A holistic resilience framework development for rural power systems in emerging economies

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Abstract

Infrastructure and services within urban areas of developed countries have established reliable definitions of resilience and its dependence on various factors as an important pathway for achieving sustainability in these energy systems. However, the assessment, design, building and maintenance of power systems situated in rural areas in emerging economies present further difficulties because there is no a clear framework for such circumstances. Aiming to address this issue, this paper combines different visions of energy-related resilience both in general and under rural conditions in order to provide a robust practical framework for local and international stakeholders to derive the right actions in the rural context of emerging economies. An in-depth review is implemented to recompile information of resilience in general, in energy systems and in rural areas in particular, and a number of existing frameworks is also consulted. In order to acknowledge the particular circumstances and identify the important factors influencing the resilience of rural electrification in emerging economies, a holistic rural power system resilience framework is developed and presented. This consists of twenty-one indicators for technical resilience, eight indicators for social resilience, and thirteen indicators for economic resilience. This framework can be used by system owners and operators, policy makers, NGOs and communities to ensure the longevity of power systems. This work also paves the way for the creation of appropriate and effective resilience standards specifically targeted for application in these regions - aiming to achieve the delivery of global and local sustainability goals.

Keywords

assessment framework; decentralized; power system; resilience; rural energy

1. Introduction

Whether powering daily activities, from cooking to heating, or driving industrial and economic progress on a national level, energy is a crucial enabler of sustainable development. Demographic projections show that the global population will increase by 2.4 billion people by 2050 [1], indicating that energy infrastructure and services will need to increase enough to overcome not only the access deficit of the billion people lacking access today (especially in emerging economies), but also to meet the needs of the extra new people expected to join the global populace over the next few decades [2].

Access to affordable, reliable and sustainable energy for all is the aim of the UN's Sustainable Development Goal 7 (UNSDG7), but most if not all other goals can benefit from an improved access to electricity. In solving the problem of providing electricity, one can both directly and indirectly solve a wide range of pressing global issues [3]. For example, the inefficient use of biomass (e.g., wood charcoal) as cooking fuel in Global South accounts for a large percentage of the global human health burden (e.g., pulmonary disease) and causes significant environmental degradation, e.g., air quality and deforestation [4,5]. Electricity makes it possible for people to switch to better, safer and cleaner alternatives, such as electric stoves and heaters, reducing the impact on health and the environment. The goal of improving levels of education (linked to UNSDG4) can be accelerated, whether by simply providing lights to read by or enabling the uptake of modern technologies in classrooms and access to information via the internet [6].

However, while providing access to electricity is a crucial first step, there are many events that clearly illustrate that there is considerable room for improvement in terms of making our power systems more resilient. Over the past decade a number of natural and man-made hazards has impacted developed and emerging economies alike, causing major damage to power infrastructure and exposing serious vulnerabilities present in vital systems. Severe weather, longer-term climatic and environmental changes and cyber-physical attacks can lead to direct damage or indirect consequences that affect the normal operation of electrical components [7]. Blackouts interfere with people's daily activities and in severe cases can result in great economic loss or pose serious danger to human health and lives. For instance, India's droughts in the 2010s, nearly the worst on record, had power networks straining under the burden of increased electricity demand while supply suffers as dams across the country ran dry [8]. In 2015 the earthquake that hit Nepal damaged over a dozen hydropower plants causing a loss of 150 MW of electricity from the national power grid. The Boxing Day Tsunami in 2004 led to a huge loss of life and significant damage to infrastructure along coastal areas in Indonesia, Sri Lanka, India and Thailand. In addition to the numerous natural hazards, human conflict has also proved to be a significant threat to electricity access. Li and Li [9] found that night-time light and lit area in Syria declined by about 74% and 73%, respectively, between March 2011 and February 2014, with the drop in electricity usage attributed to displacement of people and damage to grid infrastructure from ongoing conflict. These events clearly illustrate that there is a need to focus more on the resilience of power systems, especially in emerging economies – in planning as well as operation.

And, resilience has now become a vital part in the planning and management of all systems and networks from energy and communications, to food supply and healthcare. Two of the seventeen UNSDGs explicitly mention resilience in regard to infrastructure and human settlements, and on a broader level success in achieving any of the UNSDGs is subject to unexpected shocks and stresses that can undo years of progress and effort [10]. For power systems this means, that in order to ensure the long-term success of power systems there is a growing need to anticipate the future requirements of power networks and stakeholders, and to design and provide resilient systems that can serve communities far into the future while coping with the challenges they will face, including challenges caused by climate change. Resilience thinking could help owners and operators assess their systems and apply necessary measures, and compare similar sector or subsector sites using resilience metrics, allowing them to understand and deal with risk more effectively [11].

But what does resilience mean in this context? While there are many definitions of resilience in general and for diverse urban infrastructure and there are a number of practical frameworks for critical infrastructures, for planning, operations and policy changes for energy infrastructure in developed countries [12], for the assessment of energy access [13], as well as for the assessment of resilient cities, to the best of our knowledge, there is no overarching standard approach to assess the resilience of power systems serving rural communities in emerging economies. And recent work that provides approaches to quantify or assess resilience of energy systems, has a very narrow view on it, either as a quantification of operational and disruption costs [14] or in terms of its technical performance [15,16]. However, besides technical and economic factors these do not take into account social aspects. And, finally, no document is available providing a complete and comprehensive review of benchmarking methodologies applied in the field of power systems resilience for rural areas within developing countries. Thus, the present work aims at closing this gap, by presenting a practical framework, with key social, economic and technical resilience qualities and metrics and a simple analytic tool for understanding and assessing the current resilience of rural power systems. It is organised as follows: Firstly, an overview of different definitions and frameworks that are used as guidance for the development and assessment of a novel one. This is followed by an illustration of how to operationalize it, thereby helping to identify policy makers, industry and local stakeholders where to focus activities on to increase resilience.

2. Methodology

This section provides an overview of the definitions and the various theories of resilience from multiple disciplines including ecological and social science, risk and hazards science, and engineering.

2.1. Resilience definitions in general

Since resilience is a broad area of study, the section below attempts to summarise the key themes identified in the extensive literature starting with a general understanding of the term, then looking at its application to power systems, and finally in a rural context.

Early work in the field of Ecology produced the first robust definitions of resilience which have subsequently been adapted by various disciplines. Holling [17], who remains one of the most cited authors on the subject, defined resilience as the ability of a system to absorb variations in the factors that affect it and still persist while maintaining the relationships within it. Holling [17] further introduced the idea that resilience and stability were separate characteristics, painting resilience as a dynamic rather than a static process. Furthermore, its understanding changed according to the evolution of the ecology vision of human and natural systems [18] from separate structures to a model of mutually interacting socio-ecological sub-systems within a larger, more complex Earth or Social-Ecological system [19]. Thus, social systems are entirely reliant on resilient ecological systems [20] and no-longer over-compartmentalised or over-simplified the complex system interactions inherent in most large scale systems.

Since resilience describes an interaction between a system and any event that negatively impacts its performance for a given period, an important first step is to identify the interacting components. This covers both chronic threats or “stress”, with a lower magnitude and "threats" or "shocks" where a single unpredictable event causes a serious impact of high severity [21]. This means that, on the broadest level, resilience can be described as a general process of response to changes in the relationship between systems and their external environment [22] while a narrower approach, such as that in hazard risk management, will look at the performance of a system to a specific event such as an earthquake or storm. Such events include system inherent operational risks and variation (e.g., supply demand fluctuation) or external disruption risks caused by natural and artificial disaster (e.g., flooding, policy intervention), where resilience evaluates the system responsiveness and capacity to quickly recover, adapt and grow in response to system risks [23,24]. Alternatively, it is possible to take the view of resilience as "total resilience" or "all-hazards community resilience" [25] where terms like stress and perturbation are used to describe any or all events that may negatively impact the system.

