previous two layers, community-societal resilience usually has a much higher resilience capacity ($C_{Community, Max}$). The lack of critical services impacts both the occupants of the community and also the greater society. Here, the focus is on both of these impacts.

The maximum capacity of community-societal resilience of the system is very challenging if not impossible to ascertain. An alternative is to use a community resilience metric such as the community functionality which is measured by the amount of time-critical community functions (e.g. energy services) were adequately provided to people, divided by total amount of disruption time. This could be separated out by function or combined in a weighted manner. Practical examples of community resilience metrics are planning quality, leadership status, resource capacity, access to information, number of supporting volunteers, level of trust, and cooperation between different stakeholders [23,71]. Several studies, for example at the centre for risk-based community resilience, have been undertaken to determine community resilience [72,73]. In practice, these are heavily context-dependent and can be primarily assessed via surveys, interviews, and related means before and/or after a disruptive event.

3. Discussions and case study assessment

Although community-level energy systems (e.g. microgrids, or district heating and cooling systems) seem to increase the energy resilience [18,34,74], more explicit and consistent metrics should be employed in the planning, design, operation and evaluation of the detailed behaviour of these systems during an disruption event. The energy systems are shifting from centralised systems towards decentralised local and community-level systems. Various hazards (both chronic and acute) can have short and long-term impacts on the community level systems that should be analysed during the energy master planning process. The dependencies (one way propagation of failure A to B), interdependencies (failure in A causes failure in B causes more failure in A), and coterminous effects (many things failing at the same time due to a single stressor, but not propagated from a single component failures) of these systems can expose the community to high risks of performance disruption. These scenarios should be fully investigated in the early stages of community-level systems planning and design.

In order to demonstrate how the proposed resilience framework can be used, the flowchart in Fig. 4 illustrates the main steps of resilience planning during energy master planning. It shows how the above-mentioned resilience layers and metrics work together to evaluate various dimensions of resilience performance at a community-level energy system. In addition, the flowchart demonstrates how to incorporate resilience metrics in the planning, design, and operation of community systems to enhance their resilience. In practice, in the process of energy master planning, there might be several additional steps and iterations, as well as different level of details required in each design stage (conceptual design, preliminary design and detailed design). The proposed resilience framework offers a step forward and it is a significant addition to the existing resilience planning approaches [19,75], especially at the community level.

Input data (e.g. separate the cooling, heating, electricity demands for each node, energy prices, climate and so on), client (decision-maker) requirements (e.g. project goals, limitations and the level of energy requirements for critical buildings) and technology/components database (such as cost, lifespan, efficiency, flexibility, storage, temperature dependency and so on) will be the first step (steps marked as A_1, A_2 and A_3, respectively in Fig. 4) of the resilience planning process. Then, local resources and their availabilities e.g. energy networks, wind, sun and geothermal energy potentials and so on, should be identified (step B). In step C, threats (e.g. hazards frequency, probability, magnitude and impacts) both on local community energy system and across the grid infrastructure systems should be determined, see Section 2.

In the next step (marked as D in Fig. 4), the system should be planned and modelled which includes system architecture, system components sizing, configuration and placement. The planning stage should be based on resilience design guidelines, frameworks, approaches, e.g. biomimicry [16], or incorporating resilience criteria in a more rigorous methods such as linear programming [35], and recommended resilience attributes [19] (see Table 4). In addition to design day approach, scenarios that represent satisfying mission critical uses under disruption conditions should be considered in the system planning. The modelling approach should be chosen based on the project design phase for both new developments and existing upgrades. The proposed resilience framework and resilience dimensions can guide the overall planning and design process (see Section 4). System operation and operation strategies should be modelled for entire community system lifespan (step E).

