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# Visualizing Nepal's electricity supply resilience from a whole-systems perspective: A participatory approach

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## Abstract

Energy resilience is a complex issue, encapsulating a diversity of factors. Such complexity makes effective policymaking difficult, and requires a whole-systems approach. This paper argues that the bottom-up participatory causal loop mapping method can be helpful in facilitating a shared understanding of the issues, and can help facilitate the application of a whole-systems approach to the design of effective policy interventions. Focusing on Nepal as a case study, this paper outlines the participatory approach, highlighting the method's value in visualising the variables and interconnections affecting the resilience of Nepal's electricity supply. Through the mapping, participants identified four interconnected groups of factors as important for resilience: governance, technology, economic and social. Within these, political leadership was noted as particularly important. Environmental factors were largely absent, which is an interesting result given the emphasis on renewable sources and clean technologies in energy policy in Nepal. The outcomes of our bottom-up participatory approach show the significant benefit of using this approach for highlighting context-dependent understandings of complex issues and represents a novel methodological innovation for energy research, which could be applied in diverse geographies and contexts.

## Keywords

Energy resilience, whole system, participatory approach, causal loop, Nepal

## 1 Introduction

Resilience is discussed in the literature from a multitude of different disciplinary perspectives [1], and is an inherently contested concept [2]. Research suggests that unless interdisciplinary approaches to achieving and improving resilience are recognised, appreciated and reconciled, difficulties will persist in realising a robust understanding of what factors affect resilience and how resilience can be improved [3,4,5]. Yet despite these calls, research about the ways in which an interdisciplinary understanding of resilience can be developed and understood in practice is limited [2]. This paper aims to help fill this gap through a focus on energy resilience. In particular, a resilient electricity supply is important in the face of long-term crises, such as climate change, as well as short-term shocks, such as natural disasters.

In this paper, electricity supply is understood as a complex system, and its resilience understood to be context dependent, linked to factors across sectors and multiple scales. This challenge makes understanding and visualising the complexity of achieving electricity supply resilience particularly difficult. It is especially challenging from a policy perspective, where decision-makers tend to operate within institutional silos. Therefore, a whole-systems perspective considering the multiple sectors, scales and actors needed to help foster interdisciplinary understanding is required and one which enables stakeholders to identify interventions that can have systemic rather than siloed benefits [6]. This paper argues that a participatory causal loop mapping approach [7,8] (where stakeholders create visualisations of the factors that affect electricity supply resilience, and their interconnections) can help identify avenues for further engagement to embed resilience into the long term. This paper also highlights the ways in which a bottom-up participatory causal loop mapping approach can be used to help enable key stakeholders to create a shared understanding of energy resilience and visualise its complexity. Moreover, the paper illustrates how the method provides insights into the ways energy resilience is understood in practice, and the potential implications of this for policymaking towards resilience.

Our focus here is on electricity supply resilience in Nepal. In the past, Nepal has experienced electricity supply disruption not only due to natural disasters and political shocks, such as the Gorkha earthquake in 2015 [9,10,11] and the India-Nepal border blockade between 2015 and 2016 [10,11], but also due to lack of electricity supply access (especially in rural areas), and instability; using load-shedding to prevent the electricity system from overloading during peak demand [12,13,14]. This makes Nepal a fruitful case for exploring the ways in which electricity supply resilience is understood and ways in which interconnections between variables can be identified to explore potential avenues for future action towards resilience.

The paper is organised as follows. Section 2 reviews the literature around electricity supply resilience and the need for a whole-systems approach, as well as the background of the case study country - Nepal. Section 3 introduces the participatory causal loop mapping approach, as well as the data collected to understand and visualize the broad electricity supply resilience picture. The results from the data analysis are presented in Section 4, with more in-depth discussion and key messages covered in Section 5.

## 2 Electricity supply resilience in the context of Nepal

A whole-systems approach to electricity supply resilience starts from the understanding that resilience constitutes a complex web of interdependent factors. The strength of this approach is supported by the current ambiguity that exists in the literature as to what resilience is, with its meaning contested and open to conceptual fuzziness [15,16,17]. For example, debates include whether resilience is an outcome, a process, or a condition relating to a particular system [18]. The etymological roots of resilience come from the Latin word resilio, which means “to jump back” [19] (p. 35). Whilst continuity and recovery are commonly agreed as essential aspects of resilience in the face of rapid change [20,21], Dahlberg et al. [22] suggest resilience goes beyond those elements and includes strength, capacity, elasticity, and evolution. In turn, it has been argued that resilience is better described and applied as “a collection of ideas about how to interpret complex systems” [1] (p. 7). Such a holistic definition reduces the risk of missing crucial factors that are integral to strengthening resilience in practice. However, the ambiguity also makes it difficult to understand resilience empirically and to operationalise in support of steering policy approaches [18,19,23,24,25,26].

