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Resilience a means to development: A resilience assessment framework and a catalogue of indicators

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ABSTRACT

The concept of resilience is an important area of study within socio-technical disciplines, essentially, because of humanity's increased dependency on engineered systems and the vulnerability of such systems to different kinds of threats. To this effect, several frameworks have been proposed for assessment, monitoring, and enhancement of resilience but their uptake in the energy sector remain low, especially in developing economies. The major limitations arise from their inadequacy in demonstrating direct linkages between resilience and development, a narrow characterisation of proposed indicators, and the complexity of deploying them to real world problems. Drawing from past resilience definitions, frameworks and development theory, this study underscores the relevance of resilience as both a necessity and an outcome of development and proposes a synthesised framework for measuring resilience in light of 13 *goals* (development commitments) of the electricity supply industry (ESI). A catalogue of 303 indicators has been proposed which classifies them within 4 *components* (sub-systems), 5 *dimensions* (categories of development goals), 3 *domains* (material state of indicators) and 3 *scales* (levels of organisation). Moreover, the indicators are evaluated against 11 *qualities* (properties of resilience) and 6 *capacities* (phased responses). Using a selection of indicators, the framework is applied to a case study to demonstrate its usability by assessing the impact of COVID-19 on Uganda's ESI. The framework and the indicators are intended to inform planning, investment, operational changes, and policy formation within the ESI's moving away from reactionary contingency risk management to mainstreaming resilience strategies within the development process.

1. Introduction

Nearly 70% of the 840 million people around the world with no access to electricity live in Sub-Saharan Africa where electricity access stands at 43% in comparison to the global average of 89% [1]. This number is estimated to grow by 2030 [2] given that in many low-income countries (LICs) countries, population growth outpaces electrification efforts [3]. This dismal electricity access and utilization is evident in a country like Uganda, where household electrification stands at 22% and the annual per capita consumption of 100 kWh is 30 times less than the global average [4]. It is unsurprising that the need to expedite electricity access has been the main driver of several strategies within the electricity supply industry (ESI) but with rather modest outcomes [4]. Electricity access remains low, and utilization has not been substantively scaled beyond lighting and powering small appliances.

Furthermore, conventional power systems are usually built to respond to low-impact high-frequency (LIHF) disruptions with little attention drawn to the high-impact low-frequency (HILF) threats [5]. Over the last four years alone, Uganda has experienced a number of nationwide power outages attributed to technical faults [6], lightning [7], vandalism [8], loss of synchronism with regional interconnections [9], and floods [10]. These outages are indicative of the numerous vulnerabilities of power systems in LICs to an array of threats. From low consumer connectivity, low productive use to highly unreliable grids, piecemeal solutions have failed to satisfactorily address ESI's

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Abbreviations

AHP	Analytic Hierarchy Process
CIS	Critical Infrastructure Systems
COVID-19	The Corona Virus Disease 2019
ESI	Electricity Supply Industry
GWh	Gigawatt Hours
HILF	High-Impact Low-Frequency
IPCC	Intergovernmental Panel on Climate Change
kWh	Kilowatt Hours
LICs	Low-income Countries
LIHF	Low-Impact High-Frequency
MW	Megawatt
Ref	References

challenges. To this effect, resilience thinking has been proposed as a necessity for theorizing and operationalizing strategies that deliver holistically on the objectives of development [11–14].

A well conceptualised resilience strategy helps to limit the negative impacts of change whilst ensuring the attainment of local development commitments. By necessity, the strategy should be multifaceted and adaptable to the peculiarities of the system, the threats being investigated, and the objectives being advanced. However, existing frameworks, have been found to be unusable and narrow in their assessment of resilience which mainly focusses on quantifying system's physical and operational losses and less on community consequences [15]. Secondly, the multiple characteristics of resilience indicators have been widely reported and yet to the best of our knowledge, no study has synthesised the associated indicators into one coherent catalogue. For example, in terms of categorising goals of resilience [15], classifies them as social, economic and technical, Bruneau et.al., [16] added the organisational dimension and [17] included well-being, infrastructure as well as environment. Likewise, the inherent abilities and responses of an entity are sometimes presented as *capacities* (phases of system responses) [18] or *qualities* (characteristics of resilience) [17] even though both categories present completely different aspects of the system and the assessment would be extensive if they were jointly considered. Accordingly, the existing categorisation of indicators in most frameworks does not permit to explore linkages between resources, their performance, the consequences they extenuate and the existing organisational environment. The generic and constrictive bundling approach of indicators could potentially lead to ineffective characterization of threats, systems, vulnerabilities, and subsequently, a misappropriation of response measures.

Motivated by the need to increase the adoption of resilience thinking within power systems' planning and operations, this study aimed to develop a framework that directly links and evaluates development commitments and resilience properties. It proposes a catalogue of indicators that reflects the complexities of the resilience analysis process which entails, in the least, the assessments of multiple elements and instances of the system as well as phases of response to extreme events. To demonstrate a practical application of the framework, a brief assessment of the resilience of Uganda's ESI against the Corona Virus Disease (COVID-19) response has been conducted.

The paper is comprised of five other sections. Section 2.0 describes the methods employed in this study. Section 3.0 explores various components of resilience discourse which are pivotal in the formation of the framework's structure, indicators, and their metrics. In Section 4.0, a relationship of resilience and development is demonstrated together with a number of development commitments specific to ESIs. Section 5.0 presents and critiques some of the commonly used frameworks in resilience analysis processes. In section 6, a synthesised framework and a catalogue of indicators are presented and applied to a case study.

2. Methods

The terms used in describing any concept reveals its most valued functions and properties, and informs the structure of its application [18]. To this effect, this study followed the workflow seen in Fig. 1 starting off by interrogating the common terms used in defining resilience across multiple disciplines, periods and organisational levels (see Table 1). These categories are meant to capture the cardinal elements of the concept informed by the discipline of study, chronological development of the concept and viewpoints of championing organisations.

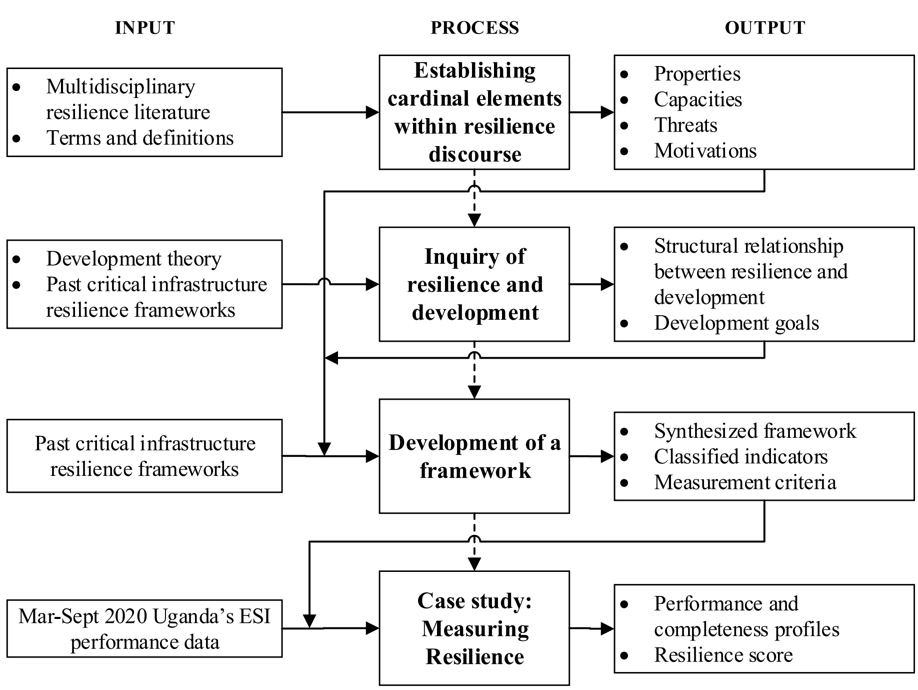

Fig. 1. Research methodology conceptual framework.

Table 1
Studies used in analysing resilience definitions, terms and drivers.

Ref	Year	Literature		Discipline						Applicable Organisational level							
		P	G	S	E	Po	Ec	Eco	Ps	I	H	C	Co	Sy	N	R	G
[20]	1919	✓			✓								✓				
[21]	1973	✓					✓							✓			
[22]	2000	✓		✓			✓					✓					
[23]	2001	✓		✓			✓					✓		✓			
[24]	2002	✓		✓			✓							✓			
[25]	2003	✓					✓							✓			
[16]	2003	✓		✓								✓					
[26]	2004	✓		✓			✓								✓	✓	
[27]	2004	✓					✓							✓			
[28]	2004	✓		✓								✓					
[29]	2004	✓		✓		✓	✓	✓				✓					
[30]	2005	✓			✓				✓	✓					✓		
[31]	2006	✓		✓			✓							✓			
[32]	2010	✓		✓								✓					
[33]	2011	✓		✓		✓	✓							✓			
[34]	2012		✓	✓	✓	✓	✓	✓		✓		✓		✓	✓		
[35]	2012	✓		✓		✓							✓				
[36]	2012	✓			✓									✓			
[37]	2012		✓	✓	✓	✓	✓	✓						✓	✓	✓	✓
[38]	2013		✓		✓												
[39]	2013		✓	✓			✓			✓	✓	✓		✓	✓		
[40]	2013	✓			✓	✓							✓				
[41]	2014		✓	✓		✓	✓								✓		✓
[42]	2014	✓			✓									✓			
[11]	2014	✓			✓					✓		✓	✓	✓	✓		
[43]	2014	✓					✓							✓			✓
[44]	2015	✓			✓							✓					
[45]	2015		✓		✓										✓		
[17]	2016	✓		✓	✓							✓					
[46]	2016	✓		✓			✓			✓		✓		✓			✓
[47]	2016	✓			✓									✓			
[48]	2016	✓			✓									✓			
[49]	2016		✓		✓										✓		✓
[50]	2016	✓		✓			✓			✓				✓			✓
[13]	2016		✓		✓									✓	✓		
[14]	2016	✓			✓									✓			
[51]	2017	✓			✓								✓				
[52]	2017	✓		✓								✓					
[53]	2018	✓			✓									✓			
[54]	2018	✓			✓							✓		✓			
[18]	2019	✓		✓						✓	✓	✓		✓	✓		✓
[55]	2019	✓		✓			✓										
[56]	2019	✓			✓								✓				
[57]	2019		✓		✓	✓						✓					
[58]	2019		✓		✓									✓			
[59]	2019	✓			✓							✓					
[60]	2019	✓			✓									✓			
[61]	2020	✓							✓		✓						

Key: **P**: Peer-reviewed; **G**: Grey-literature; **S**: Sociology; **E**: Engineering; Po: Policy and Politics; **Ec**: Ecology; **Eco**: Economics; **Ps**: Psychology;; **I** Individual; **H**: Household; **C**: Community; **Co**: Component; **Sy**: System; **N**: Nation-state; **R**: Regional; **G**: Global.

Similar to past studies which identified the most critical resilience capacities [18], qualities [17], indicators [11] and domains [19], the inquiry was extended into indentifying drivers and objectives of resilience thinking. The drivers, are simply change agents whereas the objectives are the envisaged outcomes from a resilience building process.

The overaching objectives of resilience are widely regarded as the sustenance and improvement of people's wellbeing in the face of extreme events [17,18]. Losses emerging from disasters have been reckoned to signify existing vulnerabilities, and by inference, a state of *'unresolved development problem'* [18]. For development is considered a means through which residual risks are minimised and future risks are prevented [18]. Therefore, given the seeming analogical and symbiotic relationship between resilience and development, the second stage of the study established a structural relationship between the two concepts utilising perspectives from development theory. Specifically, the study opted for Human-development theory [62,63] since it conceptualises development as both a means and an outcome of the resilience process, and the people's *'freedoms'* being the core unit of measuring valued progress. The relationship between the two concepts is then indicated by development commitments, also hereafter referred to as *goals*. In order to reduce the uncertainties in selecting goals, they were adapted from studies [17,57,64] in which a consensus-based experts elicitation method was used to determine them.

A new framework is then developed by synthesising essential elements of past resilience frameworks from ecological sciences [21], engineering [56], economics [29], psychology [30] and sociology [22]. The structure of the proposed framework and its associated indicators is an extension of the framework first developed by Ref. [65] for cyber systems and later adapted to energy systems by Ref. [11]. The categories of indicators were broadened to capture as many aspects of the system as are conceivably distinguishable. The bulk of *qualities* and *dimensions* were adapted from Refs. [15,17], *components* and *performance attributes* [12], *scales* [39], and *domains* from Ref. [65]. In line with [16–18], each goal was characterised with a set of indicators which serve as proxies for vulnerabilities, system's readiness and performance, and consequences to the society. The indicators and goals are classified across four major

Table 2
Terms used in Several Resilience Definitions.

Identity	Ref	Capacities	Ref	Drivers	Ref	Objectives	Ref
Ability	[22, 24–26, 38]	Absorb	[16,33, 44,45, 48]	Accident	[38]	**Enhance** sustainable development, diversification, competences, flexibility, interoperability, capacity for learning and adaptation	[18,25,40,47, 52,80]
Action	[39]	Accommodate	[39,49]	Adversity	[11,34, 48,52]		
Amount	[25]	Adapt	[25,33, 34,45]	Attack	[38,48]	**Maintain or restore** integrity, critical functionality, structure, identity, processes, feedback control, continual survival, social and political, environment, economic stability, order, status quo and adapt within available resources	[14,17, 20–26,31,33, 35,36,41,46]
Capacity	[17,22, 46,47]	Adjust	[55]	Changing environment	[18,21, 23,39, 46]		
Characteristic	[32]	Anticipate	[18,45, 48]	Crisis	[35]	**Minimise** risks, losses, damages, social disruptions, negative effect to socioeconomic advancement, social infrastructure and development	[16,22,36,51]
Degree	[24]	Avoid	[51]	Degradation	[58]		
Latitude	[27]	Bounce-back	[18,39, 56]	Disaster	[18,48]		
Magnitude	[23,24]	'Bounce-forward'	[18,56]	Disruption	[35,40, 45,48]		
Measure	[20,21]	Change	[24,33]	Disturbance	[23,33, 44,47]		
Potential	[25]	Circumvent	[40]	Dynamics	[20]		
Process	[18]	Collaborate	[18,50, 57]	Adverse event	[39]		
Rate	[47]	Contain	[16,28]	Effect	[13,43]		
Strategy	[39]	Create options	[28]	Extreme event	[58]		
Time of Return	[44]	Cope	[22,41, 47]	Failure	[36,53, 54]		
		Deflect	[18]	Hazards/ Hazardous events	[41,49, 80]		
		Design	[18]	Load	[60]		
		Flexibility	[29]	Impact	[39]		
		Function	[24,26, 33]	Perturbation	[33]		
		Grow	[23]	Shock	[16,23, 39]		
		Handle	[42]	Stresses	[22,35]		
		Improve	[46]	Surprises	[32]		
		Improvise	[18]	Trend	[41]		
		Innovate	[33]	Threat	[38,48]		
		Learn	[18,24, 33]	Trauma	[30,61]		
		Limit	[58]	Uncertainty	[32]		
		Maintain	[18,25]	Unexpected event	[47]		
		Manage	[18]	Unpredictability	[32,47]		
		Minimise	[18]	Variations	[20]		
		Mitigate	[16,22]				
		Overcome	[18]				
		Plan	[11,34]				
		Persist	[23,39, 46]				
		Predict	[41]				
		Prepare	[34,38, 49]				
		Prevent	[18]				
		Rapidity	[13,59]				
		Rebound	[18]				
		(Rapidly) Recover	[11,16, 45,46]				
		(Self) (Re) organize	[18,25, 33,41]				
		Reproducibility	[20]				
		Resist (ance)	[27,48]				
		Resourcefulness	[13]				
		Restore	[18]				
		Return to equilibrium	[18,47]				
		Robustness	[13]				
		Self-righting	[18]				
		Survive	[40]				
		Tolerance	[23]				
		Transform	[18,39]				
		Withstand	[22,38, 41,52]				

indicator categories (component, domain, scale, and dimension), two metric categories (qualities and capacities) and four performance attributes (strategy, asset, impact, and consequence). This attribution convention seeks to minimise the ambiguities of characterising indicators, opening possibilities of assessing several system instances whilst facilitating the examination of causalities across multiple configurations.