In step F (Fig. 4), system resilience performance should be evaluated for all three resilience layers—namely engineering-designed resilience, operational resilience, and community resilience—as defined in Section 4. For example, in case of a district heating and cooling system planning, engineering-designed resilience evaluation (e.g. pipelines and generation plant) alone would not be a representative of overall system resilience as it does not include an evaluation of system operational resilience (e.g. heating and cooling temperature setpoints and energy storage levels) and community resilience (e.g. adaptive behaviours and potential energy use-reduction) and vice versa. This hinders the exploitation of holistic and more specific resilience enhancement measures. The resilience evaluation strongly depends on the definition and consistency of resilience dimensions. Focusing on these three dimensions of resilience in parallel will enable more opportunities for enhancing the resilience with efficient use of resources. In Fig. 3, each trapezoid edge can have different behaviour with a different slope and length which is not necessarily linear. System resilience is considered an attribute of energy performance. In reality, energy performance recovery may be dynamic, as introduced by Rose [21]. Besides, robust service performance usually fluctuates due to aging effects [67]. Consideration of such aging effects and degradation profiles is well-established in service-life modelling, system maintenance as well as in asset management practice. The four main temporal phases of the energy resilience trapezoid are the robust state, after the even state, the recovery state, and the post-recovery state (Fig. 3). The duration of each state depends on the internal system features (e.g. system design and management, and available internal resources) and external factors (e.g. hazard characteristics and external resources). For example, Maliszewski and Perrings [66] have analysed several factors that impact the restoration time of the power supply.

Among the three resilience layers, engineering-designed resilience capacity has a relatively narrow focus but is the first line of defence, while community resilience capacity has a relatively broad scope but has the most significant impact on system resilience capacity. Operational resilience capacity is activated after reaching the maximum engineering-designed resilience. However, this can

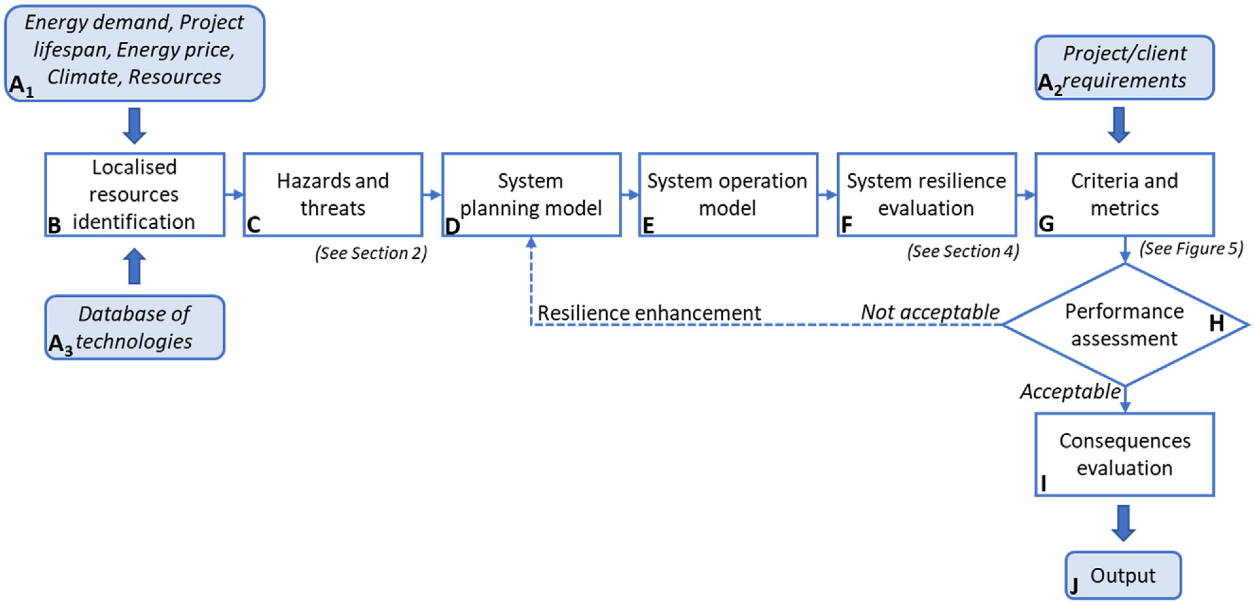

Fig. 4. Resilience planning process — steps are labelled from A to J.