The concept of energy resilience is increasingly discussed in the literature [11]. In taking a whole-systems approach to the concept, there is the potential to consider a multitude of different issues and factors. For example, the range of forms of energy supply and factors influencing provision directly and indirectly. Also, demand for electricity, including different socio-economic factors that might influence such demand (and the level and type of supply), for example access to a particular service. Moreover, electricity systems comprise both physical and non-physical components, are extraordinarily complex, and often under multiple external stresses [11,27,28]. In turn, it is important to recognise that electricity supply resilience is influenced by factors across multiple sectors and scales. For example, at household level, electricity supply resilience can relate to people's access to services, such as lighting, cooling, cooking, and communications [27]. The use of alternative energy sources during disruption of the grid system can also be understood as linked to improved resilience. For instance, individuals may purchase batteries at home for emergency use during a power outage. At national level, for example, load-shedding may result from high user demand and vulnerability of supply sources as has been experienced in Nepal [11,13,14]. At the community level, recent research has highlighted the complex, non-infrastructure based factors that may affect ability to respond effectively to electricity supply disruption – for example existing capacity and knowledge for local repair of electricity systems [29]. This highlights the need to think more broadly about the potential factors that influence resilience.

This paper recognises that a diversity of factors can affect electricity supply resilience. Moreover, the paper acknowledges that such resilience depends on the complex interdependencies of a range of different factors (from finance, to policy, to the environment) and interconnected subsystems of activity. Focusing only on one aspect of the system, at the expense of another, is therefore to risk a siloed approach that has the potential to generate unintended consequences that may weaken resilience. To strengthen resilience requires understanding these interconnections, identifying how a change in one aspect of the system can affect another, and in turn have a positive or negative effect on resilience (directly or indirectly). In relation to electricity supply, a whole-systems approach to resilience encourages us to broaden out from a focus solely on physical infrastructures and processes, to the ways in which these infrastructures interact with and are influenced by the ways electricity is used, produced, and understood [30].

This paper focuses on Nepal as a case study; a country which has faced electricity supply challenges [31,32]. Access to electricity has grown substantially in the past couple of decades, with 94% of Nepal's 28 million population having access in 2018, compared to only 19% in 2000 [31]. Mini-grid and off-grid renewable electricity systems play a vital role in the Government of Nepal's electricity access strategy for rural areas [33]. Moreover, under the Constitution of Nepal 2015, there are opportunities to grow the use of off-grid sources through decentralised electricity planning which expands the role of municipal and local governments in electricity governance [34].

In April 2015, Nepal experienced a devastating earthquake and series of aftershocks that took the lives of 8,700 people, forcing 2.6 million people to flee their homes, with over half a million houses destroyed [35]. The Government of Nepal's post-disaster assessment [9] reported that the estimated damage to the energy sector alone totalled over NPR 17, 800 million (US$ 150 million), causing issues for electricity provision and access in the short and long term. For example, the earthquake damaged 115 MW of 787 MW (over 14%) of the hydropower generation under operation and delayed the construction of 1000 MW of new hydropower projects. Damage was also caused to transmission lines and substations. While power was restored to Nepal's capital and most populous city Kathmandu within 24 hours and in other municipality areas within seven days, restoration of services in off-grid areas took longer [9,36]. Moreover, 600,000 households lost access to electricity due to house collapse or damage to electricity supply facilities. About 85% of these households were using off-grid facilities before the earthquake [36].

Only a few studies of the electricity sector post-earthquake went beyond assessing damage to infrastructure, but a pilot study conducted in four earthquake affected districts indicated that communities leveraged local technical expertise, resources and informal networks to help access energy services using renewable sources [29]. Informal networks were an important way for communities to support each other and maintain access to services [37]. The importance of looking beyond the infrastructural here in relation to electricity supply resilience is clear to see. This paper shows how a bottom-up participatory approach could enable such interconnections between technical and social to be identified and elucidated in order to create a shared understanding of the landscape of electricity supply resilience.

