Contribution of Diversity to the Resilience of Energy Systems – A literature review

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The concept of resilience has attracted an increasing attention of the research community in different fields within the last decades. In our understanding, resilience is a (socio-technical) system's ability to maintain its services under stress and in turbulent conditions. We state that certain design principles and system elements, e.g. 'diversity' contribute more strongly to a resilient system design than others. For this review, more than 40 publications regarding the resilience enhancing capabilities of diversity in energy systems, were analyzed using the following research questions: 1) Which components of an energy system need to be diversified in order to increase its resilience? 2) How can these components be diversified and to what degree is that favorable? 3) To what extent does diversification contribute to preparing the system against unknown threats?

The literature review showed that there is an agreement about which elements should be prioritized when diversifying energy systems, e.g. generation, fuel supply. Also diversity is already known to the community from reliability engineering of energy systems. On the other question, as to what degree of diversity is favorable; no consensus and no concrete design instructions were found. Hence, we conclude that, it remains an open research question to find the proper degree of diversity for energy systems and socio-technical systems, and to explain how it contributes to overcoming unknown threats.

Keywords: diversity, resilience, guiding principle, ecosystems, socio-technical system, energy system, literature review, design principles

1. Introduction

It is widely accepted that energy systems are socio-technical systems. In the last years, energy systems have experienced a radical transition towards a more decentralized structure using renewable and distributed generators. The digitalization of the systems and the growing interconnectedness of users and technologies further increase the complexity of energy systems. The rate of diffusion of these innovations in the market have never been so fast and are still speeding up. These innovations might change the system in a disruptive way. While in the 70's it took several decades to reach a distribution of 1 billion color TV-sets, the distribution of 1 billion smart phones took less than 14 years (Lee and Lee 2014). In this fast changing environment, uncertainties and ignorance are also growing as opposing challenges and have to be seen as part of the transition that cannot be omitted. Hence there is a growing need for reliability and stability in energy systems and this calls for a precautionary system design. Among the different strategies to counteract these challenges, the concept and approach of resilience is growing in popularity. It might be the "key strategy for navigating the future" (Steffen et al. 2018).

1.1. Resilience as guiding concept

Currently, multiple definitions and understanding of the resilience concept in energy systems have been proposed (Jesse, Heinrichs, and Kuckshinrichs 2019).

We propose the use of resilience as "a guiding concept" and define resilience as a (socio-technical) system's ability to maintain its services under stress and in turbulent conditions (Goessling-Reisemann and Thier 2019) based on (Gleich et al. 2010). In this context, turbulent conditions are understood as dynamic changes, irregular conditions, limited predictability or surprises.

Building or creating a resilient system is not a static activity but needs continuous adapting and learning of the system. Resilience Management proposes a process on how to build resilience in socio-technical systems (Goessling-Reisemann and Thier 2019). This process consists of a cycle with four phases: (1) Prepare and prevent, (2) Implement robust and precautionary design, (3)

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Manage and recover from crises, and (4) Learn for the future.

This paper focuses on phase (2) and especially on the proposed resilient enhancing design principle: "diversity" that is part of a robust and precautionary design of the system.

1.2. Diversity as a resilience design principle

Among the resilience design principles, e.g. diversity, redundancy, modularity, subsidiarity, buffer storages, resources, geographical dispersion, etc, 'diversity' is most known to contribute to security of systems. It is often mentioned in combination with 'redundancy'. The common understanding of system diversity is the degree of variation, disparity and balance in a system or the degree to which several different functions can be used at the same time (Andy Stirling 2010; Kharrazi et al. 2015; Sharifi and Yamagata 2016). A system with a high degree of diversity is considered to be "more flexible in its options when faced with a disruption" (Kharrazi et al. 2015) and consequently a resilient world "would promote and sustain diversity in all forms (biological, landscape, social, and economic)" (Beatley 2009; Walker and Salt 2006).

