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Combining Electricity and Ecological Resilience - Towards a New Holistic Framework

Maria Andersson[1], Louise Ödlund[1], Patrik Thollander[1]
[1]Department of Management and Engineering, Linköping University
Linköping, Sweden
maria.h.andersson@liu.se; louise.odlund@liu.se; patrik.thollander@liu.se

Abstract – The complexity of the electricity system is increasing due to various transitions and events taking place within and outside of the electricity market such as increased loads from distributed power supplies. The risk for various disturbances may increase with these transitions and events, including non-electricity system related disturbances like climate change. There is an urgent need to improve resilience of the electricity system so that it can handle also low probability and high impact disturbances. The objective of this paper is to analyse seven resilience principles, originally developed for socio-ecological systems, and interpret them for the electricity system. Results from the analysis indicate that the resilience principles can be seen to represent different categories in the socio-technical system that is the electricity system. These categories are technology, learning, information, stakeholder, organisation, and governance. The resilience principles enable a holistic view of the electricity system, and they can function as a support during the work to increase resilience of the electricity system.

***Keywords*:** energy management, electricity system, resilience, sustainability, energy transition

1. Introduction

The Swedish electricity system is undergoing major changes that can be characterized as four primary energy transitions. These are (1) the deregulation of the Swedish electricity market meaning a transition of governance from governmental to market-oriented, (2) a transition towards a green sustainable energy system, (3) a development towards increased small-scale distributed systems such as photovoltaics (PVs), and finally (4) the ongoing electrification of the vehicle fleet and industrial processes. These four primary energy transitions increase the complexity of the electricity system among other things because of an increasing number of stakeholders that can influence the electricity market and an increased share of variable electricity production. It is therefore important to increase the resilience of the electricity system, so that it can cope with all kinds of disturbances including those that can be characterized as low probability and high impact disturbances. For example, the Swedish electricity system suffered an asymmetric chock in the autumn 2022, which resulted in sharply increased electricity prices [1]. In 2005, the storm "Gudrun" hit the south of Sweden and caused power outages for close to half a million people [2]. This storm led to an extensive reconstruction of regional and local electricity networks to make the electricity system more resilient to future storms.

In this paper, a set of seven resilience principles considered crucial for building resilience in social-ecological systems [3] will be used to analyse the resilience of the electricity system. Just as an ecological system can be described as a linked system of people and nature, an electricity system can be described as a linked system of people and technology (both hardware and software) related to the electricity system. Energy systems like the electricity system can therefore be regarded as a socio-technical system as formerly argued by for example [4]. That is one of the reasons why it is of crucial importance to study the seven resilience principles of the electricity system. The paper is organized as follows. Section 2 describes the electricity system with focus on the Swedish electricity system. Section 3 presents some suggested definitions of electricity resilience and ecological resilience that can be found in the literature. Section 4 describes how the resilience principles can be interpreted for the electricity system. Finally, section 5 draws some conclusion and suggests future work.

2. The Electricity System

The electricity system generally consists of the following physical parts, supply (electricity production), transmission, distribution, and demand (final end-use). Regarding the supply, since 2004 [5] all EU member states including Sweden were enforced to have a deregulated electricity market. This meant a change of governance from state-governance to market-governance. Today, a final end-user can buy electricity from any market actor.

The transmission system transfers large amounts of electrical energy over longer distances, that is, from electricity production (which largely takes place in the north of Sweden) to electricity use in the different regions of Sweden. The transmission system is owned by the Swedish state and overseen by the Swedish TSO (transmission system operator) [6] including export and import. The distribution system is divided into regional and local distribution systems. The distribution system operators (DSOs) are responsible for the regional and local distribution systems. If an increase in load is desired, it is the DSO in charge of the corresponding distribution system that handles that. Recent development has led the TSO and the DSOs to also reinforce with flexibility solutions. All end-users currently pay two bills, one for the supply of electricity (market deregulated) and one to the DSO for the corresponding distribution system (monopoly). The price setting is overseen by the Swedish energy markets inspectorate [7].

3. Electricity and Ecological Resilience

3.1. Electricity Resilience

There is a great interest today in researching how to enhance resilience of electricity systems. So far, there has been difficulties finding common and agreed upon definitions of the term resilience for electricity systems, even though there are many definitions suggested. For example, electricity system resilience can be explained as composed by stability, reliability, redundancy, response, and recovery [8]. International Energy Agency (IEA) defines resilience of an electricity system as having the ability to anticipate, absorb, accommodate, and recover from serious climate impacts [9]. A wider perspective is taken by [10], who means that resilience should also mean to limit the consequences that come from the disruptions and power outages, and to learn from earlier incidents to better deal with future ones.