## 3 Methodology

Causal loop diagrams, and the process of creating them, are a well-recognised method for understanding the dynamics of systems and visualising interconnections between different variables. Such maps are based on identifying the factors that are part of the system (in this case, of electricity supply resilience) as 'nodes (i.e. variables)' on the map, with the connections between these nodes (i.e. 'the edges') literally drawn between and identified as either having a positive or negative effect on the 'target' (in this case, resilience) [38]. The maps enable individual elements to be seen in context, and to identify what the potential implications might be of one element of the system changing. The linkages between sets of factors often cause 'feedback loops'. Where an increase in X variable causes an increase in Y variable, and an increase in Y variable leads to an increase in X variable, the feedback loop is 'reinforcing'. Where the affect between variables is increasing in one direction, but decreasing in the other, the feedback loop is 'balancing'.

As Liebovitch et al. [39] note, these maps are a multifaceted tool; helping with diagnostics – the identification of potential gaps in current policy approaches, and helping operationally – in identifying 'leverage points' for policy intervention. Moreover, these maps can be created in a participatory way. A participatory approach involves a group of stakeholders related to the issue in question identifying, discussing, and debating the factors in the system and the nature of the links between them. In turn this process acts as a heuristic tool to facilitate learning between participants. The contribution of a bottom-up participatory approach is in helping stakeholders to reflect on their own understanding, but also the understanding of others, and their intersections, which is fundamental for designing coordinated interventions [40].

While causal mapping processes can be both qualitative and quantitative, here the focus is on producing a qualitative 'cognitive map' of the issue of electricity supply resilience, to gain a context-dependent understanding of the views of the actors involved in electricity governance in Nepal. Such maps help to identify the ways in which problems are understood by different actors, and the discussions that result help identify potential avenues for response and in essence would be the first informative stage in quantitative model building [41]. Such participatory mapping exercises have been used to identify the factors and complex interdependencies of a range of issues, including obesity [7,42], adoption of solar and battery systems [43] and sustainable consumption [8]. However, such causal loop mapping approaches have not been applied to electricity supply resilience research and therefore offers the potential to provide a new and holistic perspective to the dynamics at play in achieving electricity supply resilience, from the perspective of those involved in the system. Participatory causal loop mapping therefore also contributes a novel approach to electricity research more generally [44].

To generate understanding of the factors affecting electricity supply resilience in Nepal, 15 stakeholders were brought together for a workshop. The stakeholders were identified through the professional networks of the authors and desk-based research. They were recruited through an initial email explaining the project and the nature of their potential participation, with follow-ups made by telephone. Six out of the 15 stakeholders were identified through the professional networks of the authors, with further nine stakeholders identified using the snowball sampling approach [45]. Participants were selected based on their involvement in energy governance in Nepal, drawing from across different aspects of Nepal's energy sector (as presented in Table 1). For example, participants included an Energy Officer of a Government Department, officer from a private energy institution in Nepal, and energy expert from an NGO.

At the start of the workshop, participants were provided with an overview of the project's aims and an explanation of the causal loop method. There was also a facilitated discussion of the term resilience. For example, the facilitators provided a basic definition of resilience to the group from the International Federation of Red Cross and Red Crescent Societies – "the ability of individuals, communities, organizations or countries exposed to disasters, crises and underlying vulnerabilities to anticipate, prepare for, reduce the impact of, cope with and recover from the effect of shocks and stresses without compromising their long-term prospects" [46] (p. 6). This definition was provided as a starting point, and provocation, in order to help familiarise the participants with the types of issues that may be considered when discussing resilience, recognising that it may not be a term all participants were familiar with. It was made clear to the participants that this is not the only definition of resilience, nor should it be taken as the best one. Through the discussion that followed, we highlighted that the term is inherently contested, and covers a range of issues, and therefore no one definition or understanding is better than another. This discussion enabled the participants to feel comfortable and able to discuss resilience in relation to electricity in their context. There was also facilitated discussion of the current issues and developments on the agenda regarding energy in Nepal, for example decentralisation, in order to help provide context for the facilitators, but also to help participants start making connections between electricity supply and resilience. This ensured that the participants were not coming to the mapping exercise without already having started to think about some of the potential issues.

Table 1 Workshop participants

| **Sector** | **Government** | **NGO** | **Private sector** | **Research** | **Total** |
|---|---|---|---|---|---|
| Number of participants | 4 | 3 | 5 | 3 | 15 |

Following these discussions, first, participants were asked to identify the factors they considered as important to electricity supply resilience, and the facilitators wrote them on post it notes and placed them on the table in front of the participants. This process continued until no new factors could be identified by participants. As the second step, participants were asked to think about the links between the factors, and the post it notes were re-positioned on the table accordingly. Through these conversations, on occasion other factors were identified as steps between the two original factors. The participants were then asked to discuss whether they thought the causal link between two of the factors was positive or negative, and depending on the response a plus or minus symbol added next to the link accordingly (Figure 1). This was repeated for each connection between factors.