be changed depending on the type of energy infrastructure and the nature of the disruption. In some cases (e.g. acute operational threats) the operational resilience capacity might yield before or at the same time as engineering-designed resilience capacity. However, in most cases, there are intersections within resilience layers and also within resilience metrics, and additionally, resilience layers may have interrelated phases. Also, the metrics may potentially be used to estimate the combined capacity of the engineering-designed and operational resiliencies.

Community-level energy resilience can be assessed by employing or extending the existing frameworks, methods and models. Energy resilience assessment methods can be categorised based on level of data required (measured/simulated or simple/SME-informed), modelling approach (bottom-up or top-down), and methodology (e.g. systems modelling). Although estimating community-societal resilience performance is very challenging, the other two layers can be estimated using quantitative and/or qualitative, static or dynamic, deterministic or probabilistic approaches; for instance, a static and deterministic formulation in Ref. [28] or stochastic resilience formulation in Ref. [67] or time-dependent stochastic formulation in Ref. [30]. The approach should be chosen based on the client's requirements, data availability, and energy master planner's capability. In the case of a complex system (i.e. system of systems), the most critical lower-level system and assets should be evaluated first [60].

In Step G (Fig. 4), criteria, indicators, and metrics are selected based on the decision-maker goals. Theoretical performance-based metrics for assessing energy resilience at the community level are illustrated in Fig. 5. These metrics are categorised into four phases including prepare (T_0 to T_1), withstand (T_1 to T_2), adapt (T_2 to T_3), and recover (T_3 to T_4), see Table 5. In community-level energy systems the role of prediction is crucial. The majority of renewable energy sources and energy demands are weather-dependent. Preparation mechanisms are usually employed before an extreme event (T_0 to T_1). The time of preparation and extra resilience capacity (C_{Extra}) depend on the prediction ability, system performance, and the type of extreme event (see Fig. 2). It should be noted that this is a temporary virtual capacity, as the system performance cannot realistically exceed 100%. Also, it should be noted that the preparation measures actually enhance the other resilience features (withstand, adapt and recover). However, the difference is that these measures take place not during the energy master planning phase but just before or during the event. When the disruption event occurs, the system performance initially withstands (T_1 to T_2) the threat to its maximum resilience capacity (C_{Max}). The system performance might drop to its lowest performance level when the maximum resilience capacity is reached. At this stage, the system adapts to the new condition for a period of time (T_2 to T_3) until the recovery phase begins (T_3 to T_4). These phases are illustrated here conceptually and are defined in various ways in the literature [24,25,31,32,58,60]. In practice, in the recovery phase for example, the system performance might remain constant for a period and then start to bounce back, or the engineering-designed resilience status might be in the adaptation phase while operational resilience is in the recovery state. In all aforementioned stages, there is a probability that the system will fail.

The theoretical resilience metrics can be employed in all three resilience layers to estimate the system resilience and its related consequences (e.g. economic loss). The ratio of different areas can demonstrate the resilience behaviour of the system. For example, using A_1/A_3, the design engineer or energy master planner can compare design trade-offs and consequences of a system configuration A over system configuration B. Two systems might have the same resilience area but different resilience capacity and length. The design choice depends on the decision-maker's objectives and the impacts of performance disruptions. This can be a challenging undertaking as most of the metrics intersect with, and/or affect, other resilience metrics. Constraints such as limited economic or environmental resources are a barrier to achieving an ideal degree of energy resilience. The system should be designed for a required level of resilience to a class of disruption events that guarantees a level of system performance for the relative class of disruption events (with similar impacts). Thus, the system will be resilient to all lower impact disruption events. In general, system resilience will increase by minimising the area of the resilience trapezoid.

