Power Systems’ Resilience

Subjects: Engineering, Electrical & Electronic

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The article makes an in-depth examination of the previous literature on power systems resilience. Power systems are constructed to withstand stochastic element outage under the N-1 security theory. However, several natural disasters have caused extraordinary challenges to power systems due to climate change, emphasising the position that power systems are unprepared for extreme events of large scale and severity level.

Keywords: power system resilience ; grid ; metrics ; resilience frameworks ; climate change ; threats ; extreme events ; resilience enhancement ; resilience evaluation

1. Introduction

Electricity manages lives, economies, and cities; without it, lives would not only be inconvenienced, but could hypothetically be at risk [1]. The constant production and supply of electricity is therefore crucial to the functioning of society. Since most of the key infrastructure depends on the constant allocation of electricity, it is imperative that the grid operates consistently and is resilient in the case of unusual events [1]. The concept of resilience has been studied in various disciplines, including community, engineering, socioeconomics, and ecology [2]. Unlike reliability, resilience is characterised by low-probability high-impact (LPHI) events [3][4][5][6]. LPHI events are incidents that occur rarely but have severe impact, for example, a 300-year flood occurrence. One of the significant features of LPHI events that distinguish them from predictable power system (PS) failures is that power sources may not be accessible or available [7]. Consequently, resilient systems ought to have a variety of supply sources and should avoid overdependence on a restricted set of power supplies. In addition, systems should be adequately flexible to respond rapidly to events and to change working processes even in short times [3]. Furthermore, priorities for supplying diverse loads should be well known [8]. The frequency and intensity of LPHI events has been increasing in the wake of climate change (CC), increasing population, and economic growth [9][10][11][12]. The motivations behind generic resilience studies have been summarised [13]. Motivations for power system resilience (PSR) studies include the criticality of the grid system [3][14][15][16][17][18], sustainability and economic reasons [3][14][15], vulnerability of the grid system [6][15][19][20], and the increase in the frequency of severe weather events [20][21]. The electricity grid is considered to be a “critical lifeline system” and the “backbone of any modern society” [16][17][18], since all critical infrastructure depends on a reliable supply of electricity; thus, network outages affect millions of people and present huge risks to everyday life, economic prosperity, and national security [3][6][14][15][19]. The development of tools, methods, approaches, and/or guidelines for the assessment and enhancement of grid resilience is another cause for PSR studies. The frequent occurrence of natural hazards and malicious attacks has exerted unprecedented disturbances on power systems, accounting for the extensive attention paid to PSR [6][19], which may have unfavourable outcomes for the economy [14]. Power systems (PSs) are designed to tolerate stochastic element outages under the N minus 1 security principle [22]. However, lately, several natural hazards have caused unexpected problems to PSs due to CC, emphasising the fact that PSs are not prepared for extremely large-scale events [18]. Since its introduction, the resilience of critical infrastructure—specifically PSs—has become the priority for utilities and investigators [18]. In recent years, there has been a significant increase in the number of papers reviewing PSR, as shown in **Figure 1**.

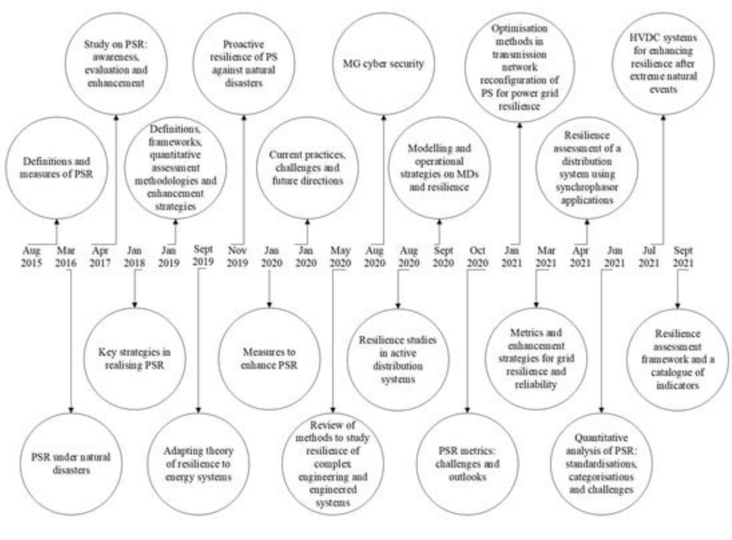

Figure 1. Evolution of power system resilience (PSR).