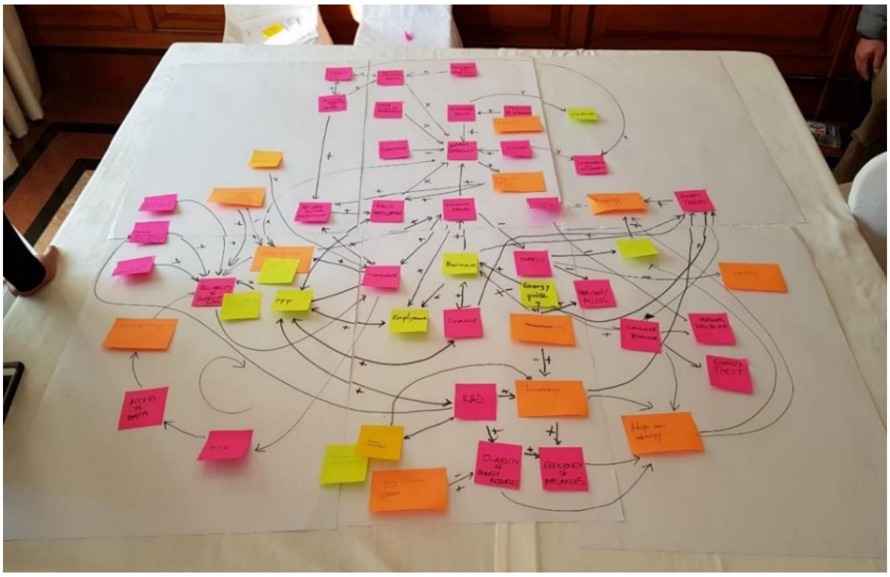

Figure 1. Causal loop mapping exercise at the workshop (no meaning of the different colours of post it notes)

After the workshop, the variables and causal links were then transferred to computer software – VenSim – in order to create a clearer and reusable map (Figure 2). The researchers re-positioned the variables on VenSim to make the categories of connections clearer but did not alter the linkages created by the participants. The map created through this process represents the participants' collective view of the variables and causal links that affect electricity supply resilience in Nepal.

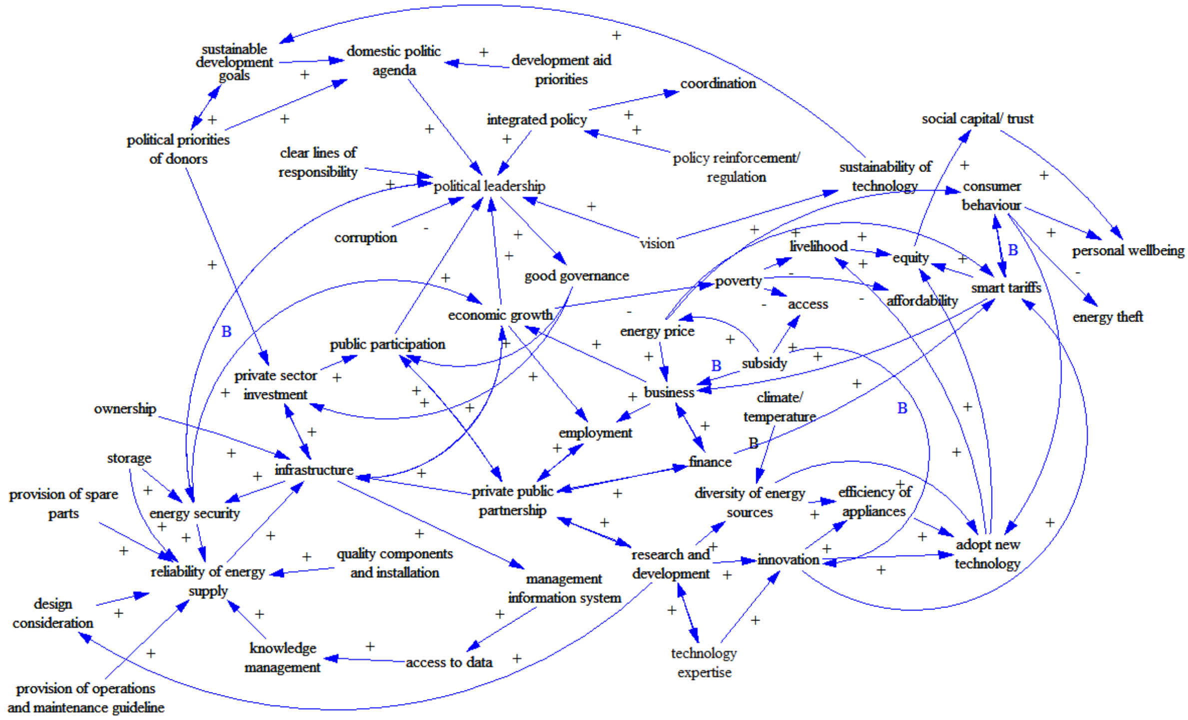


Figure 2. Variables and causal links identified during the workshop*

*"B" in the diagram means 'balancing loop'