On the one hand, the vast range of possible hazards and stresses, together with their often unpredictable nature, add greatly to the complexity of assessing resilience. By asking the question "resilience of what to what?" [26] it is possible to provide a general measure of a systems performance that applies to the specified system requirements, i.e., what service or output the system is expected to deliver, and the type of event or events under consideration. This has led to attempts to use resilience to describe performance under normal, i.e., non-stressful, conditions, with Cutter et al. [27] for example, identifying resilience as either inherent or adaptive. Under such a definition the first describes the ability of a system to function well during times of little or no stress while the second relates to the ability to respond in a flexible manner to major perturbations. Still, for the most part in the literature, resilience is associated with events, whether general or specific, that are outside the normal range of stress normally felt by a system.

Furthermore, resilience comprises a range of elements which enable a system to cope with stress. Adger [20] refers to this ability to absorb perturbations as buffer capacity, while Folke et al. [28] describe it as the magnitude of shock absorbed before a system changes state. Successfully absorbing a shock requires a system to retain its structure and function while under pressure [29]. This may involve withstanding an event through strength or brute force, often referred to as robustness, but may also involve limiting the change in state or damage to a degree that can be quickly and easily recovered from. Bruneau et al. [30] argues that for a system to be resilient it must minimise the consequences of failure and minimise the resulting recovery time. This ability to survive a shock event, whether by robustness or effective damage control, can be seen as the core of resilience.

In a broader or expanded vision, resilience includes concepts like vulnerability, risk and adaptation; because it is considered a dynamic, ongoing process that account for the period before, during and after an event. Nelson et al. [31] argued that a system's natural state is one of change, not of equilibrium, while Holling [17] challenged the ideas of system equilibrium and stable states, arguing that a resilient system will change its equilibrium over time based on experiences, in order to better deal with stressors in the future. Preparation, performance during an event, recovery and adaptation form a continuous loop which allows a system to constantly improve its resilience. Gallopin [22] takes this concept further by arguing that capacity of response should involve not just coping with the impact, but also taking advantage of the opportunities, i.e., being proactive rather than just reactive. A truly resilient system should be able to tolerate novel pressures while minimising damage, then have the capacity to asses any changes in function or state in order to identify key weaknesses in the system, which may otherwise have gone unnoticed. Doing this requires a degree of intelligence from the system and its management, and this becomes the tool that enables learning capacity and adaptability which allow vulnerabilities to be addressed and negated. These learning and adaptive capacities have been identified as key components to improve resilience by a number of authors [22,26,29,32–34]. Ultimately resilience should be viewed not as an end goal but as a continual process of learning and adapting [35].

Additionally, to understand the ability to adapt one has to take into account more than just economic development and technology [31]. Social factors like human capital and institutional and governance structures also play an important role, specifically in ensuring that positive change and adaptation is possible. Janssen et al. [36–38] similarly argue that resilience is largely a result of strong social-network structure which facilitates problem solving within the community. This has important implications for development projects seeking to improve resilience. High-tech solutions, even when made affordable, rarely succeed where local management and government is not equally resilient. This links to another aspect of resilience that appears frequently in the literature; the ability to self-organize [26,29,39,40]. The self-organising nature of complex adaptive systems [41,42] means that this process can take place within them rather than being steered from the outside. Lebel et al. [43] describe the term in a social context as the ability of a system to maintain and evolve its identity, and to buffer impacts without being continually invested in or relying on subsidization or other external contributions. Some exchange and interaction between systems at different scales will always exist, but the more a system can rely on its own resources and structural capacity, the more resilient it will be. The concept also applies to resilient management, where it describes the ability of the leadership and other actors to decide upon and compile the tools and resources needed to perform learning and adaptation to enhance its resilience [39]. This process is based on communication and cooperation to facilitate participant-led problem solving and action [44].

In the real world only few systems exist in a vacuum. Instead, they interact with environments that are highly variable over time and on different scales adding uncertainty. Gunderson & Holling [45] describe that resilience on one scale is impacted by the resilience on bigger or smaller scales. This interconnectedness means that its increase in one time period, on a certain scale or in a certain element, may decrease it in a later period or in another area of the system [26], leading to the concept of whole-system resilience, which is covered extensively in the social technical transitions literature. It maintains that the application of resilient technologies cannot be viewed in isolation. Additionaly, Markard [46] describes the process of change towards better resilience as a socio-technical transition, where changes in institutional structures and individual practices accompany the introduction of a technological solution. Elements including user practices, regulation, industrial networks, infrastructure and symbolic meaning are all combined to form a multi-level perspective of the system and the process of change [47]. Addressing all of those elements through such long-term performance thinking reinforces the resilient technology creating a more robust, synchronous system [48].

While the examples above have been mostly of positive nature, it is important to note that resilience is not only connected to positive aspects of a system [49]. Locked into an unfavourable state a system may be very resilient to remain in that state. This can be often observed with human institutions and management structures [50]. For example, Carpenter et al. [26] pointed out that a dictatorship may be resilient, able to last for several decades despite attempts to overthrow it, but this state is clearly detrimental for the rest of the social system. Similarly, the concept of “lock-in” from development economics describes how self-reinforcing effects from within a system can set it down a less prosperous path which once initiated, can be extremely difficult to correct [51]. Walker et al. [29] suggested that resilience management should aim to prevent the system from moving to such undesirable states in times of stress, while focusing on developing the positive elements that allow renewal and reorganization after acute change.

To summarize, Table 1 provides an overview of these definitions which are representative of resilience as viewed across a number of different domains. Next, the role of resilience in power systems in particular is explored.

Table 1: Overview of common working definitions of resilience

Field	Resilience Definition	Source
Government	“The ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents”	[52]
	“Anticipation, assessment, prevention, preparation, response and recovery. Resilience is about all these aspects of emergency management”	[53]
Ecology	“Resilience determines the persistence of relationships within a system and is a measure of the ability of these systems to absorb changes of state variables, driving variables, and parameters, and still persist”	[17]
Disaster, risk & hazards	“The capacity of a system to absorb recurrent disturbances, such as natural disasters, so as to retain essential structures, processes and feedback”	[54]
	“The ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient	[55]

	manner, including through the preservation and restoration of its essential basic structures and functions. The resilience of a community in respect to potential hazard events is determined by the degree to which the community has the necessary resources and is capable of organizing itself both prior to and during times of need”	
Engineering	“Power system cyber-physical resilience is the system's ability to maintain continuous electricity flow to customers given a certain load prioritization scheme. A resilient power system responds to cyber-physical disturbances in real-time or semi real-time, avoiding interruptions of critical services. A resilient power system alters itself in an agile way”	[56]
	“Success belongs to organisations, groups or individuals who are resilient in the sense that they recognise, adapt to and absorb variations, changes, disturbances, disruptions and surprises – especially disruptions that fall outside the set of disturbances the system is designed to handle”	[57]
Social	“Social resilience is the ability of groups or communities to cope with external stresses and disturbances from social, political and environmental change”	[20]
	“Psychological resilience is a relatively stable personality trait characterized by the ability to overcome, steer through, and bounce back from adversity”	[58]
	“If we think of a complex system as an individual, it only remains the same system for as long as it has a consistent identity. […] Resilience can be operationalized by quantifying identity and assessing the potential for changes in identity”	[49]

2.2. Resilience definitions for power systems

As power systems including infrastructure and energy services, interact with both the human and natural environments and thus can be viewed as socio-ecological systems [56], many of the resilience concepts from disciplines such as ecology and industrial ecology can be applied effectively in this context. A resilient power system requires the human elements of operational management and governance to work in parallel with the physical infrastructure, and both parts must work within the limits of the planetary environmental boundary and must have the ability to tolerate environmental shocks.