Lastly, the framework's application is demonstrated by a case study of the impact of COVID-19 on Uganda's ESI. The performance data of the sector covering the period of six months (March–September 2020) was obtained from reports from the regulator [66,67], distribution network operator [68] and statistics bureau [69]. The data included generation, demand, losses and reliability of the grid, infrastructure investments, consumer connections, revenue collections, impact on licensing obligations, end-user tariffs, customer satisfaction, and gross domestic product growth. The performance levels where compared to the targets and thresholds stipulated in the sector's quality-of-service and supply standards [70], primary grid code [71] and ESI business plan [72] to ascertain the level of resilience.

3. Resilience definitions and constituent elements

3.1. Definitions in resilience discourses

With its increased study, the concept of resilience has become malleable and ambiguous steeped in normative assertions and vastly extended for competing purposes [73]. It is criticised for attracting contradictions such as '*stability through change*' [74] and its supposed grandstanding posturing about change, while *'promoting technocratic managerialism in defence of the* status quo*'* [75]. For detailed critical analysis, see Refs. [73,74]. Criticisms notwithstanding, this section seeks to illustrate the most common and valued aspects of the concept, drawing from the terms employed in the various descriptions of resilience. These terms were tracked chronologically, through various disciplines of study and across varying scales of championing entities.

In the 1910s, Schlink [20] described resilience in terms of the instrument's ability to reproduce similar measurements during an induced mechanical perturbation. At the time, resilience was reckoned as a property of an instrument that allowed it to persist under dynamic environments. In 1970s, Holling [21] developed the concept further to include the entity's ability to absorb change. By the 1980s, resilience had morphed into the ability to cope, learn, bounce back whilst emphasizing that the entity emerged from disturbances unchanged [18]. In 1990s, the capabilities of prevention, anticipation, organizing and adaptation were introduced within the concept's description eventually culminating into transitioning, flexibility, '*bouncing-forward*' and transformability in 2000s [18]. Outside its historical understanding, currently, the concept is also regarded as a neoliberal instrument for de-politicising disasters, producing self-reliant citizens and acting as a breeding ground for more progressive politics [63,74]. The capacities have been broadened over the years, encompassing abilities of an entity to predict threats and responses to attainment of autonomy.

When the concept was first studied in ecological sciences, it was extended from *stability* to include system's capabilities to absorb changes whilst maintaining the same structure, relationship within the interacting entities, essential functions, control and feedbacks [21,26]. Whereas in social sciences, resilience has been described as the '*ability of groups or communities to cope with external stresses and disturbances as a result of social, political, and environmental change*' [22]. Others [17,39, 76] have described resilience as the ability to help vulnerable people, organisations and systems to persist and thrive amidst unpredictable disruptions. Zebrowski et al., [52] regards a resilient community as one that has the sustained ability to withstand, adapt to, and recover from adversity. In engineering disciplines, the classical conceptualization emphasized the entity's ability to return to a point near equilibrium upon perturbation [20], a notion lauded for being tractable but

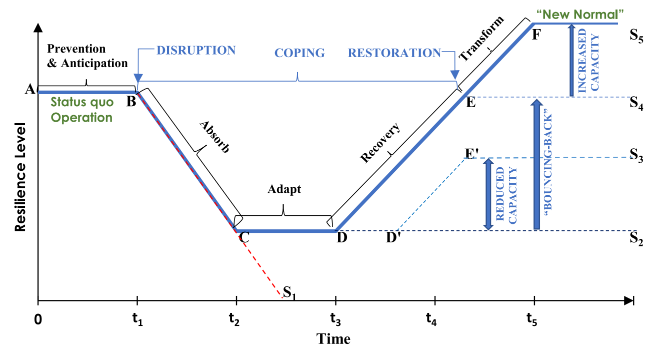

Fig. 2. Indicative scenarios and capacities of the resilience process. Adapted from Refs. [18,48,77,79].

criticised for its treatment of every disruption as a disaster requiring a reactionary response but neglecting the processes from which disruptions emerge [18,21]. Therefore recent research has provided more expansive definitions such as [58] who defined power system resilience as *'the ability to limit the extent, severity, and duration of system degradation following an extreme event'*.

On a global scale, the Intergovernmental Panel on Climate Change (IPCC) offers a more broad definition of resilience as '*the capacity of social, economic, and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation*' [41]. This definition has been reflected in several national [38] and city-wide resilience masterplans [17,57]. The adoption of the resilience agenda by state and global actors, has shifted the focus of disruptive events from just any unexpected event to extremely rare but high impact threats. It is likely that the shift is because many nation-states already have well established reliability frameworks that respond to the 'usual' LIHF events.

Although the disparities in definitions are in some cases significant, the fundamental principle is that resilient entities ought to provide sustained functionality in the face of natural and man-made disturbances. In addition, emerging from the hybridisation of the concept, its 'ecological' functions have been imported into 'engineered' systems. Recent studies presupposes that engineered systems ought to possess capacities for enabling stability, adaptation and transformation [18]; such abilities were in the past almost exclusively associated to natural systems. The extent of capacities is presented in section 3.2 by examining the constituent terms of several concept's definitions.

3.2. General constituents of the resilience definitions

The disparities in definitions are to a great extent wrought by the very nature of the concept which is premised on empiricism and its dependence on contexts of applications [25]. To expect a one-size-fits-all definition is as improbable as is impractical. Nonetheless, a common pattern is observed within the definitions by querying the terms of the descriptive identifiers, capacities, drivers, and objectives (see Table 2).

The definitions of resilience can be classified broadly in two categories: ontological (*what is it?)* or functional (*what does it do?*) [77]. The ontological descriptive identifier points to the perceived nature of the resilience property such as an *'amount'* [25], a *'measure'* [20], or a *'magnitude'* [23]. However, the functional definitions dominate literature [22,24–26] in which resilience is commonly referred to as an *'ability'* or a *'capacity'*. In both cases, resilience is measured either as a quantity of a disturbance [25,27] or a response [21,78].

In addition, nearly all definitions opt for a set of capacities from anticipation and preparation prior to a disruption [38] to transformation after its occurrence [39]. Capacities demonstrate the phases of response of an entity to disruptions. They are often presented as distinct

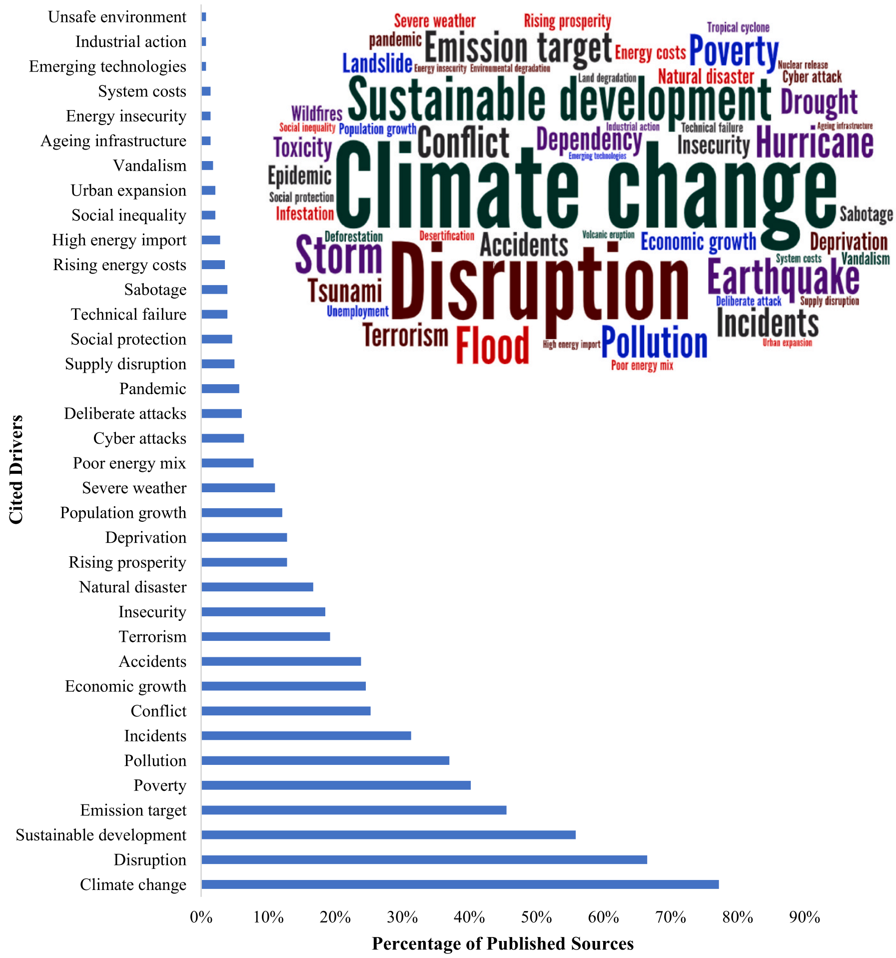

Fig. 3. Common Resilience Drivers Represented as a Bar chart and a Word Cloud.

properties but in practice there are overlaps between them, i.e., the capacity to predict a threat can be employed before, during and after an event. The most common capacities presented in recent studies are prevention, anticipation, absorption, adaptation, recover and transformation [11,18]. Fig. 2 illustrates the generic application of these capacities by a system against a disruption leading to 5 possible outcomes. If ***A-B*** represents the system's functional state prior to the disruption and Point ***B*** the instance when a disruption starts to impinge on the entity's operations, then:

(i) **B–S$_1$:** represents a system which is overwhelmed by the disruption and eventually brought to a halt.
(ii) **B–C-D-S$_2$:** the system absorbs and adapts to a disruption but does not possess restorative qualities.
(iii) **B–C-D'-E'-S$_3$:** the system embarks on restoration but never achieves its pre-event status.
(iv) **B–C-D-E-S$_4$:** the system is restored but still characterized by the same pre-event vulnerabilities.
(v) **B–C-D-E-F-S$_5$:** the system ultimately transforms within the response process leading to enhanced functionality and resilience.

Furthermore, some descriptions specify the kind of disruptions which vary from readily predictable changes in population [81] to natural disasters [82] and targeted attacks [19]. When a text query is carried out on drivers of resilience thinking cited in 48 publications presented in Tables 1 and 2, the most prominent drivers are observed to be climate change, disruptions and sustainable development (See Fig. 3). This observation reveals that resilience is regarded as an organizing concept that addresses existential vulnerabilities by advancing desirable development states.

Definitions, also, have a purposive role indicating the intended objectives of resilience capacities from maintenance of entity's functions [20,21], restoration of operations [41,52] to enhancement of performance [17]. In its normative considerations, resilience is concerned with protection, security, continuity, and transformation [39] of an entity contingent to a combination of postures, purposes and capacities that ought to improve the people's wellbeing [17]. This perspective of resilience is grounded in human development theory as illustrated in Section 4.1 below.

4. Resilience and development

4.1. Resilience a means to development

The operationalisation of resilience strategies has its ultimate function on the survival, performance, and wellbeing of people. It is a means of continuous improvement of a community enabling it to choose its most preferred actions which lead to its desired outcomes. This notion has been referred to as *development* whose principal means and overarching objective is *freedom*. Amartya Sen proposed to measure development by the expansion in the *'freedoms that people enjoy'* [62]. In this case, freedom is both an *end* and a *means* to development; an *end* serving an evaluative purpose for development, through the expansion of choice making, and a *means* because it causes it [62]. To move to a desired state, Sen's proposed removing sources of *'unfreedoms'* (vulnerabilities) which

Table 3
Goals within the electricity supply industry.

S/N	Goal	Relevance and Definition
	Adequate Security of Supply	This goal seeks for continuity, self-sufficiency, and autonomy in which a society meets its electricity energy needs whenever they arise [83].
	Affordable Cost of Energy	This is the ability to pay for necessary levels of consumption within normal spending patterns [84].
	Adequate Safety & Security	Resilience is enhanced by damage prevention and survivability [85]. These factors are premised on the safety and security of system components and people within their proximity.
	Economic Productivity	The robustness of power systems is strongly tethered to economic productivity such that a compromise in their operations has negative implications on the economic performance.
	Minimal Exposure & Vulnerability	Vulnerability is the propensity of exposed entities to suffer loss or damage from threats [49] and exposure points to scenarios that lead to entity's compromise.
	Provision of Critical Services	A power system should be built to ensure that it maintains and, in some cases, increase its support to critical services such as health facilities, schools, defence systems, fire stations, water supply, and communication services during a disaster.
	Mutual Support	Active community engagement, strong social networks and social integration breeds strong identities and culture which are vital in steering through all kinds of disruptions [17]
	Improved Portfolio Diversity	Diversity is a key indicator of transformation since it affects changes in policy directives, hardening measures, and operational procedures.
	Reliable Communication	Reliable communication enhances connectivity and reduces the recovery duration during emergencies [17].
	Effective Leadership	Effective leadership is cardinal during decision making, coordination, collaboration, risk assessment, response, emergency coordination, and management [57].
	Empowered Stakeholders	The necessity of continuous self-reorganization, all stakeholders ought to be engaged across different organizational scales to effectively transfer skills, resources, and experiences [86].
	Integrated Development Planning	This goal demonstrates how regulations, plans and projects implemented within the ESI are aligned with the overall development commitments of a society.
	Sustainability	Sustainability was adopted as the 13th goal to explicitly track how local development commitment adhere to SDG7 targets.

can either be material (e.g., absence of electrical grid in an area) or immaterial (e.g., lack of strategies for fast-tracking consumer connections). Sen viewed vulnerabilities as a set of heterogenous and interlinked set of inhibitors which eliminate choices and opportunities, thereby curtailing progress of attainment of preferred development goals [62]. Therefore, vulnerabilities are barriers that necessarily must be removed so that the choices and opportunities resulting from the development process equip communities to adapt efficiently to any change.

By merging the classical liberal understanding of development as '*freedom to choose*' [63] with Sen's treatise of *'development as freedom'* [62], Chandler theorised *'resilience as freedom'* [63]. He reckoned that, without resilience, development is at best transient. For resilience and development have a mutual effect on each other where a certain level of resilience is required to spur development and in turn a state of development catalyses resilience capacities. This conceptualization has been pivotal in the adoption of resilience in sustainable development discourse by projecting resilience as an inherent human attribute whose enhancement correspondingly improves environmental resilience [63].