## 4 Results

Over 100 causal loops are identified and illustrated through VenSim in Figure 2. The causal loops show how workshop participants felt variables in each group affect each other, which helps to determine the relationships that could have a positive influence on fostering and reinforcing electricity supply resilience within Nepal. The variables in Figure 2 can be categorised into four key groups: governance, technology, social and economic factors (see Figure 3). In order to analyse the maps, the most 'tactically significant' factors on the map were identified [47]. These factors are listed in Table 2 and are all factors with at least five causal links attached as illustrated in Figure 3. These are all factors that have the greatest number of nodes directly linked to them, and are therefore suggestive of their strategic significance for affecting electricity supply resilience in Nepal [47]. Counting of the number of nodes linked to each factor was done manually by the researchers through analysing the VenSim map. Five was used as the numerical cut-off point because it is the mid-point between the factor with the most connections (ten), and those factors with the lowest (one). Moreover, some causal loops cover variables across different factor groups, indicating that changes of variables in one factor group (for example governance) could cause reinforcing effects within one or more of the other three groups of factors identified (for example, technology factors). The most tactically significant factors with the greatest number of links (as shown in Figure 3) are set out in Sections 4.1-4.4, along with discussion points made by participants during the workshop.

Table 2 Nodes with at least five causal links

| Factor Group | Nodes | Number of causal links attached |
|---|---|---|
| Governance | Political leadership | 10 |
| | Private public partnership | 9 |
| Technology | Infrastructure | 9 |
| | Reliability of energy supply | 8 |
| | Research and development | 7 |
| | Energy security | 6 |
| | Innovation | 5 |
| Economic | Business | 8 |
| | Economic growth | 7 |
| | Smart tariffs | 7 |
| | Private sector investment | 5 |
| | Finance | 5 |
| Social | Consumer behaviour | 7 |
| | Adopt new technology | 6 |
| | Public participation | 5 |

