

Review

Resilience Thinking as an Interdisciplinary Guiding Principle for Energy System Transitions

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Abstract: Resource usage and environmental consequences of most current energy systems exceed planetary boundaries. The transition to sustainable energy systems is accompanied by a multitude of research methods, as energy systems are complex structures of technical, economical, social and ecological interactions. The description of different discipline's perspectives in this paper show that a more mutual understanding between disciplines of their respective focus is necessary as they partly create internally competitive views arising from differing emphasis of connected matters. The purpose of this paper is to present a framework for interdisciplinary proceeding in a complex energy system transition process. Resilience thinking is chosen as a core concept for a more holistic view on sustainable energy system development. It is shown that it is already widely used in different disciplines connected to energy system research and is especially suitable due to its wide application across disciplines. The seven principles of resilience thinking (maintain redundancy and diversity, manage connectivity, manage slow variables and feedback, foster complex adaptive systems thinking, encourage learning, broaden participation, and promote polycentric governance systems) are chosen as the basis for a procedure that can be utilized to increase the interdisciplinary perspectives of energy system transitions. For energy transition processes based on scenario development, backcasting and pathway definition, resilience thinking principles are used to assess the resilience of the target energy system, the pathway resilience and the design of the scenario process with respect to the probability of a resilient outcome. The described procedure consisting of questions and parameters can be applied as a first attempt for a resilience assessment of energy transition processes. The perspective of resilience in sustainable energy systems strengthens the importance of diversity, redundancy and flexibility, which reduces the current dominant focus on efficiency of the overall system.

Keywords: energy system; resilience; resilience thinking; sustainability; diversity; optimization; planetary boundaries; interdisciplinary; energy transformation

1. Introduction

The Paris agreement emphasized the need to transform our energy systems [1]. Current price developments of fossil fuels show that resource price signals do not drive this change. Whereas there is a strong focus on low-carbon solutions, there are other aspects of sustainability, such as the need for switching to systems that provide energy services without depleting resources and disturbing the interaction with social-ecological systems. Among policy fields with externalities, energy has an outstanding position due to its vertical and horizontal complexity, entailed costs and strong path dependency [2].

Scientific disciplines offer a multitude of perspectives and methods for researching on energy systems. Technical feasibility and further development of renewable energy, storage and grid

technology are part of the engineering discipline. Economical considerations discuss the most economic low-carbon pathway. Effects of providing energy services that are not covered by the generation costs are expressed in external costs. Social science related disciplines provide methods, concepts and theories that focus on the interrelations of society and technology, innovation and governance. Despite the strong interconnectedness of energy systems and society, social sciences are rather underrepresented in contemporary energy research [3]. As macro-economy as such an open subsystem of the finite natural ecosystem is [4,5], and the same holds true for the energy system, there are multitudes of environmental and ecological questions arising. They are discussed in different scales of perspectives, from local ecosystem disturbances up to global impacts.

Due to the complexity of energy systems, models are utilized to assess technically possible pathways and model-based research is widely used for policy advice [6]. The model approach usually inherits a mathematical-economic perspective coming from an engineering viewpoint. Jefferson [7] argues that looking at the numbers could lead to overlooking factors such as behavioural change, potential risks and externalities that are not as straightforward to quantify. Similarly, Pfenninger et al. [8] point out the danger of treating numbers from models more authoritative than results coming from qualitative studies and recommend strengthening the integration of methods from other disciplines.

According to Craig, et al. [9], looking at past efforts to predict future energy outcomes, long-term energy forecasts underestimate uncertainties. Along with a growing trend of modeling 100% renewable energy, thus long-term sustainable transition scenarios [10], uncertainty plays an important role in discussions about shortcomings of modeling [11–13].

The focus from the techno-economic modeling perspective is limited to environmental consequences we are able to quantify today. A fast, major reduction in greenhouse gases is required, but applying similar methods that have led to the climate problem for planning of future energy systems bears the danger of quickly reaching the next ecological limit. This also holds true for renewable energy systems. Although having less greenhouse gas emissions, they are embedded in social-ecological systems in which interrelations have to be carefully looked at.

Energy systems, no matter if low-carbon or not, are never just of technical or economical nature, but they are always in interaction with a natural and social environment. Different aspects of energy systems and their transitions are often looked at in distinct processes, which often produce competitive views. It is necessary to reconcile disconnected considerations [14]. An interdisciplinary approach of defining future energy pathways is part of sustainability science. Sustainability science is strong in specifying desired results of a change [15], but while it prioritizes on outcome, it does not consider process, dynamics and uncertainty [16] (p. 21, Table 1.3). Giving policy advice under uncertainty is a typical problem of energy system transformation. Thus, additional viewpoints bringing together disciplines at the same time is necessary. Concepts focusing on process and building capacity can be found in resilience theory [16]. This concept has experienced a wide distribution of applications across disciplines. Resilience has shown a strong upward trend in scientific publications [17]. There is an increasing importance of resilience across disciplines as a concept to understand the capacity of a system or individual to respond to change [18]. Folke et al. [19] describe it as a conceptual framework for understanding how persistence and transformation coexist. It addresses the ability of a system to continue existing in a changing world due to adaptive capacity and innovative thinking.