Human element

Resilience must encompass the human element of a power system as well as the infrastructure [59,60]. The entire process from engineering and design to operational management must take actions to predict the likely threats to the system, design and build it with those threats in mind, and then continually work towards improving resilience by learning from stressful experiences and by adapting [61]. Modelling and simulation allow its performance to be analysed under different stress scenarios, and possible responses can be tested. Though there are considerable costs and challenges in modelling the behaviour of complex systems and stochastic events such as weather and climate, the benefits of being able to anticipate numerous scenarios and their effect on different configurations means that it is now a crucial tool for improving resilience [62–64], allowing management to put in place operational procedures to cope with a wide range of disruptions, whether though automation of certain processes or by specific training of personnel and response teams. Where control and recovery procedures are not fully automated, responsibility lies in the hands of operators who must have the situational awareness and capacity to make the correct decisions, especially during conditions of power failure and stressful events [65,66]. Management is constantly under pressure to make the correct trade-offs between safety considerations and business targets and so the correct cultural norms in terms of safety and resilience must be in place within an organization [59].

Still, the human element can be a help or as much as a hindrance to resilience. The same creativity that allows humans to produce novel solutions to new threats also enables them to find unintended ways of utilising system elements outside of their intended use [67]. As a result, human error is always a possibility, especially in the event of a major hazard where operational personnel may be under severe emotional and physical stress. For that reason Venkata & Hatziargyriou [7] state that, in addition to being resilient to external threats, grids should be made elastic to these errors, relating back to the ideas of system intelligence and self-organization. Fast and accurate problem diagnosis, improvisation, effective communication and collaborative actions are all requisites for effective management when facing novel events or hazards [66], and recent advancement in computing and communications have made it possible to integrate these attributes directly into the systems themselves [68,69].

Robustness through redundancy, flexibility and agility

Early approaches to power system resilience focused on the robustness of physical infrastructure. In order to withstand extreme events, hardware components may be reinforced or replaced with more durable alternatives in a process known as “hardening” or “resilience engineering” [7,70], aiming to improve robustness of vulnerable elements only. However, Holling [17] pointed out that increasing robustness in one area of a system can inadvertently cause fragility in another, as observed for both ecological systems and electricity networks. Focusing too much on robustness may lead to fragility or brittleness, as a network may become too specialized in withstanding a single type of event at the expense of general resilience [71]. While Argandeh et al. [56] see robustness as a design consideration aimed at specific components and specific hazards, in their understanding resilience is concerned with whole system operation, i.e., the network control system and human management and exhibits attributes like flexibility and agility to cope with external threats.

Along with improving robustness, increasing the redundancy within a system can make it also more resilient to threats. Common cause failures greatly reduce a power systems resilience as it becomes more susceptible to new outages, and has fewer assets or resources available while experiencing a perturbation [66]. A single event or contingency may leave the system in a state where one key element is damaged or destroyed but the network as a whole is still functioning, a state known as N-1 secure. Network design can also play a big role in offering alternative routes, with certain nodes becoming more or less vulnerable depending on the number of routes they support. At this point it is important to have spare hardware, whether by doubling-up on certain components or by using elements with the capacity to cover multiple tasks, allowing them to take over the role of the damaged element [72]. Redundancy and the ability to recover as quickly as possible is key as damage to a two or more key elements may result in a blackout. The importance of speed of recovery was similarly stated by Hughes [73], who describes resilience as mean time for recovery from a state of stress to a normal state and by Ton and Wang [74], who define it as the ability to withstand and recover rapidly from disruptions.

Reliability and adaptive capacity

Reliability is an important consideration in power system resilience as they must be able to provide sufficient electricity to meet the needs of consumers on a consistent basis. To maintain this output, generation must have adequate capacity and be fed with a steady supply of energy, achieving energy security [75]. Any system reliant on imported fuel is at risk from a number of external factors including price volatility, geopolitical changes, reductions in production and policy measures such as widespread carbon pricing [76,77]. Similarly, any system that is too dependent on any one particular energy source leaves itself even more exposed to those external factors. The consequences of overreliance on hydrocarbons is perfectly illustrated by the impacts of the 1973 OPEC oil embargo on the US economy at the time [78]. Fossil fuels have shaped national power systems, pushing towards highly centralized and interconnected mega-grids, leading to the efficient use of high density fuel sources, but with less resilience as issues can more easily propagate through the single system and the loss of a generation facility is felt more strongly. Rather than the top-down model of traditional centralized systems, O’Brien [79] argues there must be a move towards de-centralisation. In addition to this, diversification and the addition of non-exhaustible energy resources into the energy mix are essential steps to increasing energy security and power system resilience [80–82].

However, as with hardening methods, there are trade-offs. Redundancy is costly and inefficient when implemented excessively or without careful planning, as it can lead to a large stock of components that are underutilised in normal conditions, giving low returns on investment. Rather than withstanding an attack through brute force, i.e., using hardening methods or increasing redundancy, O'Brien & Hope [35] emphasize the importance of intelligent adaptation and learning capacity due to its ability to increase both overall resilience and efficiency. This smart approach applies to both the physical systems themselves as well as to management. Resilience is achieved through intelligent institutional leadership which must be sensitive to rapid and pervasive changes and be prepared to face them effectively [83]. There are limitations to flexibility. Intelligence means understanding when to use resources in a creative manner to cope with a novel threat, but also knowing when the system needs a significant upgrade in design or operation. Hughes [73] states that when faced with novel or more prolonged events it may not be possible to return to the original state. In this case the system must either continue to function in a damaged state or adapt to form a new normal, but Hughes points out that the choice of whether to be agile and deal with certain events as they occur or to adapt the system to a new normal is primarily dependent on technical and financial feasibility. And even this can then take time.

Efficiency

The efficiency of a system will have a direct impact on its resilience [76]. Cost minimisation makes long-term maintenance achievable while addressing the issue of inclusivity by ensuring that even the most vulnerable can afford at least basic service [84–87]. Despite the range of resilience measures currently or theoretically available, Panteli & Mancarella [66] argue that at a pragmatic level, these measures come down to what the system its owner can afford to withstand. On the consumer side, a resilient power system must be able to supply electricity at an affordable price so the ability to reduce running and set-up costs is essential. Greater efficiency is also needed to increase the uptake of renewable sources, where intermittency and relatively low energy densities are an issue. In these cases, minimising electricity waste through better end-use behaviours, demand side management and intelligent distribution and control systems are the key to scaling up and turning renewable options into a viable solution [88–90]. In the end, an optimal design should aim to provide a service with standardized and appropriate levels of quality at minimum cost [84].

Long-term strategic planning

Human shortcomings including the tendency to discount environmental risks or to address cognitive dissonance by changing our beliefs rather than actions, also affect the ability to comprehend and deal with long-term, wide ranging issues like climate change on all levels, from operational management to policy [91]. On a macro scale, decision makers must consider resilience into their long-term planning. A key challenge faced by policy makers and stakeholders is to recognise the signals of impending change and to come up with solutions that can transform the current system before it is subject to change that it cannot respond to in time [76]. Current events perfectly exemplify this point. The drive to integrate more renewable sources into national energy portfolios is an attempt to transition to power systems that are resilient to future the challenges related to climate change and the depletion of hydrocarbon resources [92].