Then, the entire community system performance of each design alternative should be assessed and compared against the required level of service performance by client/normative (step H in Fig. 4); if acceptable, the process continues to the next steps, otherwise,

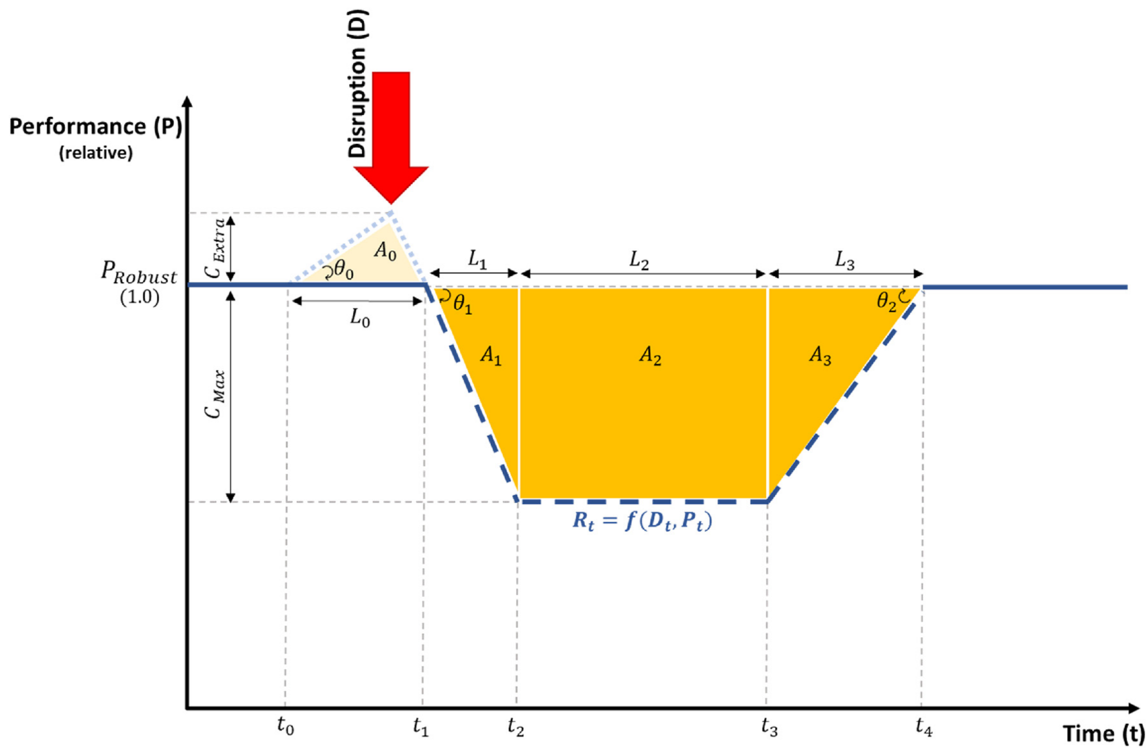

Fig. 5. Resilience metrics for community-level energy master planning.

Table 5
Summary of theoretical resilience metrics in each resilience phase.

Metrics	Unit	Phases			
		Prepare	Withstand	Adapt	Recover
Resilience length	hours	$L_0 = t_1 - t_0$	$L_1 = t_2 - t_1$	$L_2 = t_3 - t_2$	$L_3 = t_4 - t_3$
Rate of resilience	performance/hours	C_{Extra}/L_0	$\tan(\theta_1) = C_{Max}/L_1$	–	$\tan(\theta_2) = C_{Max}/L_3$
Resilience area	performance-hours	A_0	A_1	A_2	A_3
Resilience capacity	performance	C_{Extra}	C_{Max}	C_{Max}	–
Total resilience length	hours	$L = t_4 - t_0 = L_0 + L_1 + L_2 + L_3$			
Total resilience area	performance-hours	$A = A_0 + A_1 + A_2 + A_3$			
Total resilience capacity	performance	$C = C_{Extra} + C_{Max}$			

additional design alternatives with an enhanced resilience should be considered and the process (steps D to H) should be repeated. Depending on the client's (decision-maker) objectives, community-level energy system can be designed differently considering the trade-offs of resilience capacity, resilience slopes, and recovery time. However, at current practice, this might not be possible primarily because of the paucity in evidence-based knowledge to design and implement effective intervention options.