Development states of communities are analogous to freedoms resulting from *'reasoned choice-making'* [63], and resilience is the property that ensures that the choices made are reflective of the desired commitments. In the context of this study, resilience of ESI systems not only ensures that meaningful development goals are attained, but also guarantees a continuity of their pursuit regardless of the prevailing change agent. This approach broadens the long-standing notion where resilience within the ESI system was viewed as an *end* premised primarily on system's abilities to absorb and withstand perturbations. Given the erratic nature of extreme events, not all threats and vulnerabilities can be eliminated but through continuous enhancement of resilience within existing systems, the probable losses emerging from disruptions can be significantly lessened creating more and better developed communities especially in low-developed countries.

Although desired development states will vary with context, Section 4.2 describes several goals which not only results from resilience processes, but they have also been identified as means through which resilience of engineered systems can be fostered.

4.2. Goals relevant to electricity supply industry

Goals and vulnerabilities can be categorised within five dimensions as proposed by Refs. [15,16,62]: *environment, technical, social (well-being), organisation* and *economy*. The goals presented in Table 3 are primarily adapted from the extensive work of formulating resilience indexes for city infrastructure systems conducted by Refs. [17,57], in which 12 key goals were identified following consultation of 711 experts, over 100 interviews, focus groups, site visits and workshops across 4 different continents. Some goals were previously proposed in several power and energy system resilience studies [12,16,47,59].

Although the conceptualization of the symbiotic relationship between resilience and development has been made in different disciplines [18,62,63], it remains loosely studied in power systems. As demonstrated in Section 5.0, the bulk of studies assess resilience of power system as an *end* in itself untethered from the development commitments of a society.

5. Resilience analysis process in existing frameworks

Different approaches for measuring resilience have been proposed in literature depending on the objectives of the exercise, the type and complexity of the system, availability of data, and modelling approaches. The underlying principle in all approaches is that the assessment process should support decision making regarding planning, investments, process management, or policy making.

Conventional approaches, assess resilience in a phased manner in which the system, scope and indicators are identified from the onset, preferably, by all key stakeholders [17]. The system's topology, physical characteristics, operational constraints, and dynamic behaviours are then defined [14]. This is followed by identifying and characterising of threats, assessment of components' vulnerabilities, determination of the system's response, and ultimately, the evaluation of consequences to the broader society [12]. Beyond establishing baseline resilience, this approach is also used to determine resilience at varying levels of hardening measures [79], acceptable risk [13], policy changes [12] and resource constraints [87].

Given that the resilience concept is premised on an uncertain future in which the event and the response of the system cannot be precisely predicted, the continuous possibility of surprise implies that the system cannot be futureproofed against all threats [39]. This realisation has popularised probabilistic assessment approaches. Several frameworks evaluate resilience as a probability of consequences [12,87] in which they account for both the likelihood and magnitude of losses drawn from lost lives, lost production, damages or lost income. Such studies quantify resilience as a likelihood of a consequence rather than the occurrence of a threat. This is because, generally, extreme events do not necessarily

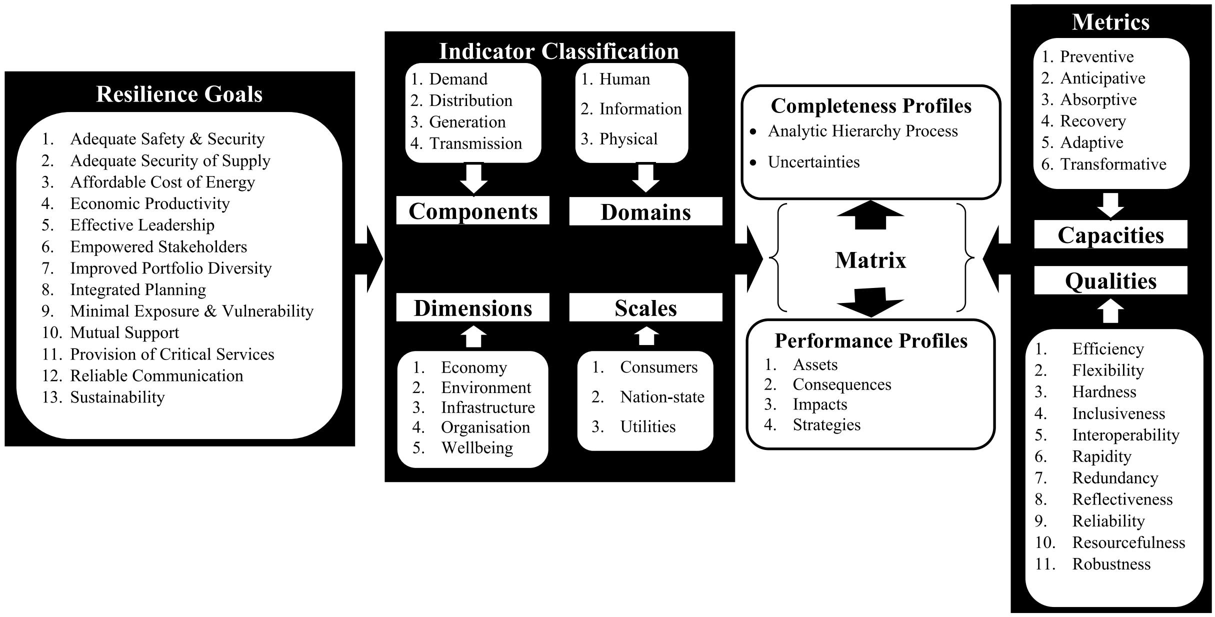

Fig. 4. A conceptual framework for measuring resilience in electricity supply industry.

translate to significant losses if the system is not exposed for a considerably long time.

Other frameworks based on either a resilience *'triangle'* [16] or *'trapezoid'* [88] adopts loss of degradation metrics measuring resilience as an offset between nominal and actual performance. One of such popular frameworks, *FLEP* [79], measures resilience by *how **F**ast, how **L**ow, and how **E**xtensive* resilience falls, *and how **P**rompt* a system reacts to a disruption. This approach is a rendition of [16] which had earlier proposed to measure resilience by *'reduced failure probabilities'*, *'reduced consequences from failures'*, and *'reduced time to recovery'*. These indicators are time-dependent, and they depict how different resilience capacities are measured over time. For example, the *absorptive* capacity to can be represented by lost load (MW/hour), the *adaptive* capacity by the duration the system stays in a degenerated operational state (hours) and *recovery* by the rate of getting the load back on line (MW/hour) [79].

Complex evaluation techniques usually involve modelling the performance of individual components and power flows when the system is subjected to disruptions from extreme events such as [82,89]. Since both threats and system responses are stochastic in nature, the outcomes of the simulation process are best interpreted as depictive rather than definitive. Such approaches focus on the function of the physical components rather than the social influences which causes or exacerbates threats. This is because social behaviour cannot be readily modelled. Therefore, other studies [15,18,57] have opted for qualitative indicators to assess social dynamics which are then validated by stakeholders and experts' judgement through workshops, focus groups and interviews. Furthermore, in frameworks where many indicators are used like in the case of [11,15–17], the usefulness of each indicator will vary depending on the context. Therefore, indicators tend to be weighted differently and the Analytic Hierarchy Process (AHP) is used to determine the relative importance of each metric and also ensures an acceptable degree of consistence of the applied prioritisation criteria [12].

There are other studies that assess resilience by modified reliability metrics. To avoid conflict with standard reliability codes, such studies focus on HILF events beyond the standard N-1 events. For example [82, 90], proposed *Expected Energy Not Supplied* and the *Energy Index of Unreliability* while [12] utilised *Value of Lost load* as metrics for resilience.

This section has briefly explained, the most common methods employed in evaluating resilience of power systems. Although the individual frameworks are useful, none is without limitations (see Appendix A.1). Therefore, Section 6.1 presents a framework that synthesizes the most crucial elements drawn from the reviewed frameworks. The framework provides a new guide of identifying, classifying, and evaluating indicators which link the constituents of resilience concept to development commitments within the ESI.

6. Proposed framework and indicators

6.1. Structure and elements of the framework

Mazur et al. [15], criticised *'academic frameworks'* for their deficiency in solving real world problems and rather commended four *'practical frameworks'*. First, Argonne National Laboratory [91], which employs a multi-quality approach for assessing three qualities (robustness, resourcefulness, and recovery) using scale-specific indicators which are aggregated at each of the proposed scales. The Sandia National Laboratories [12,87], a power system's risk-based framework which assesses the magnitude of the threat, the resultant level of disruption and the probability of consequences. The Energy Sector Management Assistance Program [92] which adopts a number of qualities (affordability, quality and level of service, reliability, and legality) in a multi-tier approach to assess energy access across community institutions whilst accounting for impact of supply on users. And, finally, the ARUP framework [17,57] which was developed to be used by cities in measuring and tracking resilience through 52 indicators, 12 goals and 4 dimensions (technical, social, economic and environmental) measured against 7 qualities (integrated, inclusive, reflective, resourceful, robust, redundant, flexible). By synthesising elements, structure and assessment criteria employed in these frameworks and others (detailed in Appendix A.1), the framework in Fig. 4 is proposed.

The frameworks takes into account Sen [62] and Chandler's [63] philosophy of development as it relates to resilience; that is, resilience is a necessary property for development and development enhances resilience. The *dimensions, qualities* and *goals* were obtained from Refs. [15–17] whereas the *domains* were adopted from Refs. [11,19]. The *scales* are adapted from Ref. [39]. The *capacities* were drawn from Refs. [11,18] while *components* were from Refs. [12,48]. The *performance attributes* which are *assets*, *impacts*, *consequences*, and *strategies* are informed by Refs. [12,15]. The framework has provision for quantifying and representing *uncertainties* and selectively prioritising different elements by using the AHP as proposed by Refs. [12,87]. The assessment process can be performed in a *matrix* in which resilience can be quantified at every single one of the 8 units of the framework; *goals, capacities, qualities, dimensions, components, scales, domains, and performance attributes*.

The synthesis process is driven by the need to support holistic assessment of resilience at every crucial element of the system. The resilience analysis process entails assessing a system's performance as a multivariate phenomenon, and the proposed framework strings together the most critical categories of indicators. Consider a scenario of redundant transformers in a substation. An asset-based framework would ordinarily highlight their mere deployment whereas a performance-based framework would extend the assessment into their utilization. The risk-based frameworks would be concerned with ascertaining the level of threats to which the transformers' redundancy is called upon whereas the consequence-based framework would seek to understand the impact of redundancy, say, on the economy. It can be objected that some of the elements in one category of the framework are implied in another, nonetheless the assessment is more holistic and meaningful when all aspects are juxtaposed informing a systematic analysis of causations between threats, components vulnerabilities, system's responses, and consequences.

Akin to states of matter, indicators can be classified by their *domains*. A domain describes the *'whatness'* of an attribute by specifying its substantive essence. Three kinds of 'substances' have been identified in literature, namely; *physical*, *information* and *human* domains [19]. The *physical* domains refers to those attributes of the system that are physical in nature (i.e., infrastructure and equipment) whereas the *information* domain describes indicators related to generation, storage and usage of information and data [11]. The *human* domain entails both the cognitive and social abilities of people. Furthermore, indicators are classified by system's *components* in order to support targeted responses at sub-system levels [48]. For ESI, the *components* are *generation*, *transmission,* and *distribution* as well as *demand* for end-users.

Several studies [15,16,93] propose an assessment approach executed within multiple dimensions, namely; *environment*, *technical*, *social*, *organisation* and *economic*. The underlying assumption is that vulnerabilities of an entity and gains from resilience measures are multifaceted and interlinked. Strategies, resources, and operations within the ESI, all contribute to building strong economies since engineered systems are primarily built to advance society's wellbeing. The actions necessary for desired outcomes are moderated by environmental constraints and are a product of good governance.

Another element of the framework are *qualities* which are signature properties known to prevent system's breakdown [17]. Eleven qualities have been identified by integrating those proposed and described in detail by Refs. [15,16,57,94], namely; *reliability*, *robustness*, *redundancy*, *hardness*, *rapidity*, *reflectiveness*, *efficiency*, *flexibility*, *inclusiveness*, *integration*, *resourcefulness*. They are thought to be essential in driving the effectiveness of resilience capacities addressing risk management needs prior, during, and after an event [13]. Even though some qualities naturally fortify specific capacities, for example redundancy inherently enhances the capacity to absorb disturbances, every single one of them tends to promote other capacities.

Multi-scale frameworks have the advantage of presenting indicators relevant for each level of organisation dealing with issues associated with geographical and organisational boundaries. In contrast, a single-scale framework is bound to mask, mix or miss altogether the unique indicators that delineates one scale's resilience from another. For example, in the event of a disaster, at a household level, it might require provision of a stand-alone photovoltaic system to momentarily restore lighting but at a community level, the response might be in form of reconstruction of the entire grid infrastructure. In practice, responses are matched to the existing vulnerabilities and damages at a particular scale.

It has been indicated in section 3.2 that resilience is widely referred to as a '*capacity*' and its functions is rooted in understanding the specific capacities of the system that effectively responds to disruptions. Several studies [18,19,79] have opted for *prevention*, *anticipation*, *absorption*,

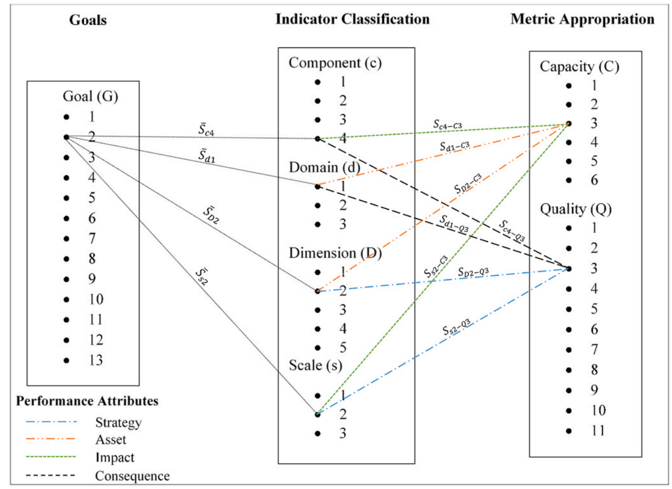

Fig. 5. A conceptual illustration of the application of the framework.

adaptation, *recovery* and *transformation* as core capacities of resilience. These are regarded to be *'stages of change'* [11] depicting the preferred progressive phases of interventions needed to counteract change moving from the simple and routine to the complex and dramatic. While several studies measure resilience by assessing the level of capacities [39,79,82], others opt for qualities [16,17]. The approach proposed in this study employs both as seen in Section 6.2 since capacities and qualities reveal entirely different properties of the system which ought not to be conflated nor presumptively cherry-picked.

6.2. Metric quantification

This section demonstrates how the framework quantifies resilience. Prior to using the framework, the threat should be identified and characterised, and the vulnerabilities, impacts, consequences, and system response should all be evaluated. In the description that follows, an *indicator* is a measurable feature of the system (i.e., *power delivered to critical services*) whereas a *metric* is how it is measured (i.e., *MW*). In addition, a *unit* of framework refers to the main structural categories such as *Goals, Components or Qualities* whereas an *element* refers to unit's constituent factors such as *Adequate Security of Supply, Transmission or Reliability,* respectively. Units and elements are collectively referred to as *instances*.