2. The Notions of Power System Resilience (PSR)

2.1. Defining and Classifying PSR

It has been suggested [23] that resilience definitions should depend on the identification of resilience domains, which are classified as: economic, engineering, organisational, and social. A PSR definition is derived from definitions provided by other disciplines [21]. The definition further considers planning as a key factor in grid resilience. The significant roles played by the grid operator, grid development agents, and the entire electricity sector, cannot be overemphasised in guaranteeing grid resilience.

The available PSR definitions are system centric, hence omitting the significant roles of PS operators and other key stakeholders such as energy policy custodians. System operators control and manage the infrastructure; thus, the ability of these system operators to maintain electricity supply during severe disturbances is not only a function of the system, but also how resilience of that PS is managed. Planning and preparation activities are key in critical infrastructure resilience management. Planning and preparedness activities, which may be undertaken by the PS operator, may include ensuring the following are in place, but not limited to these alone: (i) hazard awareness (ii) reliance documentation such as preparedness, response plans, and resilience guidelines, (iii) resilience capacity building plans, (iv) risk transfer mechanisms, (v) disaster maps, and (vi) restoration procedures. In addition, the operator may ensure resource availability in the form of: (i) infrastructure, (ii) operational resources, such as critical spares, adequate maintenance team, and (iii) and alternative supply sources. Furthermore, the operator may emphasise keeping the PS infrastructure in good shape by following approved maintenance procedures and routine equipment inspections. The operator may also consider equipment, or repair crew prepositioning [24][25]. Operators of critical infrastructures have significant responsibility when mitigating impacts of severe disturbances. Similarly, custodians of energy policies need to be instrumental in ensuring PSR through enforcement of policy implementation. Anticipatory governance and long-term policy vision are critical in the adjustment of current behaviour to address potential PS problems [26].

The majority of researchers [6][7][9][10][16][18][24][27][28][29][30][31][32][33] have highlighted the ability property, the capacity of power systems to undertake resilience activities including but not limited to preparation, anticipation, absorption, response, restoration, adaptation, recovery, withstanding, and adoption of effective measures under high-impact low-probability events. These events could be naturally, or human-induced, such as excessive vandalism. These capacities are extended to PS operators and other PS development agents. This combination introduces the concept of PSR management [34]. Therefore, effective resilience management depends on the different capacities that either the system, operator, or policy has. System capacities will focus on the system’s capability to resist damage and minimise any loss of function during a crisis, or promptly recover from the disturbances. Operator’s capacity will concentrate on the competence of the operator to manage the infrastructure before, during, and after disturbances, such as processes of capability, planning, educating, leadership, and communication. Policy capacities will focus on the strength of the policy in supporting PSR [35]. Policy is significant because the operators are answerable to government’s regulations.

While system centric capacities are mainly considered, other capacities such as financial and legal instruments are equally important. The greatest challenge when power systems are faced with extreme events is maintaining electricity supply [10]. The majority of other critical infrastructures depend on the sustainable and continuous supply of electricity, and these are linked to provisions such as social services, healthcare, education, security, transport, and water supply; it is imperative that they remain uninterrupted during extreme events.