Various measures can be implemented during the energy master planning of communities to enhance energy resilience. These measures can be applied to one or more of the energy resilience layers/phases presented. For example, DSM can contribute to both operational and community resilience. It becomes an operational measure when the facility management team decides to change the operation logic (e.g. changing set-point temperatures) of the community due to disruption without engaging the residents. However, when residents actively change their energy consumption after a disruption to adapt to the new state of the system, it is a community-societal resilience measure. Some measures (e.g. energy storage and smart operations) play an essential role in a combination of numbers of resilience phases. The resilience enhancement measures can be categorised as short-term (e.g. prediction, monitoring and priority setting) and long-term resilience measures (e.g. physical upgrades, and energy storage) [40].

The assessment of energy resilience should consider not only the system performance but also the cost and emissions associated with alternative solutions. Vugrin, Warren [25] claim that systems with lower resilience costs (sum of the systemic impact and total recovery effort) are more resilient to disruptions. Resilience metrics (Table 5) are crucial in decision-making during energy master planning and to evaluate the engineering performance, as well as consequences related to disruption in the system performance of selected design alternatives for example in terms of economic, environmental and social impacts (step I in Fig. 4). These consequences are directly linked to resilience trapezoid (including area, slopes, depths and lengths of each edge). Resilience and sustainability should be considered as complementary attributes of the system during the design and operation [76]. The difference is in the fact that sustainability impacts are normally during the standard design and operation of the energy system whereas the resilience consequences occur in unexpected extreme event conditions [76]. However, there might be trade-offs among design options based on their sustainability and resilience performances.

The proposed resilience framework enables the performance-based resilience assessment of alternative community system design and consequences related to sustainability criteria. This would enable more comprehensive, insightful and informative resilience assessment of community system performance.

The output (step J in Fig. 4) will be in the form that the decision-maker can use to compare and choose based on the resilience performance (and consequences) of each design scenario (additionally might include other performance metrics and sustainability metrics). The importance of individual assessment is that each resilience layer and relevant metrics can be weighted separately based on the decision-maker's preference. For example, in case of limited capital funding, the decision-maker can weigh the economic consequences and seek the design choices trade-offs among resilience layers (physical vs. operational vs. community) or resilience phases (preparation vs. withstand vs. adaptation vs. recovery). These comparisons of resilience dimensions during energy master planning will lead to a resilient system planning, design and operation, as well as effective resources allocation aligned with the decision-maker's objectives.

The systematic application of energy resilience at community-level systems and district energy systems is not well-practised. However, other similar approaches and energy systems are a good proxy in exploring the practical applications of energy resilience metrics in energy master planning. In the following, the proposed resilience framework is explored in five case studies in the literature focusing on district heating pipeline, power transmission network, microgrids, DER and centralised power generation systems. These case studies are summarised in Table 6.

In district heating pipeline system case study [69], authors have focused on the recovery phase (t_3 to t_4 in Fig. 5) of system resilience for finding the most effective engineering-designed system restoration/recovery process. A quantitative approach is developed for system resilience evaluation (step F in Fig. 4) based on [28]. Maximum heat load of the system, overall quality of pipelines, number of inhabitants of heated dwelling, and total heated area are considered as resilience metrics (step G in Fig. 4) for engineering-designed and operational resilience dimensions (Section 4), together with the cost consequence of each recovery scenario (step I in Fig. 4). Then, as output (step J in Fig. 4), restoration strategies are ranked in a decision-making support matrix based on selected metrics and associated weights. However, the resilience evaluation seems to be incomplete and limited to physical aspects of the system which would not represent overall system resilience performance. Implication of other dimensions, metrics, and phases presented in the resilience framework can lead to a more comprehensive evaluation of resilience performance and related consequences in planning and operation of the district heating systems. This will enable more specific resilience enhancement measures.