An example for deploying the framework is conceptually illustrated in Fig. 5. From *Goal 2* (*Adequate Security of Supply),* one can choose to analyse resilience by *Component 4* (*Transmission*), *Domain 1* (*Human*), *Dimension 2* (*Environment*) and *Scale 2* (*Nation-state*). The selection in this example is arbitrary but in real applications, it will depend on the objective of the assessment. For simplicity, the selected indicators within the four units of *Indicator Classification* are all assigned to the same capacity and quality, i.e., *Capacity 3* (*Absorptive*) and *Quality 3* (*Hardness*). Two indicators are identified for each *Indicator classification* elements with one assessed by a quality and the other by a capacity. In total, 8 indicators evaluate *Goal 2* whereas both *Capacity 3* and *Quality 3* are assessed by 4 indicators each. In addition, the *Performance Attributes* are distinguished by colour-coded lines which illustrate if the indicator is a *Strategy*, an *Asset*, *Impact,* or a *Consequence*. Each *Performance Attribute* has been designated two indicators.

The indicators associated with any instance are likely to have varying units of measurements (i.e., MW, %, hours). They can neither be aggregated nor meaningfully normalised. Therefore, all metrics are transformed into dimensionless scores using a 7-point rating scale building upon the methodology by Refs. [17,49]. Each metric is transformed into a score on a rating scale using a qualitive descriptor of performance (see Appendix A.3) ranging from *Very Poor* (1) to *Excellent*

Table 4
Generic models for evaluating the level of resilience at different instances for equally weighted indicators.

Instance	Generic Equation	Example Using Fig. 5
Indicator Classification	$\overline{S}_{xi} = \frac{1}{N}\sum_{n=1}^{N}(S_{xi-yj})_n$	$\overline{S}_{c4} = \frac{S_{c4-Q3} + S_{c4-C3}}{2}$
Metric Appropriation	$\overline{S}_{yj} = \frac{1}{N}\sum_{n=1}^{N}(S_{xi-yj})_n$	$\overline{S}_{C3} = \frac{S_{c4-C3} + S_{d1-C3} + S_{D2-C3} + S_{s2-C3}}{4}$
Goals	$\overline{S}_{Gk} = \frac{1}{N}\sum_{n=1}^{N}(\overline{S}_{xi})_n$	$\overline{S}_{G2} = \frac{\overline{S}_{c4} + \overline{S}_{d1} + \overline{S}_{D2} + \overline{S}_{s2}}{4}$
Performance Attribute	Average score of all values of the same attribute	$\overline{S}_{A} = \frac{(S_{d1-C3} + S_{D2-C3})}{2}$

A: Assets; ***c***: Component; ***C***: Capacity; ***d***: Domain; ***D***: Dimension; ***G***: Goal; ***Q***: Quality; ***s***: Scale; ***S***: Score.

(7). This transformation process is guided by the question- '*to what extent is the entity's performance improved by the indicator?*'. For equally weighted indicators, the score of an instance is computed as the average of all dimensionless values of its attendant indicators.

From Table 4, $\overline{S}_{xi}$ represents an average score of all dimensionless values at an *indicator classification* instance *xi*: where *x* is the unit (i.e., *Component*) at i^{th} position (i.e., 4th for *Transmission*). Similarly, $\overline{S}_{yj}$ represents a score at a metric appropriation instance *yj*: that is for *y* unit (i.e., *Quality*) at j^{th} position (i.e., 3rd for *Hardness*). S_{xi-yj} represents a score of an indicator evaluating resilience at *xi* against a property at *yj* i.e., '*% of elevated Substations*' can be used to assess the *Quality* of *Hardness* within the *Transmission Component*. *N* is the total number of indicators associated with any given instance, i.e., N is 2, 4 and 8 for *Indicator Classification*, *Metrics Appropriation*, and *Goals* instances, respectively. $\overline{S}_{Gk}$ is the average score of all dimensionless values at the k^{th} position of *Goals* i.e., $\overline{S}_{G2}$ is *Adequate Security of Supply*. For completeness of results, similar computations can be performed for *Uncertainties* by ascertaining the level of sufficiency and validity of data used to evaluate indicators. The certainty scores, too, are computed using the qualitative descriptors in Appendix A.3. A summary of the results can be presented in form of juxtaposed tables and graphs of performance and completeness profiles.

Critical to this analysis process is the requirement of several indicators to evaluate the resilience of the system against each of the 49 instances of the framework. Section (6.3), describes the structure of the proposed catalogue of indicators.

6.3. A catalogue of proposed indicators

A total of 303 indicators (see Appendix A.2) were identified from previous studies [11,12,18,45,48,49,59,79,83–85,87,99–112]. These are first classified within the 13 goals described in Section 4.2 and further characterized by *domains*, *dimensions*, *scales*, *components*, *capacities*, *qualities*, and *performance attributes*.

Both the number of indicators and proposed classification categories go beyond what has been presented in previous studies. For example, [11] classified indicators by capacities and domains, [17] by qualities and goals, [15] by qualities and dimensions, [39] by scales and dimensions, [12] by dimensions and components and [16] by dimensions, qualities and components. Such classification criterions are simplistic in application, and as such the assessment of resilience is more likely to be generalised and inadequate to support targeted decisions making. For example in Ref. [11], the '*capability for independent local/sub-network operation*' is an indicator classified under *physical* domain and *Absorb* capacity but it is not apparent to which *scale* or *component* it is relevant. In contrast, the proposed classification approach provides for a holistic attribution of any given indicator from the development commitments (*goals*) it evaluates to the responses it fosters (*capacities*), and in between, demonstrate what it is (*domain*), where it is relevant (*component*) and who is responsible for it (*scale*).

In addition, most studies in the past proposed a handful of indicators in order to increase their uptake [39], due to lack of data, or the inevitable loss of objectivity [12] as indicators increase in number. However, this study is cognizant of the fact that entities have different objectives of assessing resilience which in most cases cannot be restricted to a few indicators. Using the proposed catalogue, any user is not only able to select the most appropriate indicators for their objective but can also set up modes of collecting data for indicators whose data is insufficient or not available.

Within the catalogue, an indicator is assigned to a particular element based on the following criteria:

i. An indicator can only be classified by one *Domain* and one *Performance Attribute* element, i.e., 'fuel availability' under the goal of *Adequate Security of Supply* is an indicator within the *Physical* domain (and can neither be *human* nor *information*) and it is regarded as an *asset* (and not a *strategy*, an *impact,* or a *consequence*).
ii. Except for *Sustainability* goal, all other goals have unique indicators. The sustainability goal was adopted to track adherence

Table 5
Indicative display of results from a resilience analysis process using the proposed Framework.

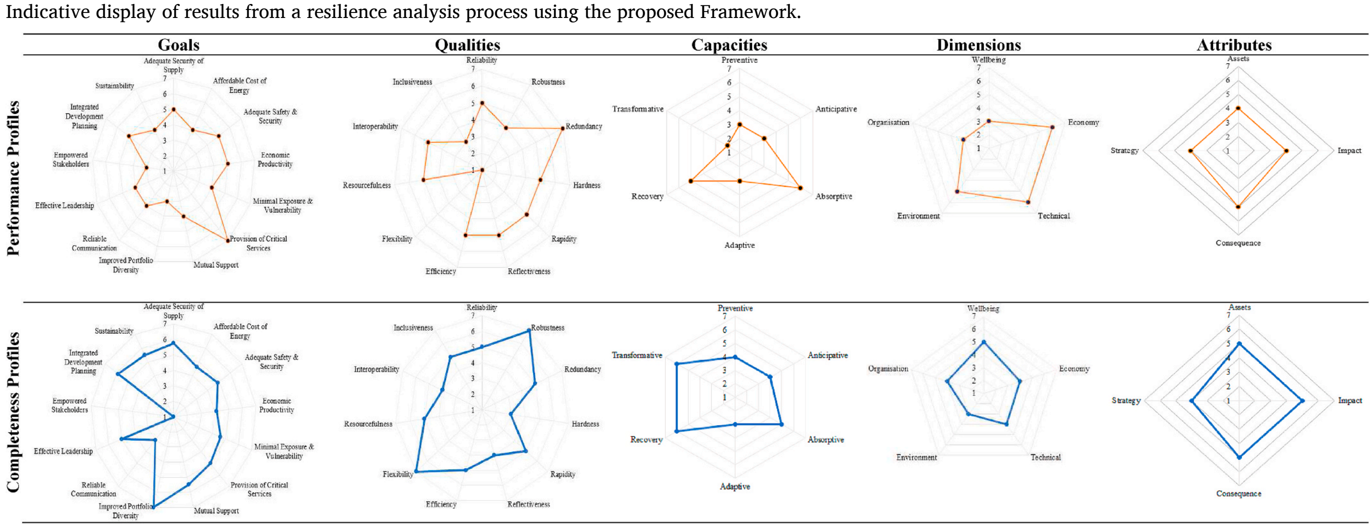

Table 6
Performance scores of various instances.

Goals	Qualities											Capacities						Goal Score
	Reliability	Robustness	Redundancy	Hardness	Rapidity	Reflectiveness	Efficiency	Flexibility	Resource fulness	Integration	Inclusiveness	Preventive	Anticipative	Absorptive	Adaptive	Recovery	Transformative	
Adequate Safety & Security				4	7	7			1			7	4	7	6			**5.4**
Adequate Security of Supply	4.5				4						3			6	7			**4.9**
Affordable Cost of Energy							6		1	4	2				5		2	**3.3**
Economic Productivity		4			4				6						6	4.3		**4.9**
Effective Leadership						4			5	5		1		3	5	4		**3.9**
Empowered Stakeholders					3	4						2				2		**2.8**
Improved Portfolio Diversity								1	7		7				4		1	**4.0**
Integrated Development Planning					5	6			5			3.3					5	**4.8**
Minimal Exposure & Vulnerability	4			7					7			4		1		1		**4.0**
Mutual Support	1								5		4	7	1		4			**3.7**
Provision of Critical Services	7		7		7									7		7		**7.0**
Reliable Communication				4		6			6			2.5	4		4			**4.3**
Sustainability	7						3				2				5		2	**3.8**
Quality & Capacity Score	**4.7**	**4.0**	**7.0**	**5.0**	**5.0**	**5.2**	**4.5**	**1.0**	**4.8**	**4.5**	**3.6**	**3.8**	**3.0**	**4.8**	**5.1**	**3.7**	**2.5**	**4.4**

to SDG targets and some of its indicators are derived from other goals.

iii. For all other categories, an indicator can be assigned to as many elements of the same unit as it is reasonably relevant. For example, 'fuel availability' can be assessed at either the *Utility* or *Nation-state* scales and similarly it can be evaluated as an indicator for *Preventive*, *Absorptive*, *Adaptive* and *Recovery* capacities.

It was demonstrated in Section 3.2 that the likeliness of pandemics is one of the leading drivers of research in resilience. In addition, the severity of disasters is regarded as a manifestations of unresolved development problems [18]. This provides grounds for assessing the impact of the pandemic on desired development outcomes. Therefore, Section 6.4 presents the results of an assessment of the impact of COVID-19 pandemic on Uganda's ESI using the proposed framework and 90 indicators whose data was obtained from Refs. [69,95–98].

6.4. Case study illustration

Following the outbreak of the COVID-19 in Uganda, the country was plunged into a nationwide lockdown in March of 2020. In the six months that followed, the impact on the ESI ranged from a reduction in demand, electricity revenues, and system's reliability to an increase in energy losses, license conditions defaulting, deemed energy payments, and vandalism [66,95]. The detailed evaluation of various indicators can be seen in Appendix A.4 in which the ESI performance was assessed against standards, codes and commitments set out in Refs. [70–72].

Table 5 presents a graphical summary of results juxtaposing instances' performance and completeness profiles. For example, the highest rated *Goal* which is *Provision of Critical Services* with a score of 7/7 was evaluated from an incomplete dataset (5/7) whereas the lowest *Quality* which is *Flexibility* (1/7) was computed from a complete dataset (7/7). At the time of this study, only macro-data was available which is sufficient to ascertain the flexibility of the ESI but inadequate to establish if every critical service was fully supplied throughout the period under inspection. Although a low performance score of any instance is undesirable since it is indicative of a high level of vulnerabilities, if it is computed from a complete dataset, it is more meaningful in determining effective responses than a high performance score derived from an incomplete dataset.

The results can also be presented in the format seen in Table 6 to establish probable causations, say, between *Goals,* and *Qualities* or *Capacities*. Consider the *Goal* of *Adequate Safety & Security,* its score is weighed down by *Resourcefulness* (1/7). To effectively improve the system's safety and security of supply against pandemics of similar impacts as COVID-19, the quality of *Resourcefulness* should be reinforced.

The overall ESI resilience against the pandemic is evaluated at 4.4/7 with a certainty of 5.0/7. These scores can be interpreted in light of the qualitative descriptors in Appendix A.3 and in this case they depict the system performance as between 'good' and 'very good' indicating that the system's infrastructure did not suffer from physical damages, and the service availability and revenue collections did not plunge below 10% of the nominal performance. Regarding data sufficiency, most datasets for the selected indicators are 10% incomplete.

Besides the level of sufficiency and validity of the data, the reliability of the assessment is influenced by the kind and number of selected indicators. For example, the qualities of *Robustness*, *Redundancy* and *Flexibility* (as seen in Table 6) could be inaccurately evaluated if the sole indicators used are not representative of the entirety of the system.

7. Conclusions

There are several frameworks proposed in the past for measuring resilience, some which have been reviewed in this study, but their uptake remains low in LICs, in part, due to the lack of clarity in demonstrating how resilience strategies are linked to development outcomes. In addition, previous studies have made calls for developing a catalogue of indicators that can be used in quantifying, tracking and, making comparable analyses of resilience across different components and systems, and subsequently, informing investment decisions, operations and policies.

This paper has presented a multifaceted synthesised framework which links resilience to development states within the ESI. It proposes 303 indicators linked to 13 development *goals*, measured against 6 *capacities* and 11 *qualities*. The framework supports analysis of resilience at various levels of *components*, *scales*, *domains*, and *dimensions*. It is premised on a mutual dependency principle borrowed from human development theory which considers resilience as a means to development and development as a promoter of resilience. By applying the framework to a case study of the impact of COVID-19 on Uganda's ESI, it has been demonstrated that its application is simple and can easily be adapted to different contexts of threats and systems. The study recognises that not all elements of the framework can be universally applied since different contexts of actors, objectives or threats would require that certain elements are more emphasized than others. Therefore, the framework and its accompanying catalogue of indicators should not be taken as prescriptive but rather as a platform upon which to build context-specific analysis.