An example of some of the common differences between rural and national scale power systems is shown in Figure 1. The extent to which some of the resilience qualities discussed above, such as redundancy or automation, can be successfully applied will differ based on the configuration or characteristics of rural power systems. A more detailed look at the unique needs of rural systems is provided in the following section.

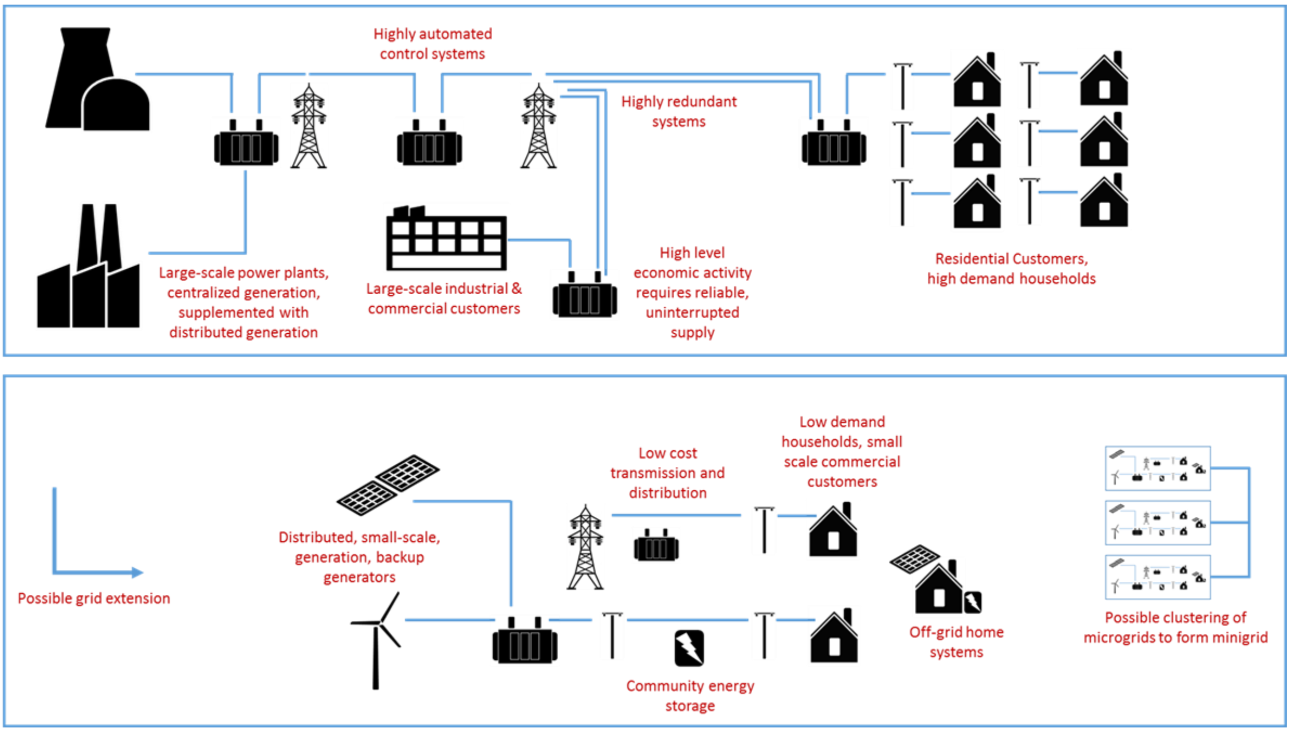

Figure 1: Comparing common features of rural and urban/national power systems

2.3. Resilience definitions for a rural context

Though certain criteria must be met for any power system to be classed as resilient, rural settlements, especially those in emerging economies, will have unique social, economic and political characteristics which will determine the level of performance deemed acceptable by the community and other stakeholders. For example, where a large, developed city may have a zero tolerance attitude towards blackouts, in developing rural areas short periods of blackouts may be deemed acceptable or even normal. The marginal cost of ensuring perfect reliability may make electricity unaffordable to consumers which negatively impacts the long-term resilience of the power system. Rural areas are far less homogenous than urban cities, making the task of producing a universally applicable framework more difficult. This section seeks to examine common power system resilience qualities through the lens of a rural setting, allowing a more tailored analysis of resilience in such cases.

Rural-specific conditions and needs

The local landscape and local needs will determine the most appropriate technologies and therefore the resilience of the community and power system. Rural areas may be relatively dense with concentrated populations or extremely remote with dispersed populations that lack access to infrastructure services, markets and information [93]. This has implications for the feasibility of different power solutions [94–96]. For example, grid extension is only possible where load concentrations are high enough to be economically viable. Even then, the main supply may still be unreliable or the generation capacity not sufficient, as is the case in many developing countries.

More remote areas may have better success with off-grid or micro grid solutions which, compared to expansion of legacy modern power systems, provide economic and environmental benefits that enhance resilience [97]. The use of such a configuration facilitates the uptake of renewables addressing the resilience concerns of security, long-term sustainability and self-organization [98]. An isolated or “islanded” system avoids the high cost of an expansion over long distances to serve sparse loads, protects from damage spreading from other areas of a centralised network and gives a local community ownership and some form of control. At the same time these distributed generation assets can also be made suitable for future grid connection as a basic infrastructure building block [99]. This is an important consideration as these systems need the ability to adapt to changing conditions in the future, since rural settlements in developing countries are often subject to micro and macro demographic changes including growth and migration, as well as changes in energy usage and behaviour. Furthermore, it is plausible that energy requirements will increase considerably because quality of life and economic status improve after the initial introduction of basic electricity provision and some studies have shown a greater dependence on electricity after initial connection also related to increasing income [100,101]. Therefore, for a rural system to be resilient it must be able to able to adapt to meet future demand.

On the other hand, it must be noted that centralisation is not always a threat to resilience. For example, in the 2004 Indian Ocean Tsunami, power system damage was mostly limited to certain elements located near the coast. This was largely due to a centralized power network where the supply network (i.e., power plants, major transmission lines and grid substations) originated from inland and branching out toward the coast [102].

Affordability

Compared to other resilience qualities, affordability carries a higher weighting in rural areas of emerging economies. On the consumer side, large upfront costs are a considerable barrier to electricity uptake, both on an individual level for household connections and on a community level [86]. It can be argued that no electrification project can survive or thrive without the accompaniment of well-designed financial and support mechanisms, providing initial support and continuous service support to the community [96]. This extends to more general financing services that provide alternative funding, banking solutions and payment methods [6]. Unbanked populations often face higher relative transaction costs when paying for a service [103]. This lack of formalized or automated payment methods can also lead to greater losses on the part of the utility provider due to users defaulting on payments.

As a business model, providing electricity to remote rural settlements is both a huge opportunity and a risk, as while the size of the potential market is large, the affordability amongst customers is low so finance must come from a mix of sources including customer service payments, government subsidies, loans (i.e., from banks and other lenders), equity from villagers and contributions from donor organisations [104,105].

Self-sufficiency and self-reliance

Self-organization and the ability to function without subsidies or constant external inputs is an important quality [43], however, in a rural setting it may not be realistic to evolve straight to full self-sufficiency. Yet, power systems must be viewed in a larger context. Developing local industries ensures a high enough demand for electricity to make these feasible, and provides consumers with a means to generate the income needed to afford the service. Generating markets for electricity leads to higher rates of return on investment for electrification projects [106], so simplifying the access to subsidies and credit is a key component of promoting market formation [104]. A resilient power system must have the financial capacity to run itself, and in the rural context cost becomes a major limiting factor when choosing an acceptable trade-off between how critical resilience is in a particular system element, and what it costs to get the “biggest bang for the buck” [70].