Also for energy systems, the characteristic of being resilient is increasingly mentioned as a goal to aspire. Not only in science but also in politics, specifically energy politics. For example, it is prominently mentioned as an aim in the EU Integrated Strategic Energy Technology (SET) plan [20].

In this paper, the potential of resilience as an interdisciplinary guiding principle for energy system transition is discussed. Although having a different understanding in the sociology/psychology dimension for the human system, the engineering/computer science for the technical system and ecological resilience for the natural environment system, resilience thinking seems to be a promising concept to give guidance in the multitude of aspects on energy system transitions where other bridging

concepts like sustainability are missing something. What makes resilience thinking a promising concept is that it accepts uncertainty and the dynamics of systems, addresses processes, capacity building as well as outcomes. Furthermore, it is widely understood and applied across disciplines although having partly different notions. Along the seven resilience thinking principles, questions and parameters are derived for assessing different resilience aspects in a energy system transition process.

The description of different existing perspectives in Section 2 gives an idea of the variety of possibilities to look at energy systems and their transformations. The development of resilience concepts and its applications in energy research is discussed (Section 3) in the following. Based on the described discipline-based viewpoints, resilience thinking as a helpful framework is introduced, which is applicable independently from discipline-perspectives. Following these meta-level descriptions, in Section 4, question and parameters for resilience assessment in energy system transition processes, which are derived from resilience thinking principles, are presented, which is then discussed (Section 5) and concluded (Section 6).

2. Perspectives on Energy System Transitions

Energy systems

- are subsystems of the global socio-ecological system;
- are in interrelation to local socio-ecological systems;
- consist of different technologies that co-evolve with society; and
- their transitions can be looked at with different methods that cover parts of these aspects.

2.1. Technical-Economic Modeling

Technical-economic modeling has been widely applied to show that it is technically feasible to achieve low-carbon energy systems [8,21]. Focus of these modeling efforts has been to detect least-cost system configurations to reach the normative target of emission reduction [22]. Since optimization models with a target function of minimal costs are useful for that aim, they are still a popular pillar in policy advice for energy system transition. In an extensive energy model review, Pfenninger et al. [8] mention the trap of modeling what is easily quantifiable rather than what are essential driving variables in the system. This questions whether models are useful in providing insight on those issues, which truly matter for reaching the set policy goals.

Technical-economical energy system modeling with the normative goal of decarbonization calculates the carbon reduction in relation to the system cost. Least-cost alternatives to the business-as-usual track are calculated under the condition of reaching carbon reduction goals.

2.2. Internalization of External Costs

In economic terminology, environmental and social effects are named externalities. Coming from welfare economics, the concept has also been applied to energy externalities, beginning with aggregated approaches [23]. External costs provide a possibility to point out benefits of investments in environmentally-friendly technologies in the language of economy, but their effect is restricted to known, quantifiable impacts [24], and they hinge on central value judgments [25]. Impacts of climate change, consumption of scarce resources and other non-linear effects to social-ecological systems can be only partly quantified [24,26]. With growing distance to the market, monetization of externalities becomes uncertain to an extent that it is not included in external cost quantifications [27,28].

At those points in time, when policy decisions with respect to energy system transition are taken, many effects of new technologies are unknown. Interdependencies with social and ecological systems cannot be fully anticipated. Looking back in history, in the time when nuclear energy, coal- and gas-fired power plants were established and individual oil-based mobility was supported, externalities could not have been estimated to the same extent as today even if the concept of externalities would have been established.

In the external cost perspective on energy system transition, technical components of the energy system with low external costs are used to a higher extent than others with higher external costs. This is the mechanism which drives technologies with high external costs out of the market due to the price signal. Due to that mechanism, future energy systems consist of the technologies with lowest known external costs. Further distance from market or current knowledge increases uncertainty about the monetary values of the socio-ecological system services.

2.3. Sustainability Measurements

Begic and Afgan [29] argue that single criterion analysis is unacceptable in decision making for energy systems since a number of economic, environmental and social aspects have to be considered simultaneously. Thus, to assess the sustainability of future energy systems, multi-criteria decision methods are used. These provide more reliable results but are more complex [30,31]. Existing sustainability indexes and metrics vary a lot in size of target region and the evaluation criteria considered, but all include economic, social and environmental aspects. Cartelle Barros et al. [31] (p. 476, Table 1) provide an overview of multi-criteria methods and sustainability aspects that are considered in energy system research. Evaluation criteria utilized for sustainable energy multi-criteria studies can be found in [32]. A very extensive attempt to measure the general sustainability of power plant technologies has been made by [31], who use quantitative and qualitative data for 27 parameters and consider potential nonlinearities of the life-cycles of the energy technologies. Whereas sustainability indexes require a