Moreover, the study underscores the complexities of developing resilient power systems given the many competing interests. For example, the popular strategies of increasing renewable energy penetration and affordability are as meaningful as to how they promote system's resistance to disruptions, yet the necessity of improving resistance could inevitably mean scaling back on renewables and increasing energy prices. Furthermore, the enabled capacities of the community are both the object and subject of resilience building; object, because the community is the ultimate beneficiary of infrastructure resilience through improved welfare, and a subject, because cognitive and social capacities are critical in mitigating and responding to disruptions. Bottomline, resilience of any infrastructure system is about sustaining people's preferred capacities, especially during extreme events, and that ought to be reflected in its analysis, measurement, tracking, enhancement, and planning.

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Credit author statement

Francis Mujjuni: Conceptualization, Methodology, Formal analysis, Writing - Original draft preparation, Writing- Reviewing and Editing, Visualization, Preparation.: Tom Betts: Supervision.: Long Seng To: Conceptualization, Writing- Reviewing and Editing.: Richard Blanchard: Conceptualization, Supervision, Writing- Reviewing and Editing.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2021.111684.

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Appendix 1

S/N	Reference	Discipline	Types of Metrics	Evaluation Approach	Limitations
1.	Béné [29]	Food security	Impacts and consequences	'Cost' of resilience at multi-scales	The cost of resilience approach shows that the higher the mitigative expenditure the lower the perceived resilience. The implication is that wealthier entities are inclined to have higher resilience costs stemming from huge ex-ante costs
2.	Roege *et al.*, [11]	Energy systems	Assets, strategies, and impacts	Multi-attribute utility approach using weighted qualitative score	The proposed metrics are classified only by domains and capacities in exclusion of all other relevant categories. No link is made between metrics and particular development goal within energy systems or just generally.
3.	Watson et al., [12]	Energy systems	Consequences	Probability distribution of consequences	Only a handful of indicators are proposed. The proposed evaluation approach benefits users who are not concerned with any other aspects outside system operational continuity and economic productivity.
4.	Preston et al., [13]	Power systems	Risk	Qualitative categorisation of the level of the dimensions of risk	Adaptation is the end goal. This poses a risk of reinforcing the same vulnerabilities or entrenching existing hegemonic systems and processes. There is no linkage between needed responses and capacities
5.	Lin and Bie [49]	Integrated energy systems	Assets, impact, and risk	Hardening and operational indicators	No link between the resilience indicators and capacities which are being measured. The proposed indicators do not indicate the interdependencies of the Integrated energy systems.
6.	Manyena et al., [20]	Disaster resilience	Risk	Combined qualitative and quantitative indexes at capacity-units	The indicators are too generic to be used to comprehensively assess resilience for electricity systems.
7.	TRF et al., [19]	Urban water systems	Strategies, assets and impacts	Blended qualitative and quantitative with Standardisation of Individual metrics using a Rating scale	The model assumes that all indicators and goals, contribute to resilience equally. Goals are not linked to desired capacities. The 5-point Rating Scale is too narrow to make useful transforms of subjective indicators
8.	Espinoza et al., [73]	Power systems	Impacts	Reliability metrics (EENS and EIU)	The employed metrics do not demonstrate any implication of loss of service to the wider society

Appendix 1

S/N	Reference	Discipline	Types of Metrics	Evaluation Approach	Limitations
9.	Panteli et al., [71]	Power systems	Risk and Performance	“Resilience Trapezoid” Time-dependent metrics (How Fast, How Low, How Extensive and How Prompt)	It is a single scale framework and it is system-centric hence neglecting consequences outside the power system infrastructure.
10.	Rodrigo et al., [80]	Power systems	Risk and consequences	Risk-aversion probabilistic-based Reliability metrics	The risk aversion approach might dissuade the utility of the framework since it is improbable to eliminate risk entirely but also it is impractical regarding the cost implications
11.	Mazur et al., [28]	Rural power systems	Strategies, assets and impacts	Technical, social and economic indicators	Indicators are strictly delineated within qualities and dimension leaving no indications how they affect resilience capacities
12.	Bruneau et al., [21]	Seismic resilience management	Impacts and consequences	Multi-dimensional and multi-quality assessment of the rate of expected degradation (Reduced failure probabilities, Reduced consequences from failures, and Reduced time to recovery)	The proposed 4 qualities of robustness, redundancy, rapidity and resourcefulness are few to be usable in current discourse of resilience but also there are no direct linkages between the proposed indicators and resilience capacities.
13.	Arghandeh et al., [14]	Power systems Cyber-physical security	Impacts	Service availability and quality (Duration of exposure)	No definitive indicators where proposed to measure the “absorbing potential” and “recovery potential” of the system. The capability of adaptation is assumed to be a subset of recovery.
14.	Linkov et al., [74]	Cyber infrastructure	Strategies and impacts	Multi-domain and multi-dimensional matrix of indicators	The proposed indicators are largely suggestive statements rather than precise quantifiable or provable properties
15.	Kwasinski [87]	Critical infrastructure	Impacts	Reliability metric using mean up time and mean down time	The proposed metric based on reliability theory concept of availability is not able to adequately capture the performance of various capacities and qualities of the system. The dimensionless metric used provides no other useful information beyond failure rate

Appendix 2

Goals	Indicators	Ref.	Domains		Dimensions						Scales			Components				Attributes				Capacities						Qualities											
			Physical	Information	Human	Wellbeing	Economy	Technical	Environment	Organisational	Consumer	Utility	Nation	Generation	Transmission	Distribution	Demand	Strategy	Asset	Impact	Consequence	Preventive	Anticipative	Absorb	Adapt	Recovery	Transform	Reliability	Robustness	Redundancy	Hardness	Rapidity	Reflectiveness	Efficiency	Flexibility	Resourcefulness	Interoperability	Inclusiveness
Adequate Security of Supply	Share of Utilisation of local resources	R3	■				■	■	■		■	■	■	■	■	■	■			■		■		■	■			■	■						■			
	Local backup power capacity	R3, E3, C	■				■	■	■		■	■					■		■			■		■		■	■	■	■	■	■				■	■	■	
	Rate of preventative maintenance	R3	■				■	■			■	■	■	■	■	■				■		■						■	■		■	■		■				
	Electrification rate	M3			■		■	■	■		■	■	■				■			■				■	■	■	■	■										
	Adequate supply of primary energy	M2, B2	■					■			■	■		■			■				■			■	■			■	■							■		
	Total energy reserves	M2	■					■			■	■		■			■				■			■	■		■	■	■							■		
	Geographical concentration of resources	M2	■					■	■				■	■					■			■										■			■	■		■
	Import dependency	M2, B2	■					■	■			■	■	■	■						■			■	■	■		■				■				■		
	Average production costs	M2	■				■	■			■	■		■			■			■			■				■							■				■
	Fluctuation of production costs	M2	■			■	■	■			■	■		■			■				■				■	■		■		■		■			■			
	Macroeconomic effects of high or volatile prices	M2			■	■	■				■	■		■			■				■				■				■			■				■		
	Degree of Complementarity between Energy Resources		■					■				■		■					■						■		■	■	■						■	■		
	Expected Unserved Ramping	H	■					■				■			■	■				■				■				■	■						■			
	Periods of Flexibility Deficits	H	■					■				■			■	■				■				■				■	■						■			
	Forced Outage Rate		■					■				■		■						■				■				■	■									
	Minimum Synchronous Generation Capacity	H	■					■				■		■						■				■				■	■						■			
	System Failure rate		■					■				■		■	■	■				■				■	■	■			■									
	Mean Restoration Time	K	■					■				■		■	■	■				■				■	■	■			■			■						
	How Fast Resilience Drops	P1	■					■				■		■	■	■				■				■					■									
	How Low Resilience Drops	P2	■					■				■		■	■	■				■				■					■									
	Mean Restoration Level		■					■				■		■	■	■				■				■					■			■						
	Deployment of Smart grid technologies		■					■				■		■	■	■	■		■					■	■		■	■	■	■	■					■		
	Minimum Up Time		■					■				■		■	■	■				■				■	■				■									
	Additional Generation a Transmission System can Accommodate		■					■				■		■	■					■				■	■			■			■					■		
	Total energy reserves per capita	B2	■			■							■	■					■					■												■		
	Proven energy reserves per capita	B2	■					■				■		■					■					■	■	■				■					■			
	Reserves-to-production ratio	M2	■					■				■		■					■					■	■	■				■					■			
	Energy return on energy invested	M2	■									■		■						■				■				■	■	■				■				
	Minimum Down Time	K	■					■				■		■	■	■				■				■	■				■			■						
	Start-up and Shut-down Times	H	■					■				■		■						■				■	■							■			■			

Goals	Indicators	Ref.	Domains		Dimensions						Scales			Components				Attributes				Capacities						Qualities										
			Physical	Information	Human	Wellbeing	Economy	Technical	Environment	Organisational	Consumer	Utility	Nation	Generation	Transmission	Distribution	Demand	Strategy	Asset	Impact	Consequence	Preventive	Anticipative	Absorb	Adapt	Recovery	Transform	Reliability	Robustness	Redundancy	Hardness	Rapidity	Reflectiveness	Efficiency	Flexibility	Resourcefulness	Interoperability	Inclusiveness
	Ramp rate and Duration	H	■					■				■		■						■				■	■							■			■			
	Investment in feasibility studies	M2	■					■			■	■	■	■	■	■				■		■	■												■			
	Operational Generation Range	H	■					■				■		■						■				■				■	■	■					■			
	Rural Electrification rate	M3			■		■	■	■		■	■	■				■			■				■	■	■	■	■										■
	Ratio of Average Load to Peak Load	L	■					■			■						■			■							■							■				
	Ratio of Average Load to Rated Capacity		■					■				■		■						■				■				■	■					■				
	Ratio of Energy Consumption to Transformer Capacity		■					■							■					■				■											■			
	Provision for of blackstart capabilities	Y	■					■				■	■	■						■		■				■		■				■				■		
	Penalties on Excessive Consumption of Reactive Energy		■					■				■					■			■				■										■				
	Response Time	K	■					■				■		■	■	■				■					■	■						■						
	Ratio of Energy Produced to Rated Output		■					■				■		■						■				■	■			■		■				■				
	Cumulative of load interruption	C, V	■					■			■	■	■				■				■					■		■							■			
	Loss of load probability	W	■					■				■			■	■					■			■				■	■									
	Effective load carrying capability	W	■					■				■		■							■			■				■	■						■			
	Loss of Load Expectation	S2	■					■				■			■	■					■			■				■	■	■				■				
	Time to restoration	C, V			■			■			■	■	■	■	■	■	■				■					■		■	■			■				■		
	Largest reconnected Load after N duration	R1	■					■				■					■			■						■						■						
	Rate of loss of Load	P1	■					■				■				■	■			■				■				■	■									
	Value of lost load	C, M2.			■		■	■	■		■	■	■	■	■	■	■				■			■	■	■			■	■		■			■	■	■	■
	Time to failure during the incidence	B1	■					■				■		■	■	■				■				■				■	■									
	Existence of temporary back-up generators	E3, C	■				■	■	■		■	■	■	■			■		■			■			■	■		■				■			■			
	Capacity of Uninterruptible Power Supply	R2	■					■				■		■					■			■		■		■		■		■								
	Use of mobile substations	E3	■				■	■				■	■		■	■	■			■		■			■	■		■				■			■			
	Existence of backup control centers	E3	■				■	■				■	■	■	■	■			■					■				■	■						■			
	How prompt the system recovers	P1	■					■				■		■	■	■	■			■						■						■						
	Defensive Islanding	P1	■					■				■		■	■	■	■			■		■		■				■								■		
	% of Demand after an event occurrence	P1	■				■	■			■	■	■				■			■				■	■	■		■										
	% of connected Transmission line	P1	■				■	■				■	■		■	■	■		■			■		■		■		■										
	Circuit segregation and automation	E3	■				■	■				■	■		■	■				■				■				■										
	Capacity margins	S2	■				■	■	■			■							■			■		■				■		■		■						
	System Average Interruption Frequency Index	W, M2.	■				■	■			■	■			■	■	■			■				■	■			■	■									

Goals	Indicators	Ref.	Domains			Dimensions					Scales			Components				Attributes				Capacities						Qualities										
			Physical	Information	Human	Wellbeing	Economy	Technical	Environment	Organisational	Consumer	Utility	Nation	Generation	Transmission	Distribution	Demand	Strategy	Asset	Impact	Consequence	Preventive	Anticipative	Absorb	Adapt	Recovery	Transform	Reliability	Robustness	Redundancy	Hardness	Rapidity	Reflectiveness	Efficiency	Flexibility	Resourcefulness	Interoperability	Inclusiveness
	System Average Interruption Duration Index	W, M2.	■				■	■			■	■			■	■	■			■				■	■			■	■			■						
	Customer Average Interruption Duration Index	W, M2.	■				■	■			■	■			■	■	■			■				■	■			■	■			■						
	Average Service Availability Index	W	■				■	■			■	■			■	■	■			■				■	■			■	■									
	Mean Time to Repair	K	■					■				■		■	■	■				■				■		■		■				■						
	Mean Time Between Failures		■					■				■		■	■	■				■				■		■	■	■				■						
	Investments in Decentralized Energy Systems		■					■			■	■	■	■			■		■					■	■	■	■	■	■	■	■	■			■	■		■
	Customers experiencing outage during a specified time period	V			■	■					■						■				■			■		■		■	■									
	Customers experiencing multiple interruptions	W	■				■	■			■	■					■			■				■	■			■	■									
	Fuel availability/shortage	W, B2	■				■					■	■	■					■			■		■	■	■		■	■	■		■						
	Cumulative customer energy demand not served	W, S2, V	■			■					■	■	■				■				■			■	■	■		■				■				■		
	Spinning reserves	W	■				■	■				■	■	■						■		■		■	■			■	■	■		■		■				
	Periodical testing and recharging back-up power for control centers	W			■			■				■		■	■	■				■		■			■			■	■		■				■	■		
	Available operating reserves	W	■				■	■				■	■	■						■		■		■	■			■	■	■		■		■				
	Existing standards Normal Operations Planning (e.g., N-1)	W		■				■				■	■		■	■		■				■		■		■		■	■	■	■	■			■			
	Systems latitude	R3			■			■				■		■	■	■				■		■				■		■				■						
	The capacity unavailable to serve load	W	■				■	■				■	■	■							■			■		■		■	■						■	■		
	Availability of demand response under constraints	Y, E3			■		■	■			■	■	■	■	■	■	■			■				■		■		■	■			■	■		■	■		
	Capability to re-route power	R3	■					■				■			■	■				■					■			■	■	■	■	■			■			
	Ability to isolate degraded components	R3	■					■				■		■	■	■				■				■				■	■							■		
	Ability to use new/alternative energy sources	R3	■				■	■	■			■	■	■						■					■		■				■		■				■	
	Recovery progress tracked, synthesized and available to decision-makers and stakeholders	R3		■						■		■	■	■	■	■				■						■	■					■	■			■	■	■
	Allocating crews to repair damaged equipment	W	■					■				■	■	■	■	■					■	■				■		■	■		■	■						
	Provide access to high quality electricity to		■				■	■			■	■	■				■			■					■			■								■		