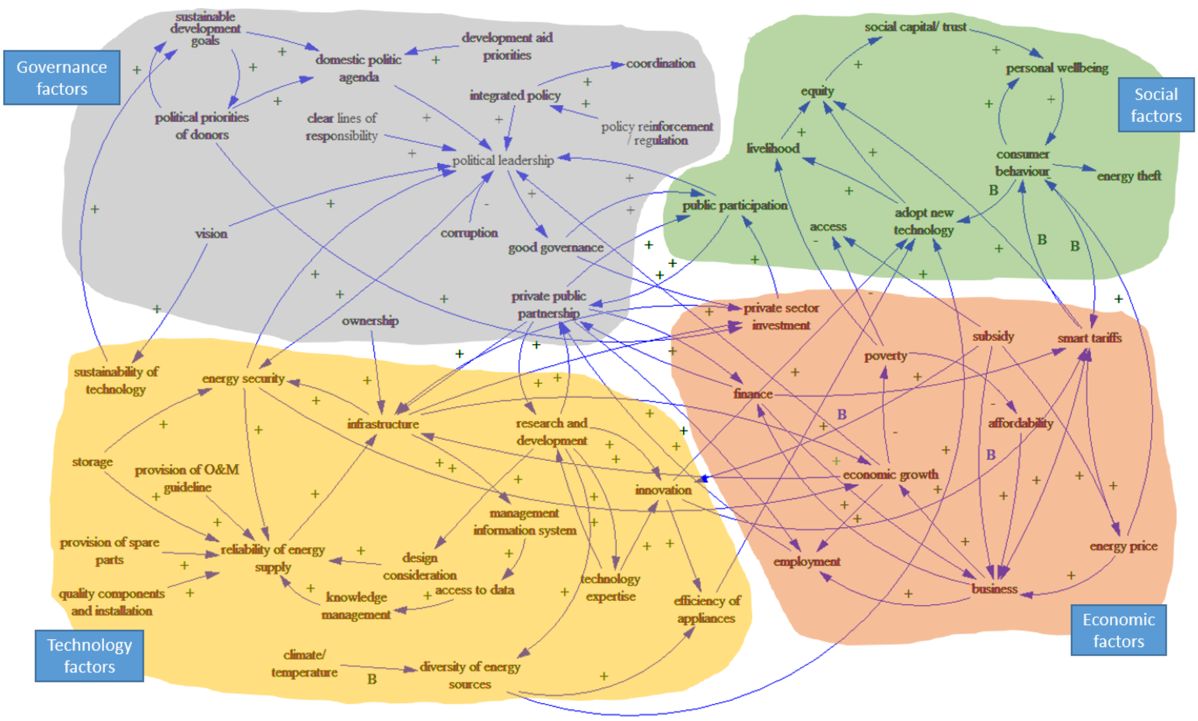


Figure 3. Categories of variables

## 4.1 Governance factors for electricity supply resilience

The most important governance factors identified by participants include political leadership (with ten causal links associated) and private public partnership (with nine causal links associated). In the discussion (and as presented in Figure 3), participants emphasised that political leadership in Nepal could be strengthened through clearer lines of responsibility, better vision, less corruption, more public participation, more integrated policy, a stronger domestic political agenda, more energy security and economic growth. As presented by the causal loop of political leadership, good governance and public participation (Figure 3), the workshop participants highlighted how strengthened political leadership would better enable good governance, which would lead to greater public participation and further enhance political leadership on electricity supply resilience. Strengthened political leadership and the better governance that results, would improve the public's trust in the governance of electricity, therefore creating more willingness to participate in electricity schemes launched by the government. This would better enable political leaders to achieve the objectives of electricity schemes and improve resilience. Nepal adopted a decentralised governance structure with the Constitution of Nepal in 2015, which gives a stronger role to municipal/local government in electricity governance. However, workshop participants commented that the lines of responsibility across various levels of governance are unclear. In particular, participants mentioned that the implementation of local governance was ill-defined in this area. According to the causal loops identified by the participants, if the detailed role and leadership of the local government could be clearly defined, it would enable better governance of the electricity system at the local level and motivate the public to participate in the relevant electricity schemes that may support resilience.

Participants highlighted public private partnerships as an important means to increase the quality of infrastructure, to enable greater reach of the electricity grid for example. This would in turn improve reliability of electricity supply. The importance of public private partnerships highlights the nexus of the four factors – governance, technology, economic and social - for electricity supply resilience. As presented in Figure 3, increased economic position improves business interest in the country, which in turn improves financing potential (economic factors) through public private partnerships. These partnerships, in turn, have the potential to strengthen research and development, to bolster technology innovation (technology factors), which in turn can have a reinforcing effect on adoption of new technology (social factors) (Figure 3).

## 4.2 Technology factors for electricity supply resilience

The most important technological factors identified by workshop participants include infrastructure (nine causal links associated) and reliability of electricity supply (eight causal links associated). The participants discussed energy supply primarily in relation to electricity, despite participants coming from organizations spanning a diversity of sectors, electricity, but also bioenergy and solar. This is in line with previous studies showing that in spite of electricity being only one part of the energy resilience story, most of the literature and debates in relation to energy access or decentralised energy systems centre around electricity [48,49].

Participants explained that improved reliability of electricity supply would enhance energy infrastructure (Figure 3). Moreover, participants emphasised the importance of infrastructure to include systems for better information management, which would enable greater access to, and use of, data to improve knowledge management; real-time electricity supply and demand data could then be used to achieve better system reliability (Figure 3). For example, knowing which areas of the electricity system were at risk of overload, and managing the supply and demand across different parts of the electricity system to reduce the risk of overload and improve energy security. Hence, the variables 'infrastructure', 'management information system', 'access to data', 'knowledge management', and 'reliability of electricity supply' form a reinforcing causal loop (Figure 3). Improving any one of those factors will lead to improvement of the other variables along this causal loop and therefore reinforce positive impacts on electricity supply resilience in Nepal. Participants also highlighted practical factors such as clear operation and maintenance guidelines, quality of physical components and their installation, alongside the availability of spare parts for improved reliability of energy supply (Figure 3). However, while infrastructure was so central to participants' understanding of electricity supply resilience, they argued that after the 2015 earthquakes in Nepal, the reconstruction effort had focused on domestic homes, with access to electricity less of a priority. According to the causal loops identified by participants, if the reconstruction after earthquakes had focused more on the infrastructure of the electricity system, it would have improved energy security with more reliable electricity supply. This would have helped political leaders to gain more trust and participation from both the public and private sectors, and mobilised private sector investment on electricity infrastructure to achieve resilience for the future.