The degree, type, or duration of an event, or potential event, is another critical property in defining PSR [36]. The system, or organisations, must have the capacity to undertake resilience activities for specific events of a defined duration. There are different types of PS threats, hence the need for specification. While the PS may be resilient to one type of event, it may not be resilient to another. How the systems or institutions can restrict the impact or loss is crucial in describing resilience. Since certain events cannot be avoided, the logical approach is limiting the level of loss [32]. How this loss is limited or restricted depends on the level of other resilience activities, such as preparation and forecasting the extent of potential damage. When all these are in place, the system or operations will be restored as quickly as possible because prompt restoration of supply is essential to ensure sustainability of critical services [9][31]. Quick restoration defines the dynamic nature of resilience [37]. Protection against any event that would significantly affect the PS was highlighted by [7], showing the need for system protection to be considered when defining PSR. Defining resilience should also take into consideration the capacity to withstand the impacts of severe events within an acceptable level and to return to pre-event status within an acceptable time frame and cost [27]. The minimum acceptable level of loss may be that which ensures that critical load supply will be sustained. Resilient systems continue to operate even in their damaged state.

2.2. The Concept of PSR

The concept of resilience is based on the “bounce back” principle [38]. A resilient grid is considered as an interconnected network of different components that has four fundamental properties of resilience [39][40]:

- Anticipation (outright avoidance/resistance/repulsion of adverse impacts of hazards/being able to prevent possible damage).

- Absorption (capacity to minimise/mitigate/lessen/limit the adverse impacts of hazards/threats and related disasters).
- Recovery (restoration and improvement, where appropriate, of disaster-affected systems, and communities, including efforts to reduce disaster risk factors).
- Adaptability (initiatives and approaches to reduce the exposure of natural and human systems against actual or expected impacts of hazards by studying the previous events and improving or advancing the systems' capacities) after the damaging events [20].

Consequently, resilience has been perceived as the adaptive ability of enhancing performance, owing to knowledge and alteration, learnt by unceasing change [38]. The simplest means to state grid resilience is through examination of the overall impact, which is the area of the grid resilience triangle [21]. This concept was adopted and modified by [41], who believed that a resilience triangle is founded on the reflection that disturbing events cause sudden fluctuations in the performance quality, and steady recapture, to the original performance quality level. Any resilience improvement approach endeavours to maximise this area under the curve or minimising the triangle [20][42]. Resilience triangles leave behind the degraded state, hence, they are not an ideal approach to estimate the impact.

3. Metrics and Quantification of Resilience

3.1. Metrics of Resilience—Definition, Classification, Attributes, and the Selection Criteria

The words metrics, index, indicator, and functionality were used interchangeably [43]. Technically, a metric is a system or standard of measurement. An indicator is anything that indicates the state or level of something; it is a guide to a metric. The PSR metrics (PSRMs) are tools to measure (quantify/assess/evaluate/calculate/determine) the resilience level of a PS [43]. The proposed metric framework system, which classifies the PSRMs into performance- and non-performance-based, can be found in [43]. While PSRMs are generally categorised as either operational or infrastructural resilience [44], in [27], they are classified into four types: metrics based on resilience features, metrics based on reliability properties [16], code-based metrics [45], and other metrics. On the contrary, the authors of [46] generalised these metrics into either flow- or centrality-based metrics. Quantitative RMs have been classified according to attributes [47], and further categorised as: generic, transmission level, distribution level, stochastic, deterministic, cost-based, energy-based, time-based, planning, operational, static, dynamic, use of simulated, and real data metrics. The metrics are categorised as analytical, probabilistic, curve-based, and reliability-based [48]. PSRMs have also been classified based on performance and system characteristics [49]. Alternatively, these indicators have been categorised based on sustainable development goals (SDGs) [50]. These classifications are summarised in **Figure 2**. It was noted that this classification was based on quantitative RMs and therefore it was proposed that PSRMs be classified into qualitative and quantitative metrics to match the PSR evaluation classification.