			Domains		Dimensions						Scales			Components				Attributes				Capacities						Qualities										
Goals	**Indicators**	**Ref.**	Physical	Information	Human	Wellbeing	Economy	Technical	Environment	Organisational	Consumer	Utility	Nation	Generation	Transmission	Distribution	Demand	Strategy	Asset	Impact	Consequence	Preventive	Anticipative	Absorb	Adapt	Recovery	Transform	Reliability	Robustness	Redundancy	Hardness	Rapidity	Reflectiveness	Efficiency	Flexibility	Resourcefulness	Interoperability	Inclusiveness
	consumers																																					
	Protect consumers from cascading faults																																					
	Capability for independent local/sub-network operation	R3																																				
	Fuel flexibility	R3																																				
	Design margin to accommodate range of conditions	R3																																				
	Limited performance degradation under changing conditions	R3																																				
	Installed/ready redundant components	R3																																				
Affordable Cost of Energy	Rise in Consumer Tariff																																					
	Stakeholder awareness of energy alternatives, cost/ benefits and implementation requirements	R3																																				
	Increase in operation cost and Production costs	W, M2.																																				
	Access to finances by utilities	M3, A																																				
	Fuel poverty	M4																																				
	Changes in connection fees	A																																				
	Level of expenditure on energy subsidies																																					
	Willingness to pay																																					
	High technical losses																																					
	Loss of utility revenue	V																																				
	Ratio of unit price of electricity by low income households to medium houses	M4																																				
	Availability and use of pre-payment	M4																																				
	Degree of monopoly	M4																																				
	Relative per capita consumption	M4																																				
	Startup Costs	H																																				
	Gini coefficient	M4, B2																																				
	% of people with energy arrears	M4																																				
	Ratio of Production Costs to Energy Output																																					
	Average level of arrears	M4																																				
	Level of energy bills devoted to paying	M4																																				

			Domains		Dimensions						Scales			Components				Attributes			Capacities							Qualities										
Goals	**Indicators**	**Ref.**	Physical	Information	Human	Wellbeing	Economy	Technical	Environment	Organisational	Consumer	Utility	Nation	Generation	Transmission	Distribution	Demand	Strategy	Asset	Impact	Consequence	Preventive	Anticipative	Absorb	Adapt	Recovery	Transform	Reliability	Robustness	Redundancy	Hardness	Rapidity	Reflectiveness	Efficiency	Flexibility	Resourcefulness	Interoperability	Inclusiveness
	arrears				■	■					■					■	■			■					■													■
	Existence of special tariff scheme	M4			■	■					■	■				■	■			■					■										■			■
	Ratio of utility debt to household debt	M4			■	■					■	■				■	■			■					■													■
	Ratio of Percentage of income spent on electricity bills by low income households to medium houses	M4			■	■					■						■				■				■													■
	Percentage of customers on prepaid meters	M4			■			■				■					■			■							■											■
	Incidences for disconnection (voluntary or forced)	M4			■	■					■						■				■					■											■	■
	Wholesale energy price	B2		■			■	■				■	■		■			■			■				■	■	■									■		■
	Fuel prices	W, E1		■			■	■				■	■	■			■				■				■											■		■
Adequate Safety & Security	Protection of the electricity sector as critical infrastructure	M3, C	■					■				■		■	■	■			■			■						■	■		■							
	Disaster mortality	M3			■	■								■	■	■	■				■					■						■						
	Number of people affected by disasters	M3			■	■								■	■	■	■				■					■						■						
	Damage to utility infrastructure	M3	■			■		■			■	■	■	■	■	■	■				■			■					■		■							
	Analysis and Mitigation of Protection System Mis-operations	W	■					■				■		■	■	■				■		■											■					
	Live GIS systems enabled command center operations	E3	■					■				■		■	■	■			■			■									■							
	Investigate and repair malfunctioning controls or sensors	R3	■					■				■		■	■	■				■						■		■	■		■							
	Protection of cyber control systems	R3	■					■				■	■	■	■	■				■		■									■						■	
	Critical system data monitored, anomalies alarmed	R3		■				■				■	■	■	■	■			■				■					■								■		
	Status/trend limits trigger safeguards and isolate components to stop cascade effect	R3	■					■				■	■	■	■	■			■					■				■										■
	Loss of key emergency equipment	E1	■					■				■		■	■	■			■					■	■	■		■	■	■	■	■			■	■	■	■
	% of Relocated Facilities and Network Elements	P1	■					■				■			■	■			■						■			■	■		■							
	Investment in hardware		■					■				■		■	■	■			■				■								■							
	Design Factor of Safety for Components	R2	■					■				■		■	■	■			■					■	■					■								
	Mitigation Spending Level	Z2	■			■		■				■		■	■	■	■	■				■														■		
	% of Elevated Substations	E3	■					■				■			■	■			■			■									■							

Goals	Indicators	Ref.	Domains		Dimensions						Scales			Components				Attributes				Capacities						Qualities										
			Physical	Information	Human	Wellbeing	Economy	Technical	Environment	Organisational	Consumer	Utility	Nation	Generation	Transmission	Distribution	Demand	Strategy	Asset	Impact	Consequence	Preventive	Anticipative	Absorb	Adapt	Recovery	Transform	Reliability	Robustness	Redundancy	Hardness	Rapidity	Reflectiveness	Efficiency	Flexibility	Resourcefulness	Interoperability	Inclusiveness
	Continuous Hazard Monitoring and Risk Assessment			■						■		■	■	■	■	■		■				■	■													■		
	Probability of Common Mode Failures for Duplicated Components	R2	■					■				■		■	■	■				■						■				■								
	Repair/restoration costs	E1	■					■				■		■	■	■					■					■						■						
	Duration of Curtailment	H	■					■				■		■							■			■	■										■			
	Use of scenario-based war gaming to develop understanding of system dependencies and interactions	R3			■			■				■	■	■	■	■	■			■		■						■					■			■		
	Physical protection of substation	Y	■					■				■		■	■	■			■			■									■							
	Degradation and destruction of assets	E3	■					■				■		■	■	■			■					■				■	■		■					■		
Economic Productivity	Direct and indirect economic losses	M3	■				■				■						■				■					■						■						
	Investment in electricity industry	M3		■			■					■	■	■	■	■					■	■			■		■		■	■	■				■			
	Change in incomes and diversification of livelihoods portfolios	M3			■		■										■				■						■		■				■			■		
	Ratio of Energy Consumption to Revenue			■		■					■						■				■					■								■				
	Average Household Income after Electrification				■	■					■						■				■						■											■
	Investment Uncertainty	E2		■			■	■				■	■	■	■	■					■				■											■		■
	Ratio of Energy Consumption to GDP			■		■	■				■		■				■				■						■							■				
	Industrial backup generation		■				■	■				■	■	■	■	■	■		■					■				■		■		■						
	Reduction in productive use of electricity	A	■				■	■					■				■				■				■							■						
	The decrease in labor hours over the course of the recovery period	W	■			■	■						■				■				■					■			■				■			■		
	Per capita consumption	M4	■			■							■				■			■							■									■		
	Business interruption costs	V		■			■					■					■				■					■		■										
	Impact on Gross Domestic Product			■		■	■						■				■				■					■		■								■		
	Valuation of unserved energy or lost revenue	E3	■				■				■	■	■				■				■					■		■				■						
Minimal Exposure & Vulnerabil	Operational system protection	R3	■					■				■		■	■	■				■				■				■			■							
	Improving uptake of low cost sustainable productive energy technologies	M3	■			■	■	■			■	■	■	■			■				■				■	■	■	■	■						■		■	
	Existing mitigation measures for risks	M3		■		■	■	■	■		■	■	■	■	■	■	■	■				■						■					■			■		
	Risk retention and risk transfer mechanisms	M3			■	■	■					■	■	■	■	■		■				■				■						■						
	Existing cyber vulnerabilities	W	■					■				■		■	■	■				■				■				■	■			■				■		

Goals	Indicators	Ref.	Domains			Dimensions					Scales			Components				Attributes				Capacities						Qualities											
			Physical	Information	Human	Wellbeing	Economy	Technical	Environment	Organisational	Consumer	Utility	Nation	Generation	Transmission	Distribution	Demand	Strategy	Asset	Impact	Consequence	Preventive	Anticipative	Absorb	Adapt	Recovery	Transform	Reliability	Robustness	Redundancy	Hardness	Rapidity	Reflectiveness	Efficiency	Flexibility	Resourcefulness	Interoperability	Inclusiveness
ity	System operation's strategies for loss of telecommunication capabilities	W	■					■				■		■	■	■		■				■				■		■								■		
	Periodical reviews of under-frequency and voltage programs	W			■			■				■		■	■	■		■				■		■		■		■								■		
	Probability and magnitude of incident	C		■				■				■	■	■	■	■				■		■						■										
	Economic cost of recovery	V, B1		■			■					■		■	■	■	■				■					■		■										
	Demand Side response	S2	■					■				■					■			■				■				■	■			■						
	Cost of grid damage	V		■				■				■	■	■	■	■					■					■		■	■		■							
	Avoided outage cost	V		■			■					■	■	■	■	■	■				■					■						■						
	Existence of techniques utilised to evaluate the risk and vulnerabilities	C			■			■				■	■	■	■	■		■				■						■										
	Level of Undergrounding Distribution and Transmission Lines		■					■				■			■	■			■			■						■	■		■							
	Continuous Hazard and Exposure Mapping			■						■		■	■	■	■	■		■				■	■										■			■		
	Research and Development Expenditure	Z2, B2		■						■		■	■	■	■	■		■				■	■										■			■		
	Level of Interchangeability of Components	R2	■					■				■		■	■	■			■			■			■	■		■		■								
	Level of Duplication of Components	R2	■					■				■		■	■	■			■			■			■	■		■		■								
	Sensors, data collection and visualization capabilities to support system performance trending	R3	■					■				■		■	■	■			■						■								■			■	■	
	Number of Containment Components	E3	■					■				■			■	■			■					■		■			■		■							
	Transmission line vegetation management plan	W			■			■				■		■	■	■		■				■						■										
	Plans for Loss of Control Center Functionality	W	■					■				■		■	■	■		■				■	■									■						
	Ability to characterise system response				■			■				■		■	■	■		■							■								■					
	Duration of interruption	P1, J.W	■			■	■	■			■	■	■	■	■	■	■				■					■			■									
	Number of locations with component failures		■					■				■		■	■	■				■				■				■	■									
	Existence and operationalisation of proactive maintenance policy	E3		■				■						■	■	■		■							■			■	■		■							
	Access to maintenance crews	E3			■			■				■		■	■	■				■						■		■	■							■		
	Measurement of real time meteorological data	E3		■				■				■	■	■	■	■				■		■						■										
	Reliance on multiple layers of pre-disaster	E3			■		■	■				■	■	■	■	■		■				■			■							■						

Goals	Indicators	Ref.	Domains		Dimensions						Scales			Components				Attributes				Capacities						Qualities											
			Physical	Information	Human	Wellbeing	Economy	Technical	Environment	Organisational	Consumer	Utility	Nation	Generation	Transmission	Distribution	Demand	Strategy	Asset	Impact	Consequence	Preventive	Anticipative	Absorb	Adapt	Recovery	Transform	Reliability	Robustness	Redundancy	Hardness	Rapidity	Reflectiveness	Efficiency	Flexibility	Resourcefulness	Interoperability	Inclusiveness
	financing mechanisms				■		■	■				■	■	■	■	■		■				■			■							■						
	Adoption of Risk management standards (ISO 31000:2018)	E3			■		■	■				■	■	■	■	■		■					■		■							■						
	Loss of assets and perishables	V	■				■				■	■		■	■	■	■				■					■		■										
	Asset insurance, risk financing, direct pass-through of costs, parametric insurance	E3	■					■				■		■	■	■		■				■	■		■	■		■	■			■				■		
	External dependency financing	A			■			■				■	■	■	■	■		■									■								■			■
	Capacity for stockpiling of spare parts	E3	■					■				■		■	■	■			■			■				■		■	■			■				■		
	Capacity of Spare Parts/Component	R2	■					■				■		■	■	■			■					■	■	■			■	■		■						
	Phase out obsolete or damaged assets and introduce new assets	R3	■					■				■		■	■	■			■						■		■	■	■		■	■						
	Integrate new interface standards and operating system upgrades	R3	■					■				■		■	■	■			■						■		■	■	■		■							
	Initiating event, incident point of entry, associated vulnerabilities and impacts identified	R3		■				■				■								■					■			■	■									
	Accurate estimation of the weather location and severity	Y. J.W	■					■				■	■	■	■	■				■		■						■										
	Lives at risk	W			■	■					■	■	■	■	■	■	■				■	■				■			■		■							
	Investment in emissions reduction	M3	■					■	■			■	■	■					■						■		■									■		
Provision of Critical Service	Redundancy of critical capabilities	R3	■					■				■	■				■			■		■						■		■	■	■			■			
	Energy network flexibility to reservice by priority	R3	■					■				■	■		■	■				■						■		■				■			■			
	Average recovery speed of system load	Z1	■					■				■					■			■						■		■				■						
	Recovery efficiency for critical loads	Z1	■					■				■					■			■						■						■						
	Awareness and focus of effort on identified critical assets and services	R3		■				■				■	■				■	■							■											■		
	Cumulative energy demand not served to Critical entities	V	■					■				■	■				■				■			■				■	■									
	Critical entities experiencing outage during a specified time period	V	■			■					■						■				■					■		■	■									
	Critical services without power for more than N hours	V	■					■				■	■				■				■				■	■		■	■	■					■			
	Ratio of load restoration in 1 hr	Z1	■					■				■					■			■						■		■	■			■						

Goals	Indicators	Ref.	Domains		Dimensions						Scales			Components				Attributes				Capacities						Qualities										
			Physical	Information	Human	Wellbeing	Economy	Technical	Environment	Organisational	Consumer	Utility	Nation	Generation	Transmission	Distribution	Demand	Strategy	Asset	Impact	Consequence	Preventive	Anticipative	Absorb	Adapt	Recovery	Transform	Reliability	Robustness	Redundancy	Hardness	Rapidity	Reflectiveness	Efficiency	Flexibility	Resourcefulness	Interoperability	Inclusiveness
	Cumulative hours of outages for Critical infrastructure	C, V	■					■				■	■				■				■			■		■		■										
Mutual Support	Design, repair parts, substitution information available to recovery teams	R3		■				■				■		■	■	■			■							■												
	Existence of mutual aid agreements	E3		■						■		■		■	■	■		■							■	■							■				■	■
	Broadly-based operational and maintenance training	R3			■			■				■		■	■	■		■				■				■										■		
	Stakeholders stay informed about threats, changing environment, protective methods and technologies	R3			■	■	■	■	■	■		■	■	■	■	■	■	■				■															■	■
	Stakeholders collaborate to develop, prioritize and implement	R3			■					■		■	■	■	■	■	■	■							■												■	■
	Existence of quality of service incentive schemes during extreme weather	C		■				■					■	■	■	■		■						■		■		■				■				■		
	Training programs on resilience or disaster management	E3			■					■		■	■	■	■	■		■				■				■										■		■
	Existing collaboration between power sector providers	E3			■					■		■	■	■		■		■							■		■									■	■	■
	Available budget to support planning and risk reduction activities	E3			■					■		■	■	■	■	■		■				■	■													■		
Diversity	Decrease overall reliance upon energy or specific sources of energy	R3			■	■	■	■	■		■	■	■	■	■	■	■			■		■			■		■						■	■			■	
	Alternative energy resource development	R3	■					■	■			■	■	■						■					■										■	■		
	Existence of Alternative Regional Markets	H			■	■	■				■	■			■		■	■							■	■									■			
	Extent of Customer Choice for Service	M1			■	■					■						■	■							■										■			■
	Functional, stable, viable and inclusive markets	M3			■		■					■	■	■	■	■	■	■									■											■
	Diversification of supply/variable generation	M3, E1	■					■	■			■	■	■							■						■								■			■
Reliable Communication	Presaged equipment	R3	■					■				■		■	■	■	■		■			■							■		■							
	Sensors, controls and communication links to support awareness and response	R3, W	■					■				■		■	■	■			■			■											■					■
	Capability to monitor and control portions of system	R3	■					■				■		■	■	■				■				■								■						
	Environmental condition forecast and event	R3		■					■			■		■	■	■				■			■										■					