3.2. Ecological resilience

The concept of resilience comes originally from psychology and is about the ability of individuals to withstand difficult events. The concept was then applied to the ability of the ecological system to withstand severe events [11]. Stockholm resilience centre further developed the concept for a socio-ecological system and describes resilience as the ability of a system to handle changes and at the same time be able to continue to develop. Here we can see another aspect, that is, the system should be able to develop despite ongoing disturbances. This means that the system does not have to return to the earlier equilibrium state but may have reached a new equilibrium state. The resilience of the socio-ecological system was further developed to seven resilience principles [3], which can be seen in Table 1. Compared to the definitions of resilience for electricity systems, mentioned in section 3.1, the resilience principles clearly encompass some new and novel perspectives. These are suggested to include technology, information, learning, stakeholder, organisation, and governance. The perspectives are needed to obtain and enhance our understanding of the electricity system and be able to come up with a new definition for resilience. The resilience principles enable a holistic view of the electricity system and can very well facilitate the work of resilience enhancement.

Table 1: The seven resilience principles according to reference [3].

No.	Resilience principle
1	Maintain diversity and redundancy
2	Manage connectivity
3	Manage slow variables and feedback
4	Foster complex adaptive systems thinking
5	Encourage learning
6	Broaden participation
7	Promote polycentric governance systems

4. Results and discussion

This section presents results from the analysis of the resilience principles [3] for the electricity system. Reference [12] has earlier analysed the resilience principles for an energy system in general and developed a method for how to perform a resilience analysis. This paper differs from [12] in that we interpret the principles specifically for the electricity system.

4.1. Maintain diversity and redundancy

Diversity can be obtained with different types of electricity production plants, battery storage and flexibility services. In the literature, there are several examples of strategies and methods for using these types in an optimal way, see for example [13]. Redundancy can be obtained by reserve capacity in the electricity system. Reserve capacity is used above all in the occurrence of unexpected faults or disturbances. Energy storage systems can provide this service too.

Diversity and redundancy also apply to the social part of the socio-technical system, that is, they could relate to key personnel with specific knowledge and experience of the electricity system, for example including a diversity of various knowledge demands such as practical knowledge and scientific knowledge. From an information technology perspective, diversity and redundancy can mean cyber security for computer networks that control different parts of the electricity system.

4.2. Manage connectivity

Connectivity can be both advantageous and disadvantageous. Connections between devices and systems can facilitate recovery after disturbances, but they can also spread disturbances. Microgrids are suggested by many as a solution for increased resilience, see for example [8]. Microgrids can disconnect from the main grid in case of disturbances and operate in island mode, and then they can gradually return to normal connections when the problem is taken care of. During the Texas freeze in February 2021 [14] several million people lost power for an extended period. The power outage had a cascading effect on services connected to the electricity system, for example the drinking water treatment and medical services. One of the suggestions for increasing resilience of the electricity system of Texas was to increase connectivity through an expansion of interstate connections [14]. On the contrary as was seen in the energy crisis that hit Europe in 2022, a high connectivity in a deregulated common European electricity market also means risk of disturbances [15].

As the electricity system becomes more digitalized, connectivity is also increased by data networks used to managing the electricity systems at different levels. Increased cyber security is therefore very important for hindering computer disturbances to spread in the data network of the electricity system.

4.3. Manage slow variables and feedbacks

Slowly changing variables may change a system over time. The change can be abrupt when a certain threshold is passed. In an ecological system, a threshold could represent a certain level in the groundwater and if this threshold is exceeded, there will be effects on other parts of the ecosystem [3]. To manage slow variables and feedbacks, critical variables related to the electricity system need to be identified and monitored. One such slow variable is the pressure on the distribution system because of the increased electrification and the increased distributed power supply. Expansion of a distribution systems is a process that is inherently slow and that takes several years. Resilience functions (or metrics) could be used for monitoring slow variables. Several resilience functions have been reported in the literature, for example by [8] and [16]. Examples of resilience functions could be loss of load probability (LOLP) and expected demand not supplied (EDNS) [8].

Slow variables do not necessarily have to be related to technical systems. Slow variables can as well reflect the sociological part of the electricity system. Such variables could be the change in people's attitudes in different aspects of the electricity system. Or people's change in political opinions. A threshold in that case could be a sufficiently large change of political opinions that leads to a new government with a different political strategy for the electricity system, for example the fostering of small modular reactors (SMRs).

4.4. Foster complex adaptive systems thinking

During the energy transitions, the electricity system or systems are becoming increasingly complex and dynamic. Increased complexity will lead to increased uncertainties that have to be taken care of in the decision-making process. A way for coping with that is to increase the use of decision-support systems that can improve the handling of uncertainties for different scenarios. Another way is to increase the use of forecasting models for wind, solar and hydro-based electricity production. In general, it is important to increase forecasting of the electricity system to understand its complexity in all its parts: production, transmission, distribution, and end-use. Increased data collection and the use of machine learning for the electricity system [17] could contribute to improved management of the complex system.

In general, an important part to foster complex adaptive systems thinking is to view the electricity system both from an operational and a strategic long-term perspective. In doing so, one thing that emerges is that for the three downstream physical parts of the electricity system, resilience and governance functions are present on both operation and strategic levels. However, for the production of electricity, the strategic part seems lacking. This is because a deregulated market means that new power production is built based on market demands. Secondly, and though naturally, there is also a governing authority lacking on where to expand new power production, since this is also something the market should take care of autonomously.