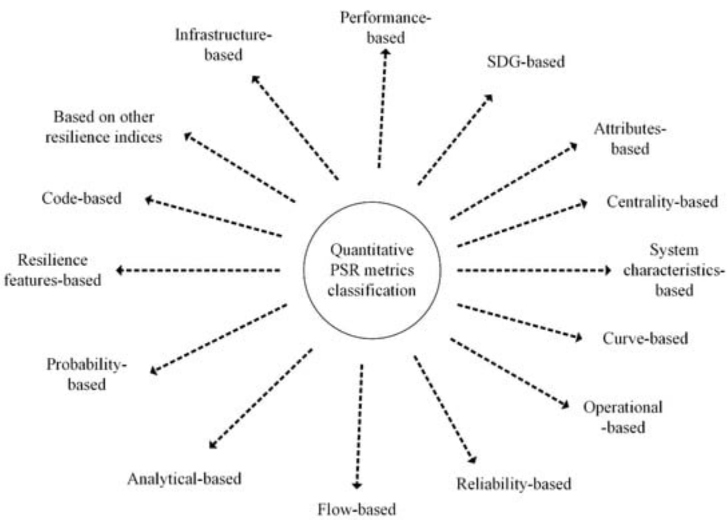

Figure 2. Classification of quantitative PSR metrics (PSRMs).

3.2. Quantification of Resilience: The Metrics

Apart from the impact assessment, some quantitative indices can be added to measure the PSR. Detailed reviews on quantitative metrics were presented in [2][21][24][27][47][48][49][50]. A collection of different quantitative indicators for different energy systems alongside their formulations has been presented [2]. The resilience triangle, RT, and other indices were presented as quantitative indicators in [21]. In [47], a comprehensive review of quantitative RMs, which were standardised and evaluated, was reported. The authors also provided a diverse categorisation of these metrics. A comprehensive and critical review of current practices of PSRMs was provided by [27]. General attributes of metrics and their categorisation were also identified. A conceptual framework to define key variables, factors, and ideas of RMs in PS and a definition of their relationships has been suggested [24]. Existing PSRMs were allocated to framework groups. RMs' attributes were also presented. A catalogue of 303 indicators across different domains, dimensions, scales, components, attributes, capacities, and qualities was developed [50]. These indicators were categorised based on SDGs. A selection of quantitative RMs proposed for PSR assessment were compared [48]. Metric formulations were also provided, as in [49]. Although these authors provide a significant contribution to resilience research, the concentration is on quantitative metrics. Quantitative metrics remain informative when assessing the efficiency of resilience actions, or comparing the degree of resilience of distinct structures [7], and in preparing and managing appropriate enhancement strategies [21].

4. PSR Frameworks

4.1. Qualitative Resilience Evaluation

Qualitative resilience evaluation is where different attributes and resilience abilities can be considered simultaneously [7]. The attributes considered in the qualitative assessment normally include the PS and other interdependent systems, for instance, information systems and fuel supply chains. Abilities include preparedness, mitigation, response, and recovery, e.g., the existence of an emergency plan, personnel training, and repair crew availability [7]. Prior studies have considered different aspects but frameworks are predominantly the main outputs of the qualitative resilience studies [40]. These qualitative frameworks can be used as guidance for long-term energy policy making, as they portray a generally complete picture of the system. Measurement of adaptive capability and notions of diversity, redundancy, system configuration, and observing were reported as some of the frequent ideas to evaluate qualitative resilience, irrespective of the field [40]. Affordability, availability, accessibility, and acceptability were also attributes of resilience that demonstrate the ability of a system to plan/prepare, absorb, recover, and adapt to external disturbances [40] (**Figure 3**).

4.2. Quantitative Resilience Evaluation

Quantitative resilience evaluation has been frequently centred on the quantification of system performances. Quantitative resilience assessment was categorised into simulation-based analytic methods and statistical analyses [18]. Out of these, the simulation-based method was most broadly used because it can simply be combined with disaster scenarios and the threat impact can easily be calculated [16]. Resilience evaluation approaches were grouped into: Monte Carlo simulations, contingency-based, machine learning-based, and Bayesian network-based approaches [27]. Multi-phase resilience evaluation has been considered [19], and the key challenges of each phase can be revealed by splitting the resilience evaluation into three elements: pre-disaster system resilience, during-disaster system endurance, and post-disaster system repair capability. Different quantitative resilience frameworks have so far been reported in the literature by [6][7][8][9][11][13][19][21][22][24][41][42][46][51][52][53][54]. These were compared and numerous conclusions or recommendations drawn; there was no standard framework. While some established threat identification and/or characterisation [6][19][22][41][51], others began by defining the resilience goals [7][13], with the remainder determining data requirements [9][21][37][46][53], as well as defining the RMs [52]. There were limited studies on pre-event resilience assessment (preparedness). One framework demonstrated the need for planning resilience [53], which helps identify weak, or potentially weak, points and informs planning and operational decisions. Identification and prioritisation of enhancement measures before cost–benefit analysis was demonstrated [37]. Much as identification should precede cost–benefit analysis, prioritisation would be ideal if it was based on the cost–benefit analysis. The need for cost–benefit analysis in the identification and implementation of enhancement measures was recognised [21]. The resilience frameworks were dependent on location; events were area specific and not universal [13]. Therefore, it has been suggested that resilience enhancement should incorporate stakeholder involvement to take into consideration the locality of resilience challenges.