Energy resilience evaluation of power transmission network operation is the focus of [31] which demonstrates the distinct behaviour of engineering-designed and operational resilience dimensions in each resilience phase and the importance of assessing them in parallel for evaluation of overall system resilience performance. Hazards (windstorm) are first identified (step C in Fig. 4) and network operation is simulated (step E in Fig. 4). The resilience trapezoid consisting of infrastructure (engineering-designed) and operational resilience dimensions are evaluated (step F in Fig. 4). Megawatts of generation capacity and load demand (engineering-designed), the number of online transmission lines (operational resilience) indicators, and five metrics related to three resilience phases (t_1 to t_4 in Fig. 5) are taken into account as resilience metrics (step G in Fig. 4). The resilience performance of a base case scenario is then compared with three system resilience enhancement scenarios namely robustness (physical measure), response and recovery (operational measures). The outcome shows that resilience trapezoid enables system behaviour modelling during the disruption. Also, the researchers have proven investing (e.g. capital funding allocation) on different resilience phases (robustness, response and recovery) lead to a different resilience performance and therefore system operation. This will enable more specific resilience enhancement measures; for example, authors demonstrated applying smart operation measures can enhance system operational resilience. This case study provides a more complete evaluation of overall system resilience compared to other case studies reviewed. However, environmental, social and economic consequences (step I in Fig. 4) of required performance level (step H in Fig. 4) seem to be lacking in this study. These are critical parts of resilience planning as they can significantly influence the energy system planning and operation. Resilience metrics should also be incorporated in system planning (step E in Fig. 4) as a complement to the system operation. In addition, a more comprehensive set of metrics including community-societal resilience (Section 4.3) should be taken into account. Although community-societal resilience is challenging to be quantified, in microgrid case study [34], a novel approach is recommended for the evolution of community-societal resilience and economic consequences.

Engineering-designed resilience dimension is considered in the planning process and design (step D in Fig. 4) of three buildings in the City of New York, including a cooling centre, a school shelter and a fire station [35]. The resilience of each design alternative, namely PV system, battery storage and diesel generator, is compared using the per cent of critical load that system can support for each hour of the year (steps F and G in Fig. 4) to satisfy required performance based on critical loads (step H in Fig. 4). The results

Table 6
Performance-based resilience metrics implication.

Hazard type/region (scale)	System	Engineering resilience metrics	Operational resilience metrics	Community resilience metrics	Reference
Flooding/Salaspils city, Latvia (district)	District heating pipeline system	- Total length of functioning pipelines [m]	- Total heated area of connected users [m^2] - Number of users connected to the network	/	[69]
Windstorm events/Great Britain (country)	Power transmission network	- Transmission lines online [%]	- Generation capacity connected [%] - Load connected [%]	/	[31]
Flooding, high winds, earthquakes, and landslide/Puerto Rico (country)	Microgrids	/	/	- Burden to community	[34]
Storm, New York City (building)	DER including PV and storage in critical infrastructure sites	- Percent of critical load system can support [%]	/	/	[35]
Heat wave and drought, South France (region)	Centralised power generation	- Total load not served [GWh]	/	/	[33]

show that the economic value of resilience (economic consequences) offers a lower payback period for design alternatives with shorter disruption hours. However, integration of operational resilience (e.g. peak demand and operation strategy), community-societal resilience dimensions and other resilience consequences (e.g. environmental impacts) can lead to more opportunities for resilience enhancement.