4.5. Encourage learning

Learning can be obtained through experience and knowledge exchange between people and between organisations as well as through mathematical modelling. Historical events such as the freeze in Texas 2021 [14] and the Swedish storm in 2005 [2] gave ideas on how the electricity system should become more resilient to withstand future similar disturbances. From the Texas freeze, a conclusion was that weatherization, demand response and increased connectivity (see section 4.2) should reduce the risk for severe negative impacts if there was a new freeze [14].

Learning about the electricity system can also be done by data analysis, simulation models, machine learning and by using digital twins [18]. A digital twin uses sensor data from the physical world for continuous analysis. The analysis can advantageously be carried out with machine learning models, as the amount of collected sensor data for the digital twin will be large over time. With a digital twin, continuous learning of a system could be achieved.

4.6. Broaden participation

During the transitions of the electricity system, new actors have entered the Swedish electricity market. Examples are actors on the European electricity market, individual end-users, and energy communities. The European electricity market influences the Swedish electricity market, among other things, via increased demand from end-users outside of Sweden, or as in the case of the European energy crisis 2022, reduced power supplies, leading to increased electricity prices in Sweden. The increased digitalization, with two-way communication of electricity and information, enables individual end-users to act on the electricity market. End-users can for example act by changing electricity use behaviour according to price signals. End-users can turn into prosumers by producing electricity from wind or solar-based plants and sell power that is not consumed to the grid operator. An energy community is a network of nearby electricity end-users. The energy community enables citizens, municipalities, and SMEs (small and medium-sized enterprises) to become more involved in the energy sector and contribute to the transition of the energy system in different ways. For example, by own renewable electricity production, electricity sharing and electricity storing [19].

4.7. Promote polycentric governance systems

The transitioning electricity system will likely need changes in the way it is controlled. Laws and regulations may need to be further developed to adapt to new actors on the electricity market, such as energy communities. Changed laws and regulations may in the long run lead to a more polycentric governance of the electricity system.

4.8. Summary of the interpretation of the resilience principles for the electricity system

Table 2 presents a summary of the interpretation of the seven resilience principles in sections 4.1 to 4.7 for the electricity system. Each of the resilience principles has been suggested one or more categories (or perspectives) that can be related to the electricity system and its management. The categories are technology, information, learning, stakeholder, organisation, and governance. The last column of Table 2 presents some comments on how the resilience principles could be further interpretated specifically for the electricity system.

Table 2: Summary of the interpretation of the seven resilience principles to the electricity system.

No.	Resilience principle	Corresponding categories in the electricity system	Comments
1	Maintain diversity and redundancy	Technology and organisation	No. 1 can be seen as the more traditional approaches to improve resilience. Can also apply to the social part of the electricity system. For example, personnel can be described in terms of diversity and redundancy.
2	Manage connectivity	Technology	No. 2 can also be seen as the more traditional approaches to improve resilience, for example by strengthening infrastructure related to the electricity system. Can apply to data networks, software and cyber security related to the electricity system.
3	Manage slow variables and feedbacks	Information and learning	No. 3 can apply to the social part of the electricity system. Slow variables can represent changes in attitudes and political opinions that in the long term may change the electricity system.
4	Foster complex adaptive systems thinking	Information and learning	No. 4 can profit from handling uncertainties with decision-support systems including also forecasting models for wind, solar and hydro-based electricity production. Should include an operational perspective as well as a strategic long-term perspective.
5	Encourage learning	Information and learning	No. 5 can involve learning at different levels, for example learning by experience and knowledge exchange between people and organisations, by data analysis, machine learning and by digital twins.
6	Broaden participation	Stakeholder, organisation, and governance	No. 6 can involve big and smaller actors, for example big actors on the European electricity market, or smaller actors like energy communities or even specific end-users.
7	Promote polycentric governance systems	Stakeholder, organisation, and governance	No. 7 can be a result of changes in rules and laws to adapt to the new electricity system and its new actors. This may develop the electricity system to become more polycentric in its governance.

5. Conclusion and future work

The resilience principles provide a broad overview of the conditions for a resilient electricity system. All resilience principles can be considered fully applicable to all areas of the physical electricity system, that is, production, transmission, distribution, and end-use, including how the physical parts are being governed.

Maintain diversity and redundancy and *manage connectivity* could be described as more traditional approaches to creating improved resilience. *Manage slow variables and feedbacks*, *foster complex adaptive systems thinking* and *encourage learning* can be related to information and learning. Here, digitalization will have a big role since it facilitates data collection and learning from all parts of the electricity system using statistics and machine learning tools. *Broaden participation* and *promote polycentric governance systems* can be related to stakeholder, organisation, and governance, that is, how people work together and are organized for managing the electricity system.

This paper describes initial results from a unique novel approach of viewing the electricity system from the seven resilience principles for ecological systems. In future work, it is suggested to deepen the analysis of the literature on electricity system resilience in comparison with the resilience principles. It is also encouraged to embrace social science methods, including stakeholder dialogues with actors in the electricity market. In this way, we can enhance our understanding of what the stakeholder views are of how to enhance the electricity system resilience.

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