The authors in [6][9][19][37][46][52] indicated that some resilience studies aimed to establish the resilience status of the PS. Despite the diversities, the common stage in resilience studies was impact assessment, which was in the form of a vulnerability assessment of a system's components [51], component functionality assessment [22], expected system performance evaluation [19], determination of the extent of system degradation [52], and establishing PS components' outage [6]. Impact assessment can also be achieved through assessing the level of preparedness, how much a system degrades, how fast a system is restored after disruption, how the system adapts to disturbance [21], the determination of the level of disruption [7], situational analysis [37], and the evaluation of affected resilience indicators [9][46] (**Figure 4**).

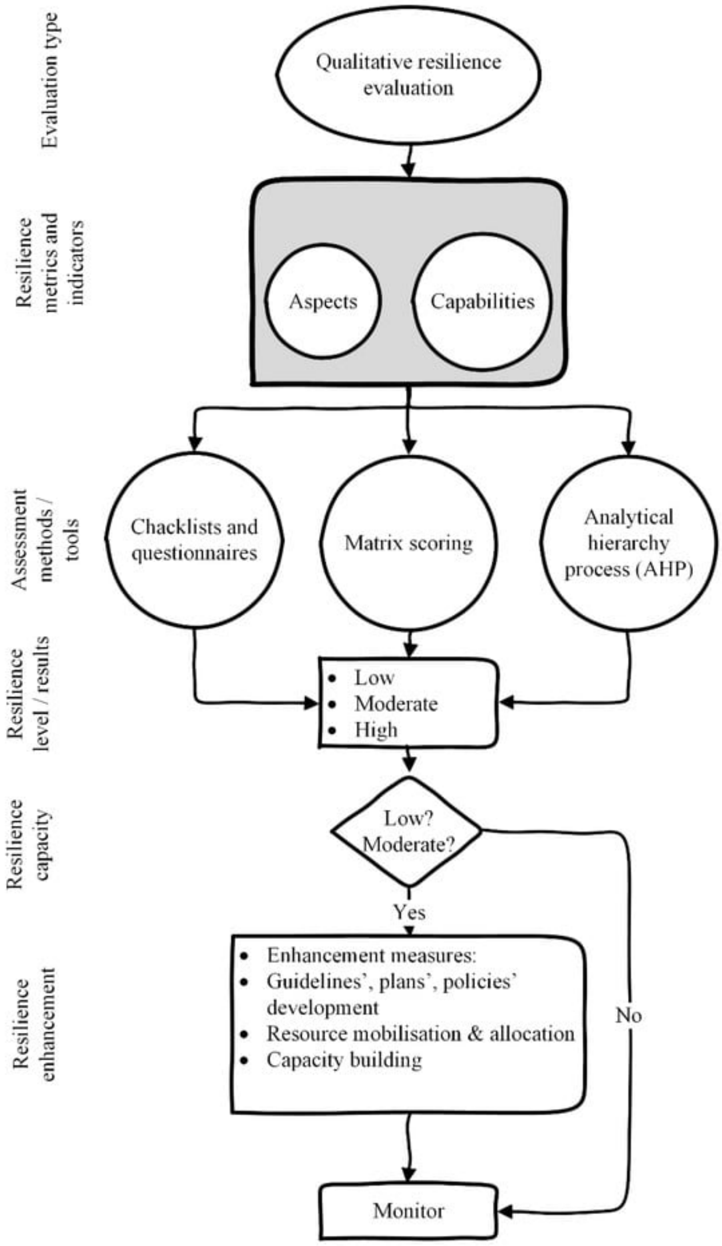

Figure 3. Qualitative resilience evaluation. Redrawn but adapted from: [7][55][56][57].