In another study [33], the resilience of centralised power generation is evaluated focusing on the resources availability (step B in Fig. 4), and the impact of heatwave and drought (step C in Fig. 4) in the planning phase (step D in Fig. 4) of the energy system by using mixed-integer linear programming. “Total load not served” is considered as engineering-designed resilience metric without distinguishing other phases and dimensions of resilience (Fig. 3). This sole indicator can only take into account the protection phase and mitigating the impacts of extreme weather conditions, and other phases of resilience e.g. adaptation and recovery seem to be lacking. The researchers have discovered resilience planning can significantly increase the energy supply and system resilience during the extreme events; although with higher capital and operational costs, these costs can be fully offset by savings due to reduced load loss. Wider consequences of resilience enhancement measures and energy performance during the system disturbance should be included in resilience planning.

Most of resilience studies focus on the operation alone and not the resilience planning, as also mentioned in Ref. [33]. Only a few studies focus on evaluation of various layers and phases of resilience, and disruption consequences which will hinder the opportunity of using all the resilience capacities of the system. Note the lack of comprehensive treatment of the three resilience layers as proposed herein. It is evident in Table 6 that employing the proposed resilience framework can potentially lead to more integrated and comprehensive energy system design options, and eventually, overall community system resilience enhancement. Conceptualising and estimating energy resilience based on the framework presented herein can provide several benefits to stakeholders. Energy master planners and engineers, facility managers, community owners, and local governments can incorporate the proposed resilience framework to develop informative system designs, minimise operational risks, make effective investment decisions, and create sustainable policies and regulations. Structure resilience in seismic design is an example of applying these resilience principles. Many local and international standards exist to guarantee resilient structural design against natural seismic events. In the future, the community-level energy resilience metrics can be similarly developed to provide a consistent and comprehensive design guideline/standard that foresees resilient energy performance not only at community level, but also for a larger energy system.

4. Conclusions and future work

We introduced a novel energy resilience framework consisting of a layered set of performance metrics to allow for structured planning and assessment of energy resilience at the community scale.

Although community-level energy systems are commonly viewed as more resilient compared to conventional energy systems against commonly expected and extreme events, assessment of climate hazards shows the risk of short and long-term impacts on various components of the system. In order to evaluate these impacts and incorporate energy resilience in the design, planning, and operation of both existing and newly built community-level energy systems, we have proposed a layered energy resilience framework that addresses engineering-designed, operational, and community-societal resilience. For each layer of resilience, a preliminary set of energy resilience metrics is identified that can support the engineering design, planning, and assessment of community-level energy systems and define the mitigation strategies. In addition, a community-level resilience planning flowchart is introduced which incorporates and demonstrates how resilience layers and metrics can be applied in the process of energy master planning. The proposed resilience framework enables evaluating the consequences of various design alternatives and enhancing the community system energy resilience which can provide benefits to multiple stakeholders. Exploring the resilience framework in five cases including district heating pipeline system, power transmission network, microgrids, DER, and centralised power generation; highlighted the need for a more comprehensive evaluation of the energy system design options, and potential system resilience enhancements, as proposed herein.

In the future, the critical components of the system should be modelled and their impact on the overall system resilience should be further investigated. The operational and community resilience measures provide a higher resilience capacity compared to engineering resilience measures but are more challenging to measure and plan for before a disruption has occurred. More research and case studies on the evaluation and quantification methods of these metrics are required to better enable forward-looking planning. In addition, an expanded type of energy master planning is needed that can incorporate the resilience metrics in the planning, design, and assessment of various typologies of communities. Much greater understanding, supported by context-based evidence, of community resilience capacity and how to enhance this (using relevant metrics) through effective intervention actions are needed. The trade-off of various resilience enhancement options and environmental and economic factors should be fully investigated. Lastly, the extension of the proposed resilience layers to other types of systems (e.g. water and transportation) should be explored, particularly when they are interconnected with community-level energy system, as well as in the transition to the fourth and fifth generation of district energy systems.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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