Furthermore, in small rural communities there is arguably less of a separation between human and engineered systems due to the need to manage them within a community. Where the majority of people in developed urban centres rarely think about the running of key infrastructure and critical services, but expects them to run without fail in the background, individuals in a smaller rural community are aware that external support for maintenance and repair may be unreliable and that problems must often be solved with only the members and resources available locally. The lack of established electricity service providers as well as the need to maintain and improve self-reliance and a sense of control within the community means that resilience thinking should be inclusive and account for multiple points of view [39]. Different stakeholder groups prioritised different factors based on their roles, interests and experiences [21] which can lead to gaps in identifying vulnerabilities within a power system. Therefore, involving a wide range of stakeholders allows more weaknesses to be identified and corrected.

Beyond that, the way in which such programmes are managed will have a big impact on their success. A strictly top-down approach to implementing local power infrastructure may fail to account for household behaviours while a bottom-up may lack specialist skills and technical expertise. These two approaches must be carefully balanced – rural communities are self-reliant and independent, but this same attribute may make residents resistant to organized efforts to make changes within the community [107]. However, already a collective assessment process can generate community awareness and contribute to community members working together towards shared goals and better resilience [107,108]. Similarly, O'Brien [79] argues that this starts at the level of the household, and that community engagement, education and inclusive management or governance are key to instilling resilience values into the community. A feeling of ownership can further contribute to the willingness to play such a role.

Data access

Data access is a major hurdle when implementing complex systems in remote rural locations [85]. The ability to accurately plan and manage any electrification project is largely dependent on access to data. Where narrow operating margins are vitally important, miscalculating the needs of the community can impact costs for both consumers and operators. Policy makers are hindered by a lack of funding and a lack of information about the factors that determine the energy choices of rural consumers [109]. Energy demand is difficult to gauge as traditional fuels are traded informally or, in case of fire wood, collected for free from the local environment, with few reliable records of transactions and total use [106]. Understanding these needs requires systematic and careful distribution planning which includes the collection and analysis of consumption data, spatial data and network analysis to determine the most appropriate technologies [85]. This information allows for a more efficient and subsequently resilient rural power system but also comes at a cost for project developers. Price-performance of computing and sensor equipment continues to improve at a near exponential rate but these smart monitoring technologies may still be just out of reach for many remote locations, both in terms of cost and due to the lack of expertise needed to manage these tools. A resilience approach to these issues must focus on improving self-organization and intelligence within the system. Practically, this often requires some input from partner organizations not only in installing and financing the infrastructure but more crucially in disseminating the knowledge required for successful long-term management of the power system and in providing the training to customers and local technicians that grows local expertise and fosters a sense of ownership and responsibility in the community [108]. Because of the cost and knowledge limitations, self-organization in a rural context will have a stronger emphasis on operational management and community response and organization, rather than on automated diagnosis and response systems.

Rural governance

The issue of governance in developing countries and rural communities affects all facets of power system performance and community culture. Trust, between community and institutions, and technology developers and implementers, is an important and largely overlooked factor that is critical for the successful implementation of technology interventions [110]. Palit & Chaurey [111] found that biases against renewable energy and distributed generation options by government were hampering the effort to increase rural electrification.

Another common issue in developing countries is electricity theft which is strongly related to the local social, economic and political environment in place. Corruption enables theft and though this activity can be reduced using technical or engineering methods, the financial limitations often make solutions like automated network monitoring unfeasible [112]. Encouraging self-policing within rural communities or enabling cooperative run rural electrification projects, is often a more practical method for stopping theft and increasing accountability [113,114]. However, this is dependent on the existence of appropriate institutional models and the right balances and checks if coercion and co-option by local power brokers is to be avoided [111].

Furthermore, alike in developed countries, the time, effort and cost required to change mature energy systems, at a holistic level, are a major barrier. In this sense, developing countries may have an advantage in being followers and able to learn from existing best-practices. Where financial limitations can be overcome, regions may have an opportunity to implement resilient systems from the outset [79]. Similarly, a smaller population size increases the chance of the successful uptake of positive household practices within the community.

2.4. Insights from related frameworks

A framework has to be grounded based on knowledge from the existing literature and is achieved by collecting, critically assessing and organizing the important factors from the range of different approaches, and finally producing a summary and display of the relevant findings [115]. For the framework proposed in this paper, by building a clear understanding of resilience, it is possible to produce a hypothesis of what a resilient rural power system is in terms of the qualities it should express, features it should have and how the different parts of the system should relate to each other. This hypothesis can be transformed into goals for communities or projects to aim for and can act as a benchmark against which to assess the system's current performance.

A key goal for any framework is to be useful, so it is important that the qualities identified by the framework are measurable and comparable across multiple case studies or against the bench-mark model. Defining resilience is relatively simple, despite the seemingly large variety of existing definitions as shown above. The more challenging task is operationalizing the chosen definition to allow communities to adapt to changing conditions in the most appropriate way for their situation [116]. For each resilience quality, one or more quantitative or qualitative indicators can be used to give a measure of resilience in that area. Multiple indicators can finally be combined to form an aggregate score that is succinct, easily communicated and reflective of overall resilience. In the following an overview of past frameworks that cover some of the domains addressed here are presented.

Madni & Jackson [70] state that the goal of a framework is to guide the attention of operational management, decision makers and other stakeholders towards key concerns such as: which elements of a system are affected by threats, where resilience improvements are most needed and what methods are appropriate for achieving resilience goals? This can be achieved by identifying the important factors and variables, the interrelationships between them and what information to be collected and analysed [117]. The National Research Council [116] argues that a resilience framework must be replicable, analysable, scalable and usable. Most importantly, the results of the analysis should be incorporated into the communities and systems entailing the need for a carefully thought out communication strategy. Overly complicated, technical or sophisticated tools and indicators may confuse rather that aid decision maker and management, failing to help decision making about resource allocation and other actions.

In the following two sections an overview of related frameworks is presented, from academia and from practice.

2.4.1. Related frameworks proposed by previous research

An approach common in research on risk or hazards is to measure resilience based on the probability of events and their consequences. The relevant threats are identified, and likelihood and expected damage or disruption is calculated for each of them. In this way the final resilience metric can be defined as the probability density function of a given threat and consequence [12], where a more resilient system will have a lower probability of experiencing serious damage from a stress event. In contrast, Bruneau et al. [30] equate loss of resilience, with respect to a threat, to the size of the expected degradation in quality (probability of failure), over time (i.e., time to recovery) which can be quantified as a percentage of maximum performance. Similarly, Kwasinski [118] uses reliability theory and the expected proportion of the time that a system performs its required function, as a metric. Importantly, this method is also able to account for the dependence on other critical infrastructures as well as human decision making at sub-optimal levels. On the other hand, Arghandeh et al. [56] make the argument that the duration of exposure to a hazard event is in fact more important than the probability of the event when designing a resilience framework. They argue that focussing on event probability is a risk assessment approach but is not a crucial factor in resilience as a long-lasting event will lead to more damage to a power system, requiring more of a real-time response, whereas a merely more likely event does not.

Other studies have focussed on modelling as a solution. One example of this approach is given by Panteli & Mancarella [66] who propose a modelling framework that incorporates a combination of weather and power components with a holistic system model to produce weather-affected system resilience indices, providing a quantitative assessment platform for analysing its impact on quality. Still, because of its high stochasticity and multi-dimensional impact, quantitatively measuring weather risks remains a challenge.