Principally, the main activities in resilience studies are represented by numbers 1 through 7 in **Figure 4**. Approaches 1–5 mean that the authors started with threat identification followed by resilience assessment. Depending on resilience goals, some studies ended at step 5 (resilience assessment) [6][13][19][37][51][52][53], while others ended with resilience enhancement [7][9][21][22][41][54]. The following approaches were noted: ***1-5*** [22][41], ***1-2-5*** [19], ***2-1-5*** [52], ***4-5*** [21][51], ***1-4-5*** [6], ***3-2-1-5*** [7], ***4-1-5*** [37], ***2-5*** [54], and ***4-2-5*** [9][46].

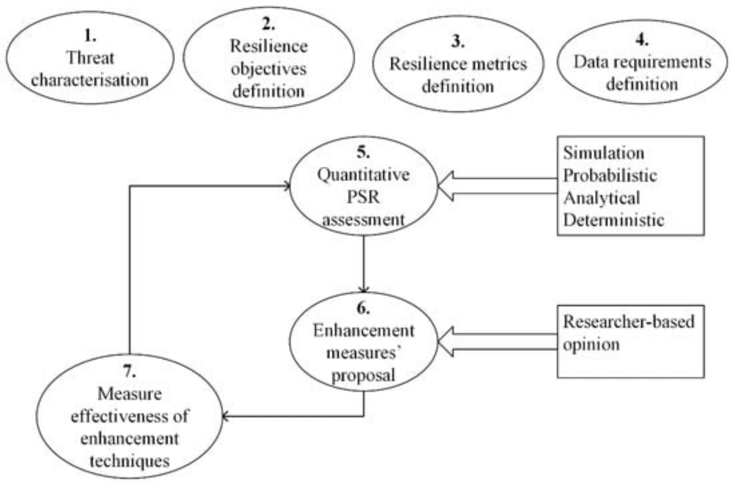

Figure 4. Summary of the available resilience frameworks.

None of the authors combined qualitative and quantitative evaluation, therefore a comprehensive PSR assessment and enhancement framework, shown in **Figure 5**, is proposed. This framework provides a platform for a mixed-methods approach to PSR assessment and enhancement. The multidisciplinary procedure of undertaking PSR research is a novel approach in PS and provides a methodology for the integration of qualitative and quantitative frameworks for the development of an integrated PSR enhancement model. It further provides for interdisciplinary enhancement measures through stakeholder engagement in the identification of resilience improvement techniques, which are key to acceptance and implementation of measures. It also addresses the locality of PSR challenges. This framework can be utilised by a variety of user groups, from researchers to industries or sectors. It may be used in resilience assessment and enhancement of other critical infrastructures, with or without modifications, depending on outcomes of implementation. The proposed framework informs long-term resilience planning with regards to both economic, political, organisational, and technical viability of enhancement measures.

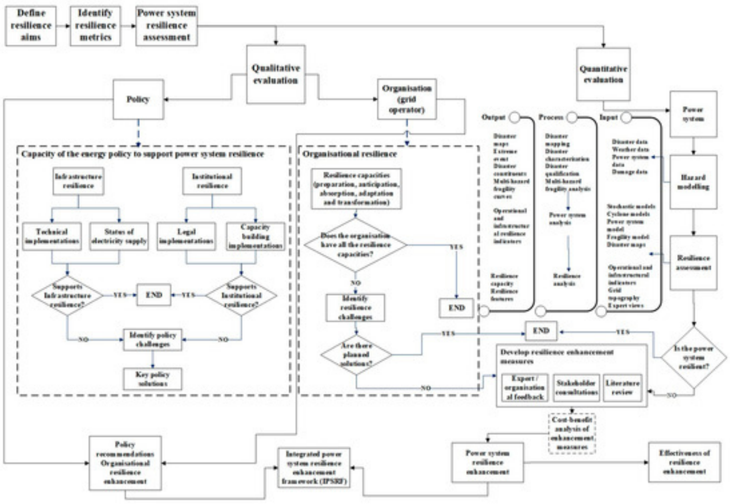

Figure 5. Proposed integrated PSR assessment and enhancement framework.