## 4.3 Economic factors for electricity supply resilience

The most important economic factors for achieving electricity supply resilience include business (eight causal links associated), economic growth (seven causal links associated), and smart tariffs (seven causal links associated). Workshop participants noted that without subsidies there is lack of viable business models for many renewable energy technologies in Nepal. For example, participants argued that the cost of solar is still high in the country; without subsidy, residents in remote areas face significant challenges in buying a Solar Home System (SHS) [50,51]. Whilst this could also apply to other forms of electricity such as grid supply, the workshop participants only discussed the subsidy in relation to renewable energy and SHS. Participants shared that boosting business could attract more financial investment, create more employment opportunities and contribute to economic growth, which are all important factors for achieving electricity supply resilience.

Participants also felt that economic growth in Nepal would benefit from more secure electricity access, improved electricity infrastructure and more business activities. Similar to findings from Nepal and Paija [52] on the relations between energy security and economic growth in Nepal, the workshop participants explained that economic growth will allow the building of better infrastructure to improve the status of energy security in Nepal, and in turn, enhanced energy security will further facilitate economic growth. The causal loop of 'economic growth', 'infrastructure' and 'energy security' is therefore reinforcing, with positive impacts for electricity supply resilience in Nepal. Boosted economic growth would then lead to more employment opportunities, enhance political leadership and reduce poverty in the country. This finding is highlighted elsewhere in the literature. For example, Trace [52] emphasized that more policy-related research is needed to address the high costs and risks associated with financing and incorporating clean energy sources into the electricity mix in Nepal, and to explore optimal institutional arrangements and new regulatory functions to achieve its electricity system resilience. The casual-loop map (Figure 3) highlights how boosted economic growth would reduce poverty in Nepal, and therefore improve the public's financial capacity to pay electricity bills, and in turn enable business to conduct more activities that require electricity. This would then further boost economic growth in Nepal, and have a reinforcing impact on achieving electricity supply resilience. Those causal links and feedback loops demonstrate how factors across economic, technology, governance and social factors closely interact and influence each other.

'Smart' tariffs, which vary according to time of day, season and amount of electricity consumed, were highlighted by the participants as an opportunity, because they could lead to more business activities, a more equitable energy price scheme and influence consumers' use of electricity. As presented with the causal loop between consumer behaviour and smart tariffs in Figure 3, consumer behaviour as to how they use electricity would then affect smart tariff design, creating a balancing loop for electricity supply resilience as better designed smart tariffs would help consumers shift their electricity use from peak demand times to off peak times when they can. According to participants, a better smart tariff scheme could also be achieved with more financial support and innovation. The causal loop of smart tariffs, business and finance (better smart tariffs would promote business activities, which would attract more finance, leading to more enhanced smart tariff scheme) again indicates how the improvement in one factor within the causal loop would lead to reinforcing impacts on electricity supply resilience. The links between smart tariffs, business activities and consumer behaviour also show how social barriers and consumer behaviours are influenced by economic and financial mechanisms in the country.

### 4.4 Social factors for electricity supply resilience

The most important social factors for achieving electricity supply resilience identified by participants include consumer behaviour (seven causal links associated), adopt new technology (six causal links associated) and public participation (five causal links associated).

Participants highlighted how better consumer behaviour in terms of electricity use could potentially improve personal wellbeing, and whether consumers are willing to adopt new technologies. Participants also felt that a useful mechanism for influencing consumer behaviour was smart tariffs. Participants considered one negative consumer behaviour to be energy theft, such as illegal connection of electricity at home from the national grid. Whether electricity consumers are willing to adopt new technology is not only affected by how they use electricity in daily routines (consumer behaviour), but also the diversity of available energy sources, efficiency of appliances and the outcomes of innovation (Figure 3). Participants also argued that adopting new technologies could have a negative impact on equity. For example, only high-income households could afford the high prices of new technology and benefit from it.

According to the workshop participants, public participation in electricity schemes could be enhanced with good governance, more private public partnership and more private sector investment (Figure 3). Public participation forms a vital link between social factors and governance factors for achieving electricity supply resilience, with four causal links between public participation and governance factors (Figure 3). In particular, as presented with the causal loop of public participation, political leadership and good governance in Figure 3, participants felt enhanced public participation would influence political leadership for achieving electricity supply resilience, which improves governance, and attracts more public participation, therefore creating a reinforcing impact on electricity supply resilience.