Expanding on the issue of quantifying resilience, Cutter et al. [27] argue that many quantitative frameworks are unable to capture accurately important social factors present at local level. Their disaster resilience of place model takes a holistic approach to measuring community resilience based on several elements including social, economic, institutional, infrastructural and community capital with specific variables within these components assigned a numerical score representing their positive/negative impact. Cutter et al. [27] point out that using local data is always a preferable option, as national data are often outdated or fail to capture the specific nuances of each case study.

Integrating social dynamics into any model is of high importance but social factors can be difficult to quantify. A qualitative analysis considering system structures, characteristics and features can be used to compliment and explain the results of quantitative measurements or can take the place of quantitative results when data is difficult to obtain or completely unavailable [119]. In their framework, Walker et al. [29] use their analysis of social ecological systems as a basis for making resilience management decisions, viewing the issue as the need for enabling social action. Using stakeholder involvement at every stage, they build a conceptual model including antecedent conditions and key functions and drivers. This can be followed by an analysis of the stochastic events or threats impacting the system as well as stakeholder visions of future resilience. The information gathered from this process allows a number of scenarios to be modelled, the results and outcomes of which can be evaluated in terms of their policy and management implications.

2.4.2. Related frameworks used in practice

Unlike academic frameworks that provide conceptual bases for understanding and assessing resilience but are not always fully refined for real world implementation, this section provides an overview of four practical frameworks that cover aspects of this work.

Constructing a resilience index for the enhanced critical infrastructure protection program by the Argonne National Laboratory [11] framework looks at resilience of critical infrastructure and key resource assets and is aimed at project owners and operators. The index provides a method to assess the system’s ability to withstand specific threats and its ability to recover and resume normal operations. Importantly, it provides a standardised platform which allows operators to compare the resilience of facilities and key assets against other similar cases. Resilience is viewed in terms of three qualities; robustness, resourcefulness and recovery. As method it uses a questionnaire, and data can be collected on various components and sub-components for each of these, making up five levels of increasing specificity. These values are aggregated into each following level using the weighted sum of the level below to produce a resilience index in the range 0 – 100 allowing assessors to identify the most effective actions out of a selection of possible measures intended to increase system resilience.

The conceptual framework for developing resilience metrics for the electricity, oil and gas American sectors, was designed by Sandia National Laboratories [12] to inform planning, operations and policy changes for energy infrastructure. Here, a risk-based approach is taken, aimed at understanding the expected consequences from various threats or disturbances. The focus was on both the impact on the system itself and on the social implications of changes in its performance. Stakeholder feedback is used to select most relevant metrics based on hazards specific to them. The expected threats and level of disruption for each of these are modelled in relation to a system's performance. The models provide data on changes in its outputs which are later tied with social implications to produce the final resilience metric represented as a density function showing the probability of certain consequences, given different threats.

The Energy Sector Management Assistance Program [13] framework "Beyond Connections, Energy Access Redefined" aims to assess energy access across various community institutions, allowing stakeholders to view baseline performance and set targets for improving energy access. Its focus on combining technical factors with social implications on a rural scale is directly applicable. Furthermore, many of the factors considered are directly relevant to resilience such as affordability, quality and level of service, reliability, and legality. Additionally, it uses a multi-tier measurement method, where 8 attributes are selected to determine energy supply and impact on individual users. Attributes are assessed for a given source of energy and each is placed into one of 6 tiers depending on performance. The overall level of energy access is represented as an index calculated by averaging the tier ratings across the different energy services. Data is collected from both the demand side and the supply side via surveys and questionnaires, for which an attempt is made to be technology and fuel neutral.

The Arup [120,121] City Resilience Index framework seeks to assess resilience and to measure relative performance over time. It is designed primarily for city governments, but also for other stakeholders, and takes a holistic view of the factors and interrelationships that affect resilience with a strong focus of integrating more vulnerable groups. Though this it is aimed at city resilience, certain aspects, such as the complete approach that combines technical, social, economic and environmental factors, or the methods for assessing infrastructure and critical services, could potentially be adopted to look at rural scales. The City Resilience Index uses 52 indicators which are assessed through 156 questions, drawing upon both qualitative and quantitative data. These are assigned scores and aggregated, however findings are presented graphically in relation to the 12 goals rather than as a single overall score.

To summarise, all the above mentioned frameworks provide valuable learnings for the creation of the one proposed in this paper. So, for instance, aside from the risk-based approach, some form of aggregation was used by each of them. They also show that during the design of the framework, a balance must be found between quantitative methods, which enable replicability and comparison between cases, and qualitative methods which allow for a subtler understanding of the full range of issues. The latter can be lost in quantitative research. Flexibility is another important consideration. Hence there is a trade-off in designing a widely or universally applicable framework as no two cases are ever identical. Thus, having a degree of flexibility when selecting indicators or specific metrics may be useful, as it allows the assessment of the same general resilience qualities based on the available data. A similar effect can also be achieved using weighting indicators based on their relative importance. Finally, it must be stressed that all approaches use surveys as a means to gather data from a range of stakeholders, emphasizing that this is not purely a technical assessment but requires a socio-technical perspective.

3. Results: Resilient framework development

The in-depth review of the resilience literature and the experiences obtained from analysis of past frameworks resulted in a list of resilience attributes that form the basis for addressing two key question: What are the most important requirements for rural power system resilience from both an operational standpoint and a community standpoint? and leading to a holistic rural power system resilience framework focused on the particular situation of emerging economies. As presented in Figure 2 and described below, it accounts for the technical, social-political, economic and environmental concerns (divided into technical, social and economic categories for simplicity) that affect rural communities in emerging economies.