5. Threats to PSR

5.1. CC, Extreme Events and PSR

Studies reveal that the increase in occurrence, extent, and intensity of extreme weather events are caused by CC [9][10][11][12]. CC is also responsible for rising global temperatures, variations in rainfall patterns, increased frequency and strength of drought days, cloudiness, higher winds, sea-level rise [9][10][12][58][59][60][61][62], cold waves, heavy snow, and lightning strikes on or near overhead conductors [63]. Each of these effects of CC can affect the PS in different ways, at different degrees, either on their own or in combination, as is normally the case. The degree of damage on the PS depends on the significance of the weather or climatic conditions, and the condition of the components. Prior works have focused on the impact of extreme weather events (as another effect of the impact of CC) on power systems along with their mitigation strategies. This extensive directional study supports the fact that LPHI events are among the principal causes of cascading outages and severe impacts following a disruption. However, CC is here to stay, and world trends indicate the possible increase in CC [62]. This calls for consideration of climate adaptation and mitigation. PS operation (contrasted to planning) has constantly been strongly related to weather conditions and vulnerable to extreme weather events that may in some cases be a large, if not the largest, contingency event. It is important to clarify that the “CC impacts” relate only to how this interdependency and vulnerability are likely to change over the years. The critical issue arising from CC is that these natural hazards are projected to intensify and become more frequent and increasingly unpredictable. It was thus significant to consider CC in the system resilience studies.

The impacts of CC on generation, transmission and distribution (T&D), and demand are reviewed in [63][64]. Rising global temperatures affect solar photovoltaic (SPV) modules, hydropower generation, T&D, and the demand landscape. Higher ambient temperatures reduce the generation efficiency of SPV modules [10]. The conversion efficiency of the photovoltaic (PV) modules is negatively affected by elevated temperatures, which reduce their optimal output. Elevated temperatures also affect generation output of hydropower plants due to increased evaporation in water bodies [10][64]. Rising temperatures further affect the T&D system in terms of transmission efficiency and capacity. Physical characteristics of different PS components, including transformers and overhead lines (OHL), have a linear relationship with allowable maximum operating temperature. Increasing global temperatures accelerate T&D losses and line sag [62], lower existing capability, and derate T&D equipment to survive the elevated temperatures [10].

There is continuous research to curb the effects of CC on critical infrastructures. A framework for risk measurement and enhancing the resilience of critical infrastructures centred upon the ideologies of elasticity, variety, and industrialised ecology, incorporating both short-term and long-term influences of climate consequence has been proposed [62]. Risk assessment is considered one of the critical activities to be undertaken in the prediction stage as a positive step toward climate risk resilience. CC mitigation and adaptation might have a positive impact, and possibly lessen the slope or rate of degradation, when LPHI events finally strike.

5.2. CC, Electricity and PSR

Many studies in CC assess the impact on demand profile. Generally, CC will increase average annual electricity demand [65][66][67][68][69][70][71][72][73][74][75][76], and it has been demonstrated that in the wake of extreme temperatures, electricity utilisation escalates more with heating demands than with cooling demands in Portugal [65]. This was explained by the adoption of other smaller cooling technologies. In contrast, the authors of [66][67] proved that the escalated need for cooling would lead to increased electricity utilisation in China, which is explained by China's climatic warming trend, which was also observed for Northern and Southern Europe [69], due to the knowledge that CC will shift the distribution of seasonal electricity consumption [68][71]. At minimum temperatures, temperature rises cause a decrease in electric space heating and, to a certain degree, a decrease in the utilisation of indoor appliances, the use of which escalates during cooler weather [70]. The impacts of space cooling through air conditioners and the use of other appliances prevail at higher temperatures. Whereas climate warming decreases electricity demand for heating in winter and increases the demand for cooling in summer, it conclusively increases demand [68][72]. Fluctuations in population, tariffs, and CC were explored in [71], where each one of the electricity demand determinants was allowed to vary, while the rest of the factors remained unchanged. The results implied that the effects of the weather variables on the overall path of electricity demand were comparatively moderate, but positive over the full projection time. Generally, studies in [61][68][72][73][74][75][76] have demonstrated an increase in electricity demand during summer and spring times due to CC. This was described by an increase in the number of buildings with air conditioners (ACs), and the extra cooling load on those air conditioners. This was attributed to the different heating and cooling techniques in different regions, such as in China [75][76].