## 5 Discussion and Conclusions

Energy resilience is complex due to the multitude of factors involved. Indeed, identifying policy responses and knowing where to start for improving resilience are particularly difficult given the interlinkages between these factors. The bottom-up participatory approach adopted in this paper enabled the key stakeholders to understand and visualise the complexity of electricity supply resilience in Nepal, the key factors that may enable electricity supply resilience, and in turn helped them begin to understand the priorities for securing resilience. The approach also enabled participants to collaborate and form a shared understanding of the electricity supply resilience issues, which is important for designing solution-driven interventions for achieving electricity system resilience. The causal loop map highlights the influencing variables across governance, economic, technical and social categories, and the causal links and feedback loops within and across the categories. The map also helped participants identify how changing one variable could lead to re-enforcing impacts on electricity supply resilience, through affecting other variables across categories. For example, participants felt better public private partnership (a governance factor) would motivate more public participation (a social factor), which further enhances public private partnership (Figure 3). Participants argued that enhanced public private partnerships would also attract more finance (an economic factor) that then enables more public private partnership (Figure 3). Policy interventions for electricity supply resilience in Nepal should therefore consider all four factor categories, their interconnections with each other, and the flow between factors within and across various categories.

One striking take away from the utilisation of the participatory method is the importance placed on factors that are not sectorally specific, including political leadership, with the process highlighting the importance of governance and political willingness for electricity supply resilience. Public private partnership and private sector investment were emphasised and discussed extensively by workshop participants, indicating their importance if Nepal is to transition from government subsidy to market-based approaches for its electricity system, technologies, and projects for long-term resilience. The mapping also highlights the tensions between stakeholder perceptions and priorities on the ground. Political leadership is identified as the most important variable (i.e., with most causal links associated) by participants, in line with findings from elsewhere in the literature that recognise a close link between political economy and access to electricity [49,54,55].

Workshop participants identified the least number of variables and causal links in relation to social factors and little on environment. However, both social and environment factors could be important to achieving electricity supply resilience in Nepal in the long term. The notable omission of environmental factors from the mapping is an interesting result given the emphasis on renewable energy sources and clean technologies in electricity policy in Nepal [29,53].

Participants argued that to achieve electricity supply resilience in Nepal, municipal/local government could play a significant role in rural areas that are not covered by the national electricity grid system. Furthermore, according to the workshop participants, due to lack of investment in electricity supply resilience nationwide, to ensure more secure access to electricity services at home many households buy batteries to store at home for emergencies during power cuts. The cost of buying batteries is high and though it normally does not fully bridge the absence of grid supply, keeping batteries at home is seen as a convenient option for more secured access to electricity services and therefore individual electricity supply resilience at home. In addition, there is a lack of skills for the maintenance of the system and infrastructure, especially at a local level.

Overall, participants provided positive feedback and appreciated the group mapping exercise for understanding the broad electricity supply resilience picture utilising whole-systems thinking. Participants expressed their willingness to use this bottom-up participatory approach for other group exercises in the future as well. The group exercises at the workshop also facilitated deeper and more detailed discussions among participants on issues that affect electricity supply resilience in Nepal, as well as a better understanding of the urgent need for a more co-ordinated approach to improving electricity supply resilience.

A limitation of the causal loop approach is that it does not present changes over time. Furthermore, the map created at the workshop is inherently dependent on who the participants are, as well as the experience and knowledge of the participants (what they bring into the mapping exercise). Despite the causal loop diagram being context specific and subject to the views of the participants in the room, the systems approach and participatory causal loop mapping exercise is valuable in eliciting how certain stakeholders view interconnectedness for electricity supply resilience. The four main categories (governance, technology, economic and social factors) identified could be useful guidelines for identifying variables affecting energy resilience in other contexts.

The causal loop diagram created by the participants showed that resilience is more than infrastructure. However, the focus of post-earthquake recovery in Nepal has been on physical infrastructure, with little consideration of all the other crucial factors for electricity supply resilience identified by participants. There is therefore an urgent need to address electricity supply resilience from a whole-systems perspective to recover from and be prepared for shocks, stress, and pandemics.

This study demonstrates a systematic process to engage participants in developing whole-systems thinking and mapping for understanding energy resilience. As the approach is context dependent, it can be applied to understanding energy resilience at different scales (e.g. national, city or community) and within different areas (e.g. rural and local). This will enable comparison of participants' understanding of key challenges and elucidate priorities in terms of energy resilience. The results could also be used for designing policy interventions and strategies, and to identify gaps between the understanding of electricity supply resilience and policy strategy in Nepal. In addition to identifying factors crucial for electricity supply resilience and their linkages, this paper presents a novel methodological approach for energy research. The participatory causal loop mapping approach is a useful qualitative research method for exploring how a whole-systems approach to energy resilience might be achieved and can help build a common understanding between stakeholders.

**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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