Goals	Indicators	Ref.	Domains			Dimensions					Scales			Components				Attributes				Capacities						Qualities										
			Physical	Information	Human	Wellbeing	Economy	Technical	Environment	Organisational	Consumer	Utility	Nation	Generation	Transmission	Distribution	Demand	Strategy	Asset	Impact	Consequence	Preventive	Anticipative	Absorb	Adapt	Recovery	Transform	Reliability	Robustness	Redundancy	Hardness	Rapidity	Reflectiveness	Efficiency	Flexibility	Resourcefulness	Interoperability	Inclusiveness
	warnings broadcast			■					■			■		■	■	■				■			■										■					
	Assessment of sensitivity to perturbation	R3	■					■				■		■	■	■				■		■						■										
	Enhancing early warning information and knowledge management systems	M3	■					■				■	■	■	■	■			■				■													■		
	Use of remote sensors following a disruptive event	E3	■					■				■		■	■	■				■						■						■				■		
	Use of satellite phones and mobile multiuse communication units	E3	■					■				■		■	■	■				■						■						■				■		
	Local seasonal plans developed, and advisories disseminated	M3		■						■		■	■	■	■	■		■					■									■						
	Existing Policies for Interoperability standardization			■						■		■	■	■	■	■		■							■	■										■	■	■
	Interorganizational and Intercomponent Data Exchange	O		■						■		■	■	■	■	■		■							■	■										■	■	■
	Existing standards for disturbance reporting	W		■						■		■	■	■	■	■		■								■						■			■			
	Response plans updated with lessons learned	R3		■						■		■	■	■	■	■		■							■								■			■		
	Update system configuration/ functionality based upon lessons learned	R3	■					■				■	■	■	■	■		■							■								■					
	Level of Automation of the System		■					■				■		■	■	■			■					■	■	■		■							■	■	■	
	Continuous Monitoring & Data Management			■				■		■	■		■	■	■	■		■				■											■			■	■	
	Existence of Consultative Planning Process				■					■		■	■	■	■	■		■				■											■			■		
	Level of Autonomy by Entities in Decision Making	Z2			■					■		■	■	■	■	■		■				■														■		
	Intelligence Management	Z2			■					■		■	■	■	■	■		■				■														■		
	Regular Updating of Codes, Standards & Enforcement Approaches				■					■			■	■	■	■	■	■							■								■			■		
	Redundant Communication Channels	R2	■					■				■	■	■	■	■			■					■		■				■					■		■	
	Existence of Feedback Loops in Communication Networks	M1	■					■				■	■	■	■	■			■					■	■	■									■		■	■
	Design, control, operational and maintenance data archived and protected	R3	■					■				■	■	■	■	■		■				■											■					
	Vendor information available	R3		■				■				■	■				■	■				■											■					
	Response/recovery plans established and distributed	R3		■						■		■		■	■	■		■				■	■															

Goals	Indicators	Ref.	Domains		Dimensions						Scales			Components				Attributes				Capacities						Qualities										
			Physical	Information	Human	Wellbeing	Economy	Technical	Environment	Organisational	Consumer	Utility	Nation	Generation	Transmission	Distribution	Demand	Strategy	Asset	Impact	Consequence	Preventive	Anticipative	Absorb	Adapt	Recovery	Transform	Reliability	Robustness	Redundancy	Hardness	Rapidity	Reflectiveness	Efficiency	Flexibility	Resourcefulness	Interoperability	Inclusiveness
Effective Leadership	Status/response/mitigation information transmitted effectively and efficiently to stakeholders/decision makers	R3		■						■		■	■	■	■	■		■						■									■				■	■
	Existing system restoration plans	W			■			■				■	■	■	■	■		■								■						■						
	Existence of Authority accountable for the resilience programme and coordination	C			■					■		■	■	■	■	■		■				■											■			■		
	Adoption of resilience as a security obligation	C			■					■		■	■	■	■	■		■				■											■					
	Level of Standardization of Processes	K			■			■		■		■	■	■	■	■		■							■							■				■	■	
	Bureaucracy Flexibility	Z2			■					■		■	■	■	■	■		■							■											■		
	Existence of Robust Planning Approval Process			■						■		■	■	■	■	■		■				■											■					
	Adopting risk-informed decision-making for extreme incidents	C			■					■		■	■	■	■	■		■					■										■					
	Coordinating information, communications available among recovery organizations	R3		■						■		■		■	■	■		■								■						■						
	Community stakeholders participate in establishment of energy priorities and coordination of restoration actions	R3			■					■		■	■	■	■	■		■								■											■	■
	Decision making protocol or aid to determine proper course of action	R3			■					■		■	■	■	■	■		■						■								■	■					
	Operators and managers utilize critical thinking and maintain proactive posture to recognize and arrest events	R3			■					■		■	■	■	■	■		■						■												■		
	Reallocate human resources to better address adverse events	R3			■					■		■	■	■	■	■		■							■										■	■		
	energy portfolio improvements Incentivize customers and stakeholders to implement more resilient energy solutions	R3			■					■	■	■		■		■	■	■							■		■								■	■		
	Disaster assessment and priority setting	Y			■					■		■	■	■	■	■		■				■											■					
Empowered Stakeholder	Periodic operator, management and community drills	R3			■					■		■	■	■	■	■		■				■														■	■	■
	Develop individual expertise in electricity impacts, techniques and alternatives (energy-	R3			■					■		■		■	■	■		■				■														■		

Goals	Indicators	Ref.	Domains			Dimensions					Scales			Components				Attributes				Capacities						Qualities										
			Physical	Information	Human	Wellbeing	Economy	Technical	Environment	Organisational	Consumer	Utility	Nation	Generation	Transmission	Distribution	Demand	Strategy	Asset	Impact	Consequence	Preventive	Anticipative	Absorb	Adapt	Recovery	Transform	Reliability	Robustness	Redundancy	Hardness	Rapidity	Reflectiveness	Efficiency	Flexibility	Resourcefulness	Interoperability	Inclusiveness
s	informed culture)				■					■		■		■	■	■		■				■														■		
	Definition and standard of resilience at different levels	C		■						■		■	■	■	■	■		■				■												■		■		
	Possibility of reallocation of budget lines to support recovery	C			■					■		■	■	■	■	■		■								■						■						
	Community response to mitigate impacts (e.g. demand curtailment)	R3			■			■				■		■	■	■				■				■					■									
	Community members manage constrained energy resources responsibly and consistent with public guidance	R3			■			■				■		■	■	■		■								■							■					
	Strategy and Mechanisms to monitor for major incidents within the electricity industry	R3			■			■				■		■	■	■		■				■											■					
	System Personnel Training	W			■					■		■		■	■	■		■				■											■					
	Verification of restoration procedures through simulation and testing of black start units	W			■			■				■		■	■	■				■		■											■					
Integrated Development Planning	Flexible network architecture to facilitate modernization and new energy sources	R3	■					■				■	■	■	■	■			■						■		■				■				■		■	
	Existence of contingency plans	E3			■					■		■	■	■	■	■		■					■									■						
	Existence of business continuity plans	E3			■					■		■	■	■	■	■		■							■							■						
	Development and enforcement of energy policies	M3			■					■		■	■	■	■	■		■				■											■					
	Plans for Loss of Control Center functionality	W			■					■		■	■	■	■	■		■					■									■	■					
	System Integration and Transaction Costs	E2		■				■				■		■	■	■					■				■										■	■	■	
	Ratio of Consumption to Regional Average			■		■					■		■				■				■						■											■
	Developing Integrated Disaster Risk Management and Resilience Plans	M3			■					■		■	■	■	■	■		■					■										■			■		
	Capabilities and services prioritized based on criticality or performance requirements	R3		■				■				■	■	■	■	■		■				■										■	■					
	Internal and external system dependencies identified			■				■				■	■	■	■	■		■				■										■	■					
	Operating environment forecasts captured in planning scenarios	R3		■						■		■	■	■	■	■		■				■										■	■					

Goals	Indicators	Ref.	Domains		Dimensions						Scales			Components				Attributes				Capacities						Qualities											
			Physical	Information	Human	Wellbeing	Economy	Technical	Environment	Organisational	Consumer	Utility	Nation	Generation	Transmission	Distribution	Demand	Strategy	Asset	Impact	Consequence	Preventive	Anticipative	Absorb	Adapt	Recovery	Transform	Reliability	Robustness	Redundancy	Hardness	Rapidity	Reflectiveness	Efficiency	Flexibility	Resourcefulness	Interoperability	Inclusiveness
	System's ability to learn				■					■		■	■	■	■	■		■							■								■					
	Event data and operating environment forecasts utilized to anticipate future conditions/ events	R3		■						■		■	■	■	■	■		■					■										■			■		
	Understand performance trade-offs of organizational goals	R3			■					■		■	■	■	■	■		■				■											■					
	Robust risk analysis and decision support capabilities to facilitate response	R3			■					■		■	■	■	■	■		■				■	■										■					
	Emergency Operations Planning	W			■					■		■	■	■	■	■		■				■											■					
Sustainability	Universal access to electricity	S1			■	■					■						■			■							■	■										■
	Population with primary reliance on clean fuels and technology	S1			■	■					■		■				■			■							■											■
	Ability to pay	S1			■		■										■				■						■											■
	Share of Renewable energy in the energy mix	S1	■					■					■	■						■					■			■							■			
	Investment in energy efficiency as proportion to GDP	S1	■					■					■	■	■	■	■			■		■												■				
	Ratio of primary energy to GDP	S1	■				■					■		■							■						■							■				
	International cooperation to facilitate access to clean energy research, technology or financing	S1			■					■		■	■	■	■	■	■	■				■					■						■			■	■	■
	Number of installed residential solar photovoltaic systems	B2	■					■	■		■			■					■			■		■	■	■	■	■	■		■	■			■	■		■
	Investment in Renewable energy	S1	■				■	■	■		■	■	■	■						■		■		■	■	■	■	■	■		■	■	■		■	■	■	■
	Expanded use electrical energy	S1	■			■											■			■					■									■				
	Expansion of infrastructure and upgrade of technology	S1	■					■				■		■	■	■	■		■					■	■		■	■	■	■	■	■		■	■	■	■	■
	Ratio of kg CO2 equivalent to Production	S1	■			■			■			■		■						■							■							■				
	Energy Poverty Rate	M1			■	■					■		■				■				■						■											■
	Reduction in energy poverty	S1			■	■					■		■				■				■						■											■

Reference key: A: [100]; **B1**: [101]; **B2**: [102]; **C**: [103]; **E1**: [85]; **E2**: [104]; **E3**: [49]; **H**: [105]; **K**: [59]; **L**: [106]; **M1**: [107]; **M2**: [83]; **M3**: [18]; **M4**: [84]; **O**: [104]; **P**: [79]; **R1**: [108]; **R2**: [109]; **R3**: [11]; **S1**: [110]; **S2:** [45]; **V**: [87]; **W**: [12]; **Y**: [48]; **Z1**: [111]; **Z2**: [112]

Appendix 3

DESCRIPTORS	ASSET DAMAGE	LOSS OF SERVICE	FINANCIAL LOSS	HEALTH/ SAFETY	LIKELIHOOD & COMPLIANCE	STRATEGY & INFORMATION	DATA AVAILABILITY
Exceptional	No infrastructure damage	Localized interruption of service for less than 1% of the agreed level of service.	Loss of less than 1% of annual revenues or negligible CAPEX value.	Negligible or no changes to the health/safety profile	≤1%	Act, Policy, Regulations, Strategies and Plan Existent and are fully implemented and are enforceable/ disaster information is reliably shared and there are systems to respond to the public's queries	≤99% of required data
Excellent	No significant damage; repair works not required	Localized interruption of service for less than 5% of the agreed level of service.	Asset damage greater than 1% but less than 5% of annual revenues or less than 1% of CAPEX value	Negligible or no changes to the health/safety profile; low risk of minor injuries	1-5%	Act, Policy, Regulations, Strategies and Plan Existent and are partially implemented and are enforceable/ disaster information is shared most of the times and there are systems to respond to the public's queries	95-99% of required data
Very Good	No permanent damage; some minor restoration work required	Localized interruption of service for less than 10% of the agreed level of service.	Asset damage greater than 5% but less than 10% of annual revenues or less than 5% of CAPEX value	Slight changes to the health/safety profile; risk of minor injuries as a result of extreme events	5-10%	Act, Policy, Regulations, Strategies and Plan Existent and are partially implemented but are not enforceable/ disaster information is shared sometimes and there are systems to respond to the public's queries	90-95% of required data
Good	Damage recoverable by maintenance and minor repair; partial loss of local infrastructure.	Widespread interruption of service for less than 20% of the agreed level of service, resulting in minor contractual penalties.	Asset damage greater than 10% but less than 25% of annual revenues or less than 10% of CAPEX value.	Noticeable changes to the health/safety profile; risk of severe injuries as a result of extreme events.	10-25%	Strategies and Plan Existent and are and voluntarily implemented/ disaster information is shared voluntarily to the public with no enforceable policies	95-75% of required data
Fair	Damage recoverable by maintenance and significant repair; partial loss of local infrastructure.	Widespread interruption of service for less than 35% of the agreed level of service, resulting in minor contractual penalties.	Asset damage greater than 25% but less than 50% of annual revenues or less than 25% of CAPEX value.	Noticeable changes to the health/safety profile; risk of severe injuries or fatalities as a result of extreme events.	25-50%	Strategy and plan exists and are implemented but without guiding regulatory framework/ there are means to communicate with the public directly concerning disaster related information	75-50% of required data
Poor	Extensive infrastructure damage, requiring extensive repair; permanent loss of local infrastructure services.	Widespread and extended (several days) interruption of service for less than 50% of the agreed level of service, resulting in severe contractual penalties. Catastrophic	Asset damage of 50% or greater of annual maintenance budget or less than 50% of CAPEX value.	Marked changes in the health/safety profile; risk of severe injuries and even fatalities as a result of extreme events.	50-75%	Plan exists and are implemented but without guiding regulatory framework/ there are means to communicate with the public but not directly concerning disaster related information	25-50% of required data

Appendix 3

DESCRIPTORS	ASSET DAMAGE	LOSS OF SERVICE	FINANCIAL LOSS	HEALTH/ SAFETY	LIKELIHOOD & COMPLIANCE	STRATEGY & INFORMATION	DATA AVAILABILITY
Very Poor	Permanent damage and/or less of infrastructure; retreat of infrastructure.	Widespread, extended (several weeks) interruption of service of the agreed level of service, resulting in extreme contractual penalties or contract breach.	Asset damage exceeding 75% or more than 25% of CAPEX value.	Substantial changes to the health/safety profile; risk of multiple fatalities as a result of extreme events.	≥75%	No Act, Policy, Regulations, Strategies and Plan existent and are implemented/ no communication with the public and key stakeholders	25% to no data at all