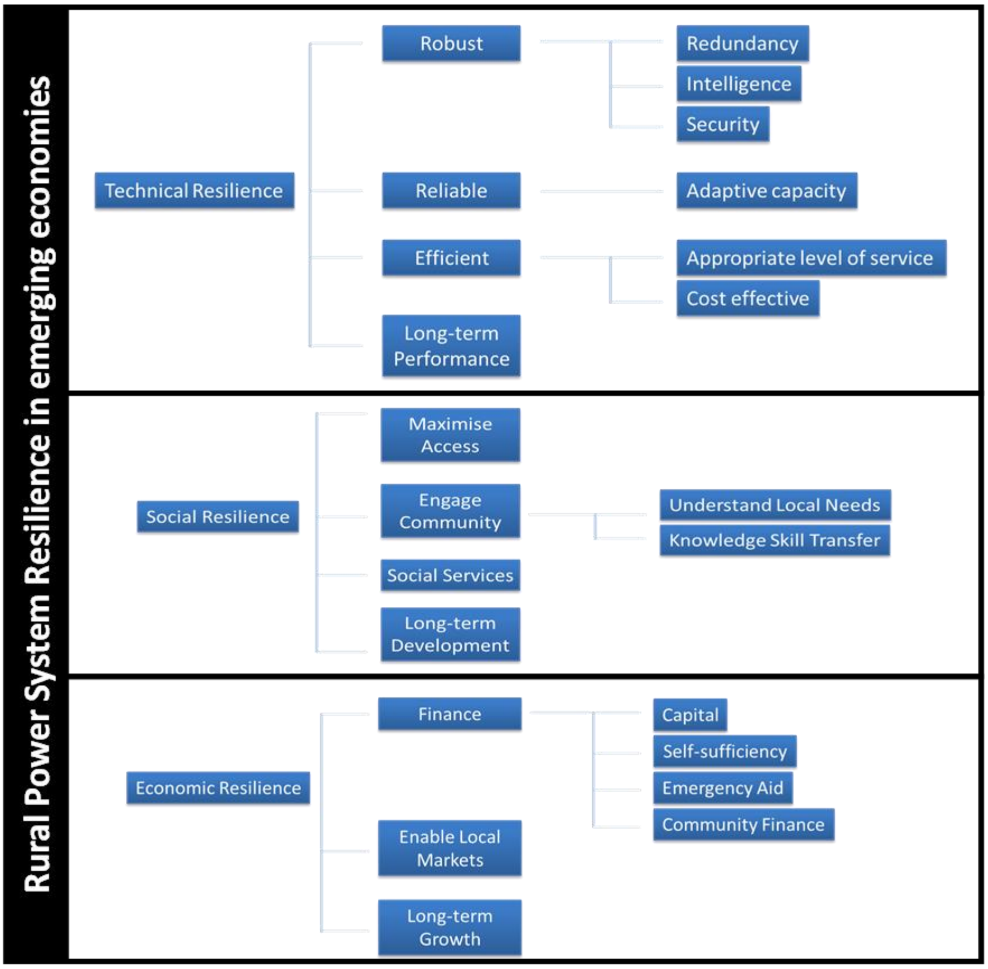

Figure 2: Proposed framework for rural power system resilience

3.1. Resilience in rural power systems: Technical component

Technical resilience examines the performance and operational management of power system infrastructure in supplying energy to customers with respect to four qualities: robustness, reliability, efficiency and long-term performance.

The first one is robustness, as to be resilient, a rural power system must be robust enough to cope with or absorb stress [20,28], allowing it to withstand acute threats such as natural hazards and human attacks as well as long term threats like climate change. It includes minimising the time taken to recover from high impact, low probability events [30] and applies to design considerations to decide where to apply hardening methods or infrastructure reinforcement to reduce the systems susceptibility to extreme events [7,56].

A number of additional qualities can be viewed as subsets of robustness as they contribute to the ability of a power system to survive the impacts of a threat. These include intelligence, redundancy and security. In a rural context, intelligence applies mostly to the human component of the system – rather than the widespread use of automation – on reliance on self-organizing systems although it has been shown that smart grid technologies can be used effectively and affordably in rural systems in certain situations [122]. Training local management and personnel in resilient operation and emergency response procedures should be the priority [83]. Intelligent management should have the flexibility, agility and creativity to make use of available assets to deal with threats, and to prepare for them by modelling and planning for different future scenarios. Redundancy ensures that alternative options exist in case of damage to a system element [66] and is directly related to resourcefulness which allows the system to maximise the number of assets and possible actions available to deal with a threat. Finally, the security of the system should be enhanced by protecting key assets from human tampering and preventing electricity theft via illegal connections [123], and having a diverse mix of energy sources including renewables or sufficient backup generation [76]. In a rural context, these physical and governance issues are of greater concern than cyber-security.

The second point, reliability, translates in a rural context to providing a level of service quality that meets the specific needs of a community of users at the minimum cost, i.e., the level of reliability must be appropriate. This may not necessarily require 24-hour provision as some degree of rationing or load shedding may be perfectly acceptable to the community in question, and may be necessary to protect the grid in certain situations. Adaptive capacity is a major factor in achieving continued reliability over time [26,32]. The introduction of electricity to previously unserved communities drastically changes usage habits over time as households take up more energy intensive appliances, whether consequentially or because of education and active promotion. Moreover the growth of local industries over time leads to greater load demands and a lower tolerance for blackouts [100,124].

Furthermore, efficiency, as operational cost is a major limiting factor when implementing resilience measures in the context of rural locations. This makes efficiency a critical consideration, but beyond this, quality of service must also be appropriate to the customer base [84]. This requires accuracy in data about customer needs and behaviour, in load analysis to match electricity demand and supply as closely as possible and in geographic location to minimise connection infrastructure costs [85]. Automation, for instance, should be used only in cases where it is essential or cost effective and redundancy of both available assets and generation capacity must be carefully planned and implemented to minimise cost [125]. To ensure the success of renewable energy systems, especially where an energy source is intermittent or where storage is necessary, wasteful use of electricity should be minimised as far as possible. This requires that generation, transmission, distribution and end-use is as efficient as possible [79,126].

Finally, long-term performance should be a key part of the planning, implementation and adaptation strategies for rural power systems**.** Each of the qualities mentioned above must be met in a way that ensures the it has a sufficiently long lifespan to allow the community to meet its social and economic resilience goals (see Section 2.3).

3.2. Resilience in rural power systems: Social component

Social resilience is concerned with social welfare and governance, as well as environmental preservation, and is split into four categories: maximise access, engage community, social services and long-term development.

Firstly, a resilient rural power system should aim to maximise access to electricity within the community with an added focus on ensuring service for the most vulnerable members. Having the largest possible customer base ensures providers can generate the income needed to cover starting and running costs while ensuring that benefits of electrification are felt by all in the community and furthering the development goals associated with universal electrification [85,124]. In addition, engaging communities is necessary to ensure that the service provided matches the needs of the target them and should be a give-and-take, where information is sought from it to make the project appropriate and knowledge and skills are imparted to enable the community. Local consultations at all stages of the project are essential and should include individuals and community comities, as well as the involvement of local organizational structures [85,127]. Additionally the aim should be to enable the personal development of individuals within it through knowledge and skill transfer. This must be done with a long term view as the turnover of experienced personnel can hinder the effective transfer of experiential knowledge over time. Providers and local government should encourage long-term management structures, redundancy of trained personnel and should maintain links with communities even after project handover [128].

Furthermore, a resilient rural power system should lead to better social services, leading to improvements in education and healthcare by providing reliable electricity to key facilities like hospitals, schools, community centres. Enabling social services will often require strong partnerships with government and utility providers to include integration of rural electrification with rural development [124,129]. This is also directly linked to access to ICT infrastructure, for example through access to charging mobile phones and smart phones.

And, finally, as a long-term development component, another aim should be to improve social welfare by protecting and maintaining the natural environment and allowing more sustainable use of natural resources, as well as improving living and working environments by providing cleaner energy and appliances for household use [130,131]. As with technical resilience, all of the social resilience qualities must work towards improving long term development for the community. Successful adaptation is needed to serve the community long into the future by continually adjusting to changing needs and conditions.

3.3. Resilience in rural power systems: Economic component

Economic resilience looks at the financial health of power system and the utilities providers focusing on initial investment, running costs of operation and management and finance options available for both infrastructure and the community. In addition to this, economic resilience also covers the economic benefits to the community from having a resilient power system. Qualities included here are: finance, enable local markets and long-term growth.

To begin with, the success and resilience of rural power systems is dependent on available finance. Having access to capital for initial investment and to cover revenue expenditure for operation and management of infrastructure is necessary. The system should aim to be self-sufficient in the long run, but funding or aid options should always be available to deal with emergencies or to cover adaptation costs. In cases were costs make rural connection unattractive to a private utility, government subsidies must be used to create the right incentives for rural electrification. Studies have shown that subsidies are more successful when used to incentivise investment rather than aid consumption [129]. Providers can still make finance options available to the community for help with initial connection and lifetime service costs, e.g., pay as you go schemes.

Furthermore, it requires a long-term view and so any power system should enable the creation and expansion of local businesses, markets and industry with a focus on sustainable economic growth. Raising average income means that individuals and small business can afford the service ensuring a consistent influx of income needed to run and improve the system [93,96,104,106]. Alike the social and technical components, all aspects of economic resilience should be planned with long-term growth in mind.