It is a tradition in engineering science to use diversity as a strategy to raise the security of supply and the adaptive capacity (Norberg and Cumming 2008; Roege et al. 2014). The idea behind the tradition is that having not only redundant structures and elements, but ones that can be distinguished in terms of diversity, e.g. components from different manufactures', usage of different protocols for the control of devices, usage of different construction devices (functional diversity), contributes to overall system properties (Baumgärtner 2006; Erker, Stangl, and Stoeglehner 2017; Godschalk 2003), regardless of the lower level of efficiency in terms of cost (Barakoti et al. 2019). The report NUREG/CR-6303 defines six attributes of diversity: design diversity, equipment diversity, functional diversity, human diversity, signal diversity, and software diversity as found in best practice implementations of diversity strategies in international nuclear power industry and several non-nuclear industries, e.g. aerospace (space shuttle), aviation, chemical process, rail transportation (Wood et al. 2010).

The idea is that the diversified elements react differently to disruptions thereby increasing the probability of continuity in the system functions (Fath, Dean, and Katzmair 2015). In Biology, the diversity of species has a similar effect. Diversity of an ecosystem is also called bio-diversity, it can be the variety of species in an ecosystem or the genetic diversity within a species (Hummel et al. 2018). Also, response diversity and functional diversity can be differentiated for ecosystems (Biggs et al. 2012; Carpenter et al. 2012; Magurran 2013). By studying the behavior of ecosystems, it has been observed that ecosystems with a high diversity rate are more likely to contain species that can survive and even flourish during environmental hazards than ecosystems with low diversity (Tilman and Downing 1994). This is because diversity causes an ecosystem to contain or accommodate many species which respond differently to threats (Capra and Luisi 2014; Tilman and Downing 1994). For socio-technical systems it has been found that diversity can be broken down to: variety, balance and disparity (Andy Stirling 2010).

In terms of quantification of diversity popular indices are the Shannon-Wiener Index, the Gini Index and Stirling-Index (Shannon and Weaver 1963; Gini, Corrado 1912; Andy Stirling 2007). Other diversity indices are mentioned in (Pielou 1966; Solow and Polasky 1994; Kruyt et al. 2009; Kharrazi et al. 2015; Ranjan and Hughes 2014; Kharbach 2016).

With regard to the mode of action of diversity there is a saying that states: "No matter how great the resources, nor how complete the knowledge, nor how sophisticated the decision making process, only fools put all their eggs in one basket." (Andrew Stirling 1994). Using this argument common in investment theory seems logical and comprehensible, especially when there is a direct relation between the diversifying objects and a possible loss. However, looking at energy systems reveals a different picture. In energy systems, multiple energy sources are used and coordinated to guarantee security of supply. Responsible for an undisturbed conduction of electricity is the operability and good functionality of a multitude of components, cables and control centers thereby making the energy system an interconnected complex system. A direct relationship between the diversification level of specific components and the prevented loss can to our knowledge not be found on a system level. The reason for that lies in the interdependencies and interconnections between different system components. The picture changes, when looking just at one object, that should be supplied with power. Diversifying the direct supply and related energy sources for it, e.g. by supplying the specific object through different lines and sources, e.g. PV, a generator, a battery stack, increases the reliability of the object. In this case the beneficial aspect of diversification is obvious, if one line fails another source can fill in, e.g. a generator or battery stack.

At the same time several authors point at problems with the design principle of diversity e.g. (Bazilian and Roques 2008) calling the concept of diversity applied to energy systems ill-defined, because it remains unclear what should be diversified, nor is it straightforward to quantify the costs and benefits of increased diversity. Similar questions had been raised by (Stirling 1994). He made a nice analysis on ignorance and developed an analytical approach to diversity, but does not answer questions about the parametrization of diversity in resilience science. This paper summarizes the current knowledge of diversity in energy systems. It focuses on finding justified arguments in literature regarding the resilience enhancing properties of diversity, as well as concrete design instructions.

2. Methods

The analysis has been done studying primarily the most cited publications regarding the resilience enhancing capabilities of diversity for energy systems. Table 1 gives an overview of the search engines and keywords used for finding the appropriate literature. Furthermore, references mentioned by the respective authors on the subject of diversity were reviewed. This adds to a total number of 104 examined papers, articles, books and book chapters.

Table 1. Overview of the used search engines and Keywords for the literature research.