Appendix 4

Goals	Indicator Classification		Metric Appropriation			Attribute	Metric Value	Metric Descriptor	Rating Scale Score	Certainty
Adequate Security of Supply	Component	Demand	Capacity	Absorptive	Rate of loss load	Impact	140 MW/Month	Good	4	Exceptional
		4	Quality	rapidity	Promptness of system's recovery	Impact	0.725 GWh/Month	Good	4	Exceptional
	Domain	Physical	Capacity	Adaptive	Large Capacity margins	Impact	113%	Exceptional	7	Excellent
		6	Quality	Reliability	Supply of primary energy	Asset	92%	Very good	5	Excellent
	Dimension	Wellbeing	Capacity	Absorptive	Increase in number of Customers experiencing outages	Consequence	0%	Exceptional	7	Very poor
		5.5	Quality	Reliability	Increase in number of customer energy demand not served	Consequence		Good	4	Exceptional
	Scale	Consumer	Capacity	Absorptive	Cumulative of load interruption	Impact	0 MWh	Exceptional	7	Excellent
		5	Quality	Inclusiveness	Demand Growth	Consequence	-29%	Fair	3	Excellent
									5.13	5.75
Affordable Cost of Energy	Component	Distribution	Capacity	Adaptive	Loss of utility revenue	Consequence	-20%	Good	4	Exceptional
		5	Quality	Efficiency	Increase in operational expenses	Consequence	4%	Excellent	6	Excellent
	Domain	Information	Capacity	Adaptive	Existing Information on time of use tarrifs	Strategy	YES	Exceptional	7	Exceptional
		4	Quality	Resourcefulness	Information on access to consumer subsidies	Strategy	No	Very poor	1	Exceptional
	Dimension	Wellbeing	Capacity	Adaptive	Changes in tariff	Consequence	-0.1%	Good	4	Exceptional
		3	Quality	Inclusiveness	Percentage of income spent on domestic electricity bills	Consequence	73.0%	Poor	2	Very poor
	Scale	Consumer	Capacity	Transformative	% of people whose income can not support average energy consumption	Consequence	60%	Poor	2	Very poor
		3	Quality	Interoperability	Change in Incidences for disconnection (voluntary & forced)	Consequence	0%	Good	4	Very poor
									3.75	4.625
Adequate Safety & Security	Component	Transmission	Capacity	Absorptive	Damage to the transmission system	Impact	0 $ or 0 Lines	Exceptional	7	Very good
		7	Quality	Reflectiveness	Analysis and Mitigation of Protection System Mis-operations	Impact	YES	Exceptional	7	Exceptional
	Domain	Human	Capacity	Adaptive	Number of people injured	Consequence	0	Excellent	6	Excellent
		6.5	Quality	rapidity	Mortalities	Consequence	2	Exceptional	7	Excellent
	Dimension	Technical	Capacity	Anticipative	Critical system data monitored, anomalies alarmed	Impact	Partially	Good	4	Very good
		4	Quality	Hardness	Protection of cyber control systems	Impact	Partially	Good	4	Poor
	Scale	Utility	Capacity	Preventive	Existence of live GIS systems enabled command center operations	Asset	YES	Exceptional	7	Excellent
		4	Quality	Resourcefulness	Use of scenario-based war gaming to develop understanding of system dependencies and interactions	Strategy	NO	Very poor	1	Poor
									5.38	4.875
Economic Productivity	Component	Distribution	Capacity	Recovery	Direct economic losses	Consequence	-43%	Fair	3	Good
		3.5	Quality	Robustness	Change in revenue	Consequence	-15%	Good	4	Exceptional
	Domain	Physical	Capacity	Adaptive	Reduction in productive use of electricity	Consequence	-4%	Excellent	6	Excellent
		6	Quality	Resourcefulness	Per capita consumption	Consequence	-4%	Excellent	6	Excellent
	Dimension	Economy	Capacity	Recovery	Decrease in Industrial labour hours	Consequence	-20%	Good	4	Very poor
		5	Quality	Resourcefulness	Impact on GDP	Consequence	-2%	Excellent	6	Very poor
	Scale	Utility	Capacity	Recovery	Valuation of unserved energy	Consequence	-5%	Excellent	6	Very good
		5	Quality	rapidity	Decrease in Utilities' labour hours	Consequence	-11%	Good	4	Fair
									4.88	4.125
Minimal Exposure & Vulnerability	Component	Demand	Capacity	Recovery	Duration of interruption	Consequence	6 Months	Very poor	1	Exceptional
		4	Quality	Reliability	Damage to Loads	Consequence	No	Exceptional	7	Very good
	Domain	Physical	Capacity	Recovery	System operation's strategies for loss of telecommunication	Strategy	NO	Very poor	1	Very poor
		4	Quality	Hardness	Cost of grid damage	Consequence	$ 0	Exceptional	7	Very good
	Dimension	Environment	Capacity	Preventive	Existing mitigation measures for risks	Strategy	Partially	Good	4	Good
		5.5	Quality	Resourcefulness	Investment in emissions reduction	Asset	YES	Exceptional	7	Exceptional
	Scale	Utility	Capacity	Absorptive	Reduction in existing cyber vulnerabilities	Asset	NO	Very poor	1	Good
		1	Quality	Reliability	Accurate estimation of the weather location and severity	Asset	NO	Very poor	1	Good
									3.63	4.625
Provision of Critical	Component	Demand	Capacity	Absorptive	Average recovery speed of Critical loads	Consequence	Unaffected	Exceptional	7	Very good
		7	Quality	Redundancy	Critical services without power for more than 1 hours	Asset	None	Exceptional	7	Very good

Appendix 4

Goals	Indicator Classification		Metric Appropriation			Attribute	Metric			Certainty
							Value	Descriptor	Rating Scale Score	
Services	Domain	**Physical**	Capacity	Absorptive	Cumulative energy demand not served to Critical entities	Consequence	**0 MWh**	**Exceptional**	7	**Very good**
		7	Quality	Reliability	Cumulative hours of outages for Critical infrastructure	Consequence	**0 MWh**	**Exceptional**	7	**Very good**
	Dimension	**Technical**	Capacity	Absorptive	Number of Critical and essential load interruptions	Consequence	**None**	**Exceptional**	7	**Very good**
		7	Quality	Reliability		Consequence	**None**	**Exceptional**	7	**Very good**
	Scale	**Utility**	Capacity	Recovery	Energy network flexibility to reservice by priority	Impact	**Not Required**	**Exceptional**	7	**Very good**
		7	Quality	rapidity	Recovery efficiency for critical loads	Impact	**Unaffected**	**Exceptional**	7	**Very good**
									7.00	**5**
Mutual Support	Component	**Transmission**	Capacity	Preventive	Stakeholders stay informed about threats, changing environment, protective methods and technologies	Strategy	**YES**	**Exceptional**	7	**Exceptional**
		7	Quality	Inclusiveness	Stakeholders collaborate to develop, prioritize and implement	Strategy	**YES**	**Exceptional**	7	**Exceptional**
	Domain	**Human**	Capacity	Adaptive	Existing collaboration between power sector providers	Strategy	**YES**	**Exceptional**	7	**Exceptional**
		6	Quality	Resourcefulness	Available budget to support planning and risk reduction activities	Strategy	**Partially**	**Very good**	5	**Very good**
	Dimension	**Organisation**	Capacity	Anticipative	Existence of mutual aid agreements	Strategy	**No**	**Very poor**	1	**Very good**
		1	Quality	Inclusiveness	Training programs on resilience or disaster management	Strategy	**No**	**Very poor**	1	**Very good**
	Scale	**Nation-state**	Capacity	Adaptive	Existence of quality of service incentive schemes during extreme events	Strategy	**No**	**Very poor**	1	**Good**
		1	Quality	Reliability		Strategy	**No**	**Very poor**	1	**Good**
									3.75	**5.5**
Improved Portfolio Diversity	Component	**Generation**	Capacity	Transformative	Overall reliance upon specific sources of energy	Impact	**Unchanged**	**Very poor**	1	**Exceptional**
		1	Quality	Flexibility		Impact	**Unchanged**	**Very poor**	1	**Exceptional**
	Domain	**Physical**	Capacity	Adaptive	Alternative energy resource development	Impact	**Unchanged**	**Very poor**	1	**Exceptional**
		4	Quality	Resourcefulness		Impact	**Unchanged**	**Exceptional**	7	**Exceptional**
	Dimension	**Economy**	Capacity	Adaptive	Functional, stable, viable and inclusive markets	Strategy	**Unchanged**	**Exceptional**	7	**Exceptional**
		7	Quality	Inclusiveness		Strategy	**Unchanged**	**Exceptional**	7	**Exceptional**
	Scale	**Nation-state**	Capacity	Transformative	Diversification of supply	Consequence	**Unchanged**	**Very poor**	1	**Exceptional**
		1	Quality	Flexibility		Consequence	**Unchanged**	**Very poor**	1	**Exceptional**
									3.25	**7**
Reliable Communication	Component	**Distribution**	Capacity	Preventive	Use of presaged equipment	Asset	**No**	**Very poor**	1	**Very poor**
		2.5	Quality	Hardness	Assessment of sensitivity to perturbation	Impact	**Partially**	**Good**	4	**Very poor**
	Domain	**Information**	Capacity	Adaptive	Response plans updated with lessons learned	Strategy	**Partially**	**Good**	4	**Very good**
		5.5	Quality	Reflectiveness	Vendor information available	Strategy	**YES**	**Exceptional**	7	**Exceptional**
	Dimension	**Environment**	Capacity	Anticipative	Environmental condition forecast and event warnings broadcast	Impact	**Partially**	**Good**	4	**Very poor**
		4	Quality	Reflectiveness		Impact	**Partially**	**Good**	4	**Very poor**
	Scale	**Nation-state**	Capacity	Preventive	Seasonal plans developed and advisories disseminated	Strategy	**Partially**	**Good**	4	**Very poor**
		5	Quality	Resourcefulness	Existing standards for disturbance reporting	Strategy	**Partially**	**Excellent**	6	**Exceptional**
									4.25	**3**
Effective Leadership	Component	**Distribution**	Capacity	Preventive	Adoption of resilience as a security obligation	Strategy	**NO**	**Very poor**	1	**Excellent**
		2.5	Quality	Reflectiveness	Disaster assessment and priority setting	Strategy	**Partially**	**Good**	4	**Exceptional**
	Domain	**Information**	Capacity	Recovery	Coordinating information, communications available among recovery organizations	Strategy	**Partially**	**Good**	4	**Fair**
		4	Quality	Reflectiveness		Strategy	**Partially**	**Good**	4	**Fair**
	Dimension	**Organisation**	Capacity	Absorptive	Decision making protocol or aid to determine proper course of action	Strategy	**Partially**	**Fair**	3	**Fair**
		4	Quality	Resourcefulness	Operators and managers utilize critical thinking and maintain proactive posture to recognize and arrest events	Strategy	**Partially**	**Very good**	5	**Excellent**

Appendix 4

Goals	Indicator Classification		Metric Appropriation			Attribute	Metric			Certainty
							Value	Descriptor	Rating Scale Score	
	Scale	**Consumer** 5	Capacity	Adaptive	Energy portfolio improvements Incentivize customers and stakeholders to implement more resilient energy solutions	Strategy	**Partially**	**Very good**	5	**Excellent**
			Quality	Interoperability		Strategy	**Partially**	**Very good**	5	**Excellent**
									3.88	**5**
Empowered Stakeholders	Component	**Transmission** 2.5	Capacity	Preventive	Periodic operator, management and community drills	Strategy	**NO**	**Very poor**	1	**Very poor**
			Quality	Reflectiveness	Strategy and Mechanisms to monitor for major incidents within the electricity industry	Strategy	**Partially**	**Good**	4	**Very poor**
	Domain	**Human** 4	Capacity	Preventive	Develop individual expertise in electricity impacts, techniques and alternatives (energy-informed culture)	Strategy	**Partially**	**Good**	4	**Very poor**
			Quality	Reflectiveness	System Personnel Training	Strategy	**Partially**	**Good**	4	**Very poor**
	Dimension	**Organisation** 3	Capacity	Recovery	Possibility of reallocation of budget lines to support recovery	Strategy	**Likely**	**Fair**	3	**Very poor**
			Quality	rapidity		Strategy	**Likely**	**Fair**	3	**Very poor**
	Scale	**Nation-state** 1	Capacity	Preventive	Definition and standard of resilience at different levels	Strategy	**NO**	**Very poor**	1	**Very poor**
			Capacity	Recovery		Strategy		**Very poor**	1	**Very poor**
									2.63	**1**
Integrated Development Planning	Component	**Generation** 5	Capacity	Transformative	Flexible network architecture to facilitate modernization and new energy sources	Assets	**Somewhat**	**Very good**	5	**Excellent**
			Quality	rapidity	Existence of contingency plans	Strategy	**Somewhat**	**Very good**	5	**Excellent**
	Domain	**Human** 6	Quality	Preventive	Robust risk analysis and decision support capabilities to facilitate response	Strategy	**Somewhat**	**Very good**	5	**Exceptional**
			Quality	Reflectiveness	Development and enforcement of energy policies	Strategy	**YES**	**Exceptional**	7	**Exceptional**
	Dimension	**Organisation** 2.5	Capacity	Preventive	Developing Integrated Disaster Risk Management and Resilience Plans	Strategy	**NO**	**Very poor**	1	**Excellent**
			Quality	Reflectiveness	Understand performance trade-offs of organizational goals	Strategy	**Somewhat**	**Good**	4	**Good**
	Scale	**Utility** 4.5	Capacity	Preventive	Emergency Operations Planning	Strategy	**Somewhat**	**Good**	4	**Very good**
			Capacity	Resourcefulness	Event data and operating environment forecasts utilized to anticipate future conditions/ events	Strategy	**Somewhat**	**Very good**	5	**Excellent**
									4.50	**5.875**
Sustainability	Component	**Generation** 7	Capacity	Adaptive	Share of Renewables in the energy mix	Impact	**0.95**	**Exceptional**	7	**Exceptional**
			Quality	Reliability		Impact	**YES**	**Exceptional**	7	**Exceptional**
	Domain	**Human** 3	Capacity	Transformative	Ability to pay	Consequence	**Somewhat**	**Fair**	3	**Excellent**
			Quality	Inclusiveness		Consequence	**Somewhat**	**Fair**	3	**Excellent**
	Dimension	Wellbeing 1	Capacity	Transformative	Universal access to electricity	Impact	**-0.75**	**Very poor**	1	**Exceptional**
			Quality	Inclusiveness	Energy poverty	Consequence	**-0.8**	**Very poor**	1	**Very good**
	Scale	**Consumer** 3	Capacity	Adaptive	Improvement in energy efficiency	Impact	**Somewhat**	**Fair**	3	**Fair**
			Quality	Efficiency		Impact	**Somewhat**	**Fair**	3	**Fair**
									3.50	**5.5**