To summarize, these three categories with their components can help to describe whether a system is resilient or help with the design of resilient systems. Still, although qualities have been separated into different categories, it is important to note that in any dynamic system there will be significant overlap between factors [27]. For example, maximising electricity access provides social benefits to members of the community by using modern energy to improve quality of life and the natural environment, but also provides economic benefits by ensuring a wide enough customer base to cover the system’s running costs. Similarly, knowledge and skill transfer affect technical resilience by enabling quality management, operation and maintenance of power infrastructure, as well as economic resilience by introducing management techniques that can be applied to local industries and social resilience by enabling personal education and development. One of the most important factors is long-term sustainability which is a key requirement for technical, social and economic resilience.

3.4. Operationalization of the indicator framework

3.4.1. Defining case-specific indicators to measure resilience

The ultimate aim is to direct focus to areas that are in need of improvement. Thus the exact values for various indicators are less important than the overall picture they provide about the resilience of the system and the community. Scores should be based on the relative success of a particular indicator in enhancing community resilience, whether relative to a chosen baseline or the past performance of a particular system. The scores can be estimated through collaboration with local stakeholders, for example in workshops or interviews to gather input from a range of actors and views. Managing the complexity of resilience analysis was an important consideration when forming the rural power system resilience framework. Heterogeneity between rural case studies is considerably greater than when assessing urban or national power systems. The collection of resilience proxies must be sufficiently reduced in order to arrive at the most important factors that are relevant in any case, especially when attempting to create a resilience framework that is generally rather than specifically applicable. Refining the metrics to identify only the key components also addresses the issue of data availability commonly faced by power projects in a developing country/rural setting.

Under the proposed framework, a total of 42 indicators were chosen as measures of the different system qualities with 21 indicators for technical resilience, 8 for social resilience and 13 for economic resilience. Table 2, Table 5 and Table 4 show these qualities with examples for each corresponding indicator.

Table 2: Indicators for technical resilience

Resilience qualities/sub-qualities	Indicators
Robust	Overall severity of impact
Robust	Affected elements & components
Robust	Number of households affected
Robust	Hardening measures implemented
Robust	Power system configuration
Redundancy	Available energy sources/generation methods
Redundancy	Number of service connections able to handle entire load
Redundancy	Replacement inventories
Intelligence, reliable	Damage assessment methods
Intelligence, efficiency	Data availability on electricity usage and state of the system
Intelligence, long-term performance	Scenario/contingency planning
Security	Security/protection measures
Security	Local availability of tools/expertise to address damage
Reliable	Recovery time (basic services, full capacity)
Reliable	Load shedding
Reliable	Maintenance practices
Efficiency	Load factor
Cost-effective	Average consumer cost of electricity
Appropriate	Capacity
Long-term performance	Estimated lifespan of generation plant
Long-term performance, security	Use of renewable energy resources

Table 3: Indicators for economic resilience

Resilience Qualities	Indicators
Capital finance	Subsidies available for rural power system projects
Capital finance	Sources for initial investment
Capital finance	Subsidies received quantity
Emergency aid	Time to receive aid after disaster
Self-sufficiency	Sources of funding/aid available for rehabilitation
Self-sufficiency	Estimated payback time
Self-sufficiency	Revenue, profit
Self-sufficiency	Subsidies received frequency
Community finance	Customer views on affordability
Self-sufficiency	No. of defaults on service payments
Community finance	Finance options available to cover connection/monthly service costs
Community finance	Avg. % of income spent on electricity bills
Enable local markets, long-term growth	No. of new local businesses due to electrification

Table 4: Indicators for social resilience

Qualities	Indicators
Maximise access	Connected households
Maximise access	Provision of options for vulnerable community members
Engage the community	Existence of Knowledge & skill transfer
Social services	Main sources of income/livelihoods
Engage the community	Assessment of community needs
Knowledge and skill transfer	Local management and operation personnel
Long-term development	Technology uptake by community
Social services	Benefits for healthcare and education facilities

3.4.2. Example for the application: Definition of thresholds to capture local conditions

Once the indicators are defined, it is also crucial to define thresholds. By scoring each indicator along a range representing the highest and lowest levels of resilience, it is possible to form a baseline level of resilience and to track improvement over time. For simplicity, the continuous scale can be divided into a few categories or tiers, in this case weak, acceptable and strong. To achieve this, boundary thresholds for each categorisation of a given indicator should be decided based on stakeholder feedback on what performance would be considered poor, acceptable or high. These can be either quantitative or qualitative as shown in Table 5. The highest ones should be realistic and achievable based on the resources available to the system under assessment. Past performance during previous threats can help to inform the lowest thresholds, especially where there has been catastrophic failure to some elements.

Table 5: Examples of thresholds for two resilience indicators

Indicator	**Weak**	**Acceptable**	**Strong**
Generation capacity	< 75 kW	75-150 kW	> 150 kW
Technology uptake by community	Basic lighting/mobile phone charging facilities	Effective use of electrical appliances, e.g., refrigerators, electric stoves, televisions in most households	Increase commercial and industrial loads by enabling productive end-use technologies

The definition of the indicator threshold is a crucial process for itself and requires an understanding of the local conditions to identify what can be achieved. While this paper does not provide insights on the specification of these thresholds, it provides a set of indicators that can help describe resilience.

4. Conclusions

In this paper, a resilience framework for rural power systems in emerging economies was presented. This framework features twenty-one indicators for technical resilience (listed in Table 2), eight indicators for social resilience (listed in Table 3), and thirteen indicators for economic resilience (listed in Table 4). Unlike past resilience frameworks in both academia and practice that have been developed for urbanized, developed regions, and yet still also deployed in rural areas of emerging economies, this work addressed the specific circumstances associated with the latter. Furthermore, it went beyond the quantification of solely economic and technological factors but also covers social ones. A wide range of relevant factors, from definitions of resilience in general, to aspects relating to the energy-related issues and to the rural conditions found in countries of interest have been used as a basis. The benefits of this work are that it will provide a diverse range of stakeholder (including system owners and operators, policy makers, NGOs, communities) a comprehensive solution with which to design, build, operate and maintain rural power systems in emerging economies, and also in the consideration of important issues that go beyond only energy technology dimensions. Furthermore, the importance of this work lies in the fact that it provides a pathway for the creation of appropriate and effective future resilience standards specifically targeted for application in these regions - aiming to achieve the delivery of global and local sustainability goals.

Beyond these observations, three conclusions can be drawn from this research. Firstly, power-system resilience is a broader issue that includes beyond technology-only considerations. While these are still engineered solutions, the review shows that social and economic aspects play a crucial role, and cannot be neglected in the development of future resilience frameworks or quantification approaches.

Secondly, when power systems are designed it is necessary to understand the local circumstances. As many of the factors outline require the knowledge that only locals may have, this will requires that relevant systems are not designed from behind desks that are thousands of miles away from the sites but physical presence and direct on-site analysis. This is necessary not only for appropriate data gathering, but also for directly involving the local stakeholders, who will also hold a lot of the data and be a part of the energy system being designed – as both users and as experts. This means that solution providers will either need to be in the field or work together with local agencies or NGOs that bring the right stakeholders together in the design of resilient systems.

Finally, since resilient systems depend as much on the quality of social and economic aspects as they do on technology, it is important to design such systems as well as future quantitative frameworks from the beginning with all these components in mind. This implies a move away from an approach where energy-technology solutions are implemented without further consideration, towards an approach where holistic solutions are designed, established and delivered that are supported by a whole socio-technical system around them that helps to maintain them. For policy makers or development agencies this means that they should request solution providers to articulate how they aim to achieve all of these aspects, beyond technology-only issues and considerations.

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