Search engines	Keywords
Google scholar	Diversity socio technical system, Diversity energy system resilience, Energy resilience, Diversity energy system,
Science direct	Resilience diversity energy system, Diversity energy resilience,

In a second step the search was refined having in mind the motivation for this research, which is to identify justifications and reasons why diversity enhances the resilience of systems. As part of this process, for most of the publication it was found that their content did not exactly correspond to the topic in question. In this case these publications were not analyzed in depth, but omitted. The same was done with the publications where their topic matched our research questions, but reading the articles carefully, they were not found to be helpful in terms of answering our research questions.
At the end of the refining process, 27 publications were chosen. These publications are the basis of the presented analysis and will be referenced in the following sections. Table 2 shows the considered literature, categorized by their subject and intention.

Table 2. Categorization of the literature considered in the review with regard to 1) "existing concepts", 2) "new concepts" and 3) "analysis of system properties". Authors own compilation

Category	Publications
1) Discussion, evaluation and / or extension of existing resilience-related action concepts / approaches to system development / operationalization methods	Stirling 1994, Baumgärtner 2006, O'Brien et al. 2010, Gonzalès and Parrott 2012, Roege et al. 2014, Biggs et al. 2015, Kharbach 2016, Lin and Bie 2016, Molyneaux et al. 2016, Erker 2017
2) Review of earlier work in the field of resilience (and proposal of a new framework / model / conceptualization)	Folke et al. 2002, Godschalk 2003, Stirling (2007, 2010), Biggs et al. 2012, Baek et al. 2015, Fath et al. 2015, Sharifi and Yamagata 2016, Erker et al. 2017, Binder et al. 2017, Steffen et al. 2018, Jesse et al. 2019
3) Modelling or Evaluation of data to specify properties of systems / resilience development	Grubb et al. 2006, Kharrazi et al. 2015, Nahmmacher et al. 2016, Chalvatzis and Ioannidis 2017, Fraser 2019

Regarding the methodology used to extract the content from the chosen literature, no specific format was followed. This was done manually and is subjective to the author. However, guidance for the extraction of the content was given by the research questions, which are:

1) Which components of an energy system need to be diversified in order to increase its resilience?
2) How can these components be diversified and to what degree is that favorable?
3) To what extent does diversification contribute to prepare the system against unknown threats?

We looked closely at all the references having these questions in mind. The papers were read several times and passages related to the research questions marked. The result section of this paper is a summary of the most fitting and representative quotes found in the papers.

3. Results

Diversity has been used for many centuries as a principle to protect systems in the face of ignorance. In multiple sectors and branches, diversification plays an important role, e.g. in the financial sector, aviation, critical infrastructure. Examples were also found in the reviewed resilient energy systems literature. Most of the authors introduce diversity as a resilience enhancing principle and claim that it is crucial for the energy system and its resilience (Erker, Stangl, and Stoeglehner 2017). Diversity contributes to provide resilience in the face of ignorance and surprises and gives insurance to cope with uncertainty (Andy Stirling 2007; Folke et al. 2002). Its incorporation in a system might ensure adaptability, transformability and a higher quality of planning processes (Stoeglehner et al. 2016).

Lovins and Lovins state in Brittle Power that failures do not propagate, and can be repaired from areas that are still functioning if a system has many differing components that vary from one place to another (Lovins and Lovins 1982).

Moreover, according to Stirling, increasing the variety of options in a portfolio, enhancing their mutual disparity or maximizing the balance in their proportional contributions all offer ways to directly hedge against ignorance and surprise (Andy Stirling 2006).

According to Biggs, it is pure evidence, that diversity is attributed to increase the robustness and reliability of the system (Biggs, Schluter, and Schoon 2015). Some Authors just state that diversity, often in combination with redundancy, is important for resilience without detailed specifications (Baek, Meroni, and Manzini 2015). One argument used is that if you have more (spare) plants, in case of disasters that take plants out, remaining plants can provide power to homes and businesses as soon as power lines are restored (Fraser 2019). (Sharifi and Yamagata 2016) explained it like this: “Diversification of energy supply and infrastructure is one of the most important measures to enhance energy resilience. This is to ensure continuity of supply in case supply of one energy source is disrupted.”

And generally, the more components filling similar functions in the system, the higher are the chances that these components will have different responses to disturbance (Gonzalès and Parrott 2012).

3.1. Which components of an energy system need to be diversified in order to increase its resilience?

In general, it is seen that it is better to diversify more than less elements, in particular if the objects are sources of ignorance in energy policy. Reducing the diversification to just some components or a single criterion imposes boundaries and reduces its breath with the consequence of impairing the usefulness of the concept (Andrew Stirling 1994).