5.3. Adaptation Measures against CC and Its Impacts

Adaptation works on coping principles. CC adaptation has been defined as a means to cope with CC impacts [77]. Adaptability studies target the enhancement of strategic resilient elements to assist in mitigating the impact of future climatic events [78]. These studies further boost sturdiness, resourcefulness, and recuperation before an imminent disaster. Improvement in resilience for the energy sector can be on both the large-scale and household level.

Forms of climate adaptation strategies can be classified into: (1) structural, which was further subdivided into technological-, engineering-, and eco-system-based, (2) capacity building, which was further classified into educational, informational, or behavioural adaptation, and (3) institutional, which was further categorised into economic tools, laws and regulations, and governance [9]. Adaptation approaches for a single classic event, or several events, fall into either one, or a combination of two or more, of all the forms. The authors in [79] demonstrate the relationship between resilience and CC adaptation. It was perceived that principles of resilience were inherent in CC adaptation approaches and that different forms of adaptation approaches build resilience.

CC adaptation measures were classified as: (1) hardening (structural), which might comprise undergrounding power delivery structures, upgrading, rerouting, elevating structures or having redundant structures, and (2) effective operating procedures [78][79]. The structural adaptation measures aim at lessening the exposure of the PS to impacts of CC, while effective operating procedures aim at minimising the restoration time, which improves the recovery features of resilience. Microgrids (MGs) and distributed energy resources (DERs) were considered as means of reinforcing PSR against the impacts of CC in [78], which were performed to enhance operational capability. Geothermal energy was used as a climate adaptation strategy where a double relationship was observed [80]. One point of view is that there was maladaptation, which takes place if geothermal resources were not properly or sustainably implemented, and conversely, that there was adaptation, which was achieved through sustainable water heating, electricity generation, sustainable livelihoods, and eradication of effects of drought in hydropower. Renewable energy technologies (RETs) such as biogas, improved cookstoves, micro hydro and solar power were also recommended as a way of rural adaptation to CC, as these reduce not only traditional biomass use but also carbon dioxide emissions [81]. Policy and regulatory instruments in solar energy were recognised as adaptation methods in PS, which can be applied either at an enterprise, regional, national, or international level [77].

6. PSR Enhancement Strategies

Two purposes served by grid resilience enhancement strategies are: (1) reducing the magnitude of the immediate impact caused by a severe weather event, and (2) reinstating the grid functionality to its pre-event state as quickly as possible after a severe weather event. Many researchers categorised grid enhancement into (structural) physical hardiness and (non-structural) operational capability [3][14][16][42][82][83]. Structural improvement is used to reduce the magnitude of the impact, and non-structural enhancement is applied to reduce the restoration time or increase grid functionality [21]. Thus, embracing both measures ("Hybrid enhancement") might guarantee both impact and restoration time reduction. On the contrary, the resilience enhancement approaches can be grouped into planning and operational methods, which can either be short or long term [18]. It was argued that underlying enhancement principles can be categorised into system executions; regional methods; community methods; national methods; methods highlighting the role of the valuation; methods emphasising the notion of security and plea for risk supervision studies; and sectoral methods [38]. Prior studies have evaluated both structural [3][20][30][83][84][85][86] and non-structural or operational [14][16][22][24][25][87][88][89][90][91][92] PSR enhancement techniques separately.

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