There is agreement in the reviewed literature on a number of components which need to be diversified. These include the energy generation, in particular; the sources of energy and the resource use, the technologies employed (Andrew Stirling 1994; Grubb, Butler, and Twomey 2006; Andy Stirling 2007; Bazilian and Roques 2008; Binder, Mühlemeier, and Wyss 2017; Molyneaux et al. 2016), the energy supply in terms of the supplier states or companies, the regions of origin and the energy imports (Andrew Stirling 1994; Andy Stirling 2010; Molyneaux et al. 2016; Sharifi and Yamagata 2016; Lin and Bie 2016) and other infrastructural aspects such as the regulatory and institutional frameworks (Andrew Stirling 1994; Andy Stirling 2010; Sharifi and Yamagata 2016).

In terms of renewable energies (Stoeglehner et al. 2016) point out, that “disposing off the biggest pool of available land in rural areas can make the largest contribution to diversified energy generation. (O’Brien and Hope 2010) particularly suggest to use decentralized renewable energy technologies, smart metering, and a participatory approach to stakeholder engagement during competitive dialogue.

Diversity of energy imports and fuel suppliers have also become important after the oil boycott experiences in the 70s (Kharrazi et al. 2015; Molyneaux et al. 2016). Furthermore, some authors present more detailed approaches for a resilient system. According to (Sharifi and Yamagata 2016), energy systems should also be diverse in terms of land use patterns, knowledge, economy and demographic structures.

(Andrew Stirling 1994; Andy Stirling 2010) points out that even the regional distribution of major energy facilities, the scale of these facilities, the socio-political communities (such as unions) involved in different energy production chains, mitigation strategies, transport routes, facility operators and infrastructure dispositions, equipment vendors and component manufacturers, labour unions and professional associations and various kinds of environmental, health or social effects could be worthy objects of diversification, as they are “sources of ignorance in energy policy”.

Other options for diversification are actors and operators (e.g. plant operators) (Andy Stirling 2007; Bazilian and Roques 2008), power lines (Fraser 2019) and reactor shutdown devices (Lovins and Lovins 1982). (Molyneaux et al. 2016) state: The consumption structures should be versatile in order to avoid peaks in consumption (e.g. due to a mix of working and residential locations) and a broad spectrum of energy sources and technologies should be enforced.”

Table 3. gives an overview of the gathered suggestions by several authors on the question: which energy system components should be diversified.

Table 3. Overview of the components to be diversified suggested by the authors of the revised literature.

Category	Component	Reference
energy generation	sources of energy	Lovins 1977, Grubb et al. 2006, Stirling 2007, Bazilian and Roques 2008, Kharrazi et al. 2015, Molyneaux et al. 2016, Sharifi and Yamagata 2016, Stoeglehner et al. 2016
	the resource use / land use patterns	Stirling 1994, O'Brien and Hope 2010, Kharrazi et al. 2015, Molyneaux et al. 2016, Sharifi and Yamagata 2016
	Technologies and facilities	Stirling 1994, Grubb et al. 2006, Stirling 2007, Bazilian and Roques 2008, Binder et al. 2017, Molyneaux et al. 2016
	reactor shut-down devices	Lovins and Lovins 1982
energy supply	Supply states or companies	Stirling 1994, Molyneaux et al. 2016, Sharifi and Yamagata 2016, Lin and Bie 2017
	regions of origin	Stirling (1994, 2010), Molyneaux et al. 2016, Sharifi and Yamagata 2016, Lin and Bie 2017
	import countries	Stirling 1994, Kharrazi et al. 2015, Molyneaux et al. 2016, Sharifi and Yamagata 2016, Lin and Bie 2017
	power lines	Fraser 2019
Institutional frameworks	regulators	Stirling (1994, 2010), Sharifi and Yamagata 2016
social and economic aspects	consumption structure	Molyneaux et al. 2016
	actors	Stirling 2007, Bazilian and Roques 2008

3.2. How can these components be diversified and to what degree is that favorable?

Most authors of the literature reviewed agreed that there is no known way how to measure what degree of diversity in a system achieves the best results. On the question of how the components should be diversified, Stirling suggests to take into account variety, balance and disparity. Stirling further proposes to not limit the diversification level to certain components. On the other hand (Konstantinos et al. 2017) write: "There is no absolute guidance over the appropriate fuel mix diversity[…]." "The fact that there are no particular thresholds providing a clear benchmarking direction has been previously identified as a general weakness of diversity indices, which are beyond doubt useful for comparative purposes." (Bazilian and Roques 2008) concluded that "Importantly, it remains unclear as to exactly what should be diversified, and how much diversity is optimal. Because the generation mix diversity is a multi-faceted issue, it is difficult to quantify the costs and benefits associated with greater fuel mix diversity." In contrast Binder states the higher the diversification level the better for the resilience (Binder, Mühlemeier, and Wyss 2017). Also (Lovins and Lovins 1982) plead for "many small, simple things" meaning the increase in diversity from small renewable plants but both authors stay vague with their positions.

3.3. To what extent does diversification contribute to prepare the system against unknown threats?

It seems that the most difficult question to answer is how diversity helps against unknown threats. Of course there is no direct proof, but Stirling argues that "diversity provides greater strength in guarding against unforeseen events". It does this by 'reducing the potential impact of interruptions in any single source and by providing additional options for its replacement'. In short, the maintenance of diversity is widely seen to confer 'resilience' in the face of ignorance" (Andrew Stirling 1994).

Even though most of the authors agree that diversity contributes positively to the resilience of the system, several authors question if diversity really helps in increasing the systems resilience.

(Bazilian and Roques 2008) state: "In short, diversity helps to manage the risks that are associated with individual energy technologies or sources, but diversity is not a necessary characteristic of a secure system." They continue giving examples of energy systems, e.g. the French electricity system, the old UK coal-based system, that were not diverse, but up to date very secure. Even though they discuss vulnerabilities arising from relying on one type of fuel, one technology and a small number of related designs or the exposure to trade unions, in the UK case.

There is less evidence of negative effects of high diversity or redundancy in the ecological domain. However, antagonistic interactions between species have been shown to be detrimental to aspects of system functioning at high diversity in bacterial communities (Becker et al. 2012). Greater diversity and redundancy may therefore not always increase ecosystem-service resilience (Biggs, Schluter, and Schoon 2015).

(Nahmmacher et al. 2016) modelled future power systems which follow strategies based upon common energy security indicators such as diversity, self-sufficiency, redundancy, flexibility and interconnectivity. The striking outcome is that even though diversification is claimed to be the most popular strategy against an unknown future, the diversity strategy is found not to be effective in improving the system's robustness, when dealing with known threats.

4. Conclusions and Outlook

'Diversity' is an important design principle in risk management approaches in order to raise reliability and security in complex systems (Wood et al. 2010). Also in many resilience approaches diversity is regarded as valuable and resilience enhancing. This paper summarizes the current knowledge of diversity of energy systems focusing on finding justified arguments in literature regarding the resilience enhancing properties of diversity, as well as concrete design instructions. In our research we asked how diversity can be characterized, quantified and what degree of diversity is favorable for the resilience of systems. About 27 publications (papers, articles, books and book chapters) have been considered useful in order to answer our research questions and were reviewed.

The review showed that there is an agreement about some elements that should be prioritized when diversifying energy systems, e.g. generation, supply sources. On the question of what degree of diversity is favorable, there is no consensus. Ecosystems are often used as a reference for the effectiveness of diversity and some examples were found. However, it is reasonable to question whether this knowledge can successfully be transferred without adaptations to energy systems, as is done in (Lietaer et al. 2010). We also found that the implementation of diversity in the European power system model LIMES-EU did not have an effect on the robustness of the system (Nahmmacher et al. 2016).

Therefore even though resilience enhancing properties have been investigated in depth in the last years, and diversity seems to be a promising resilience design principle, the resilience enhancing capabilities of diversity stays fuzzy. The answers offered by the resilience literature are not satisfying. They do not help us fulfil the task in guiding the implementation of diversity when designing resilient systems. For specific unwanted incidents, risk management has developed recommendations for the implementation of diversity in systems but regarding resilience management approaches, we conclude that it is still an open research question to find the right level of diversity for energy systems or in general socio-technical systems, and to explain how it contributes to, and enhances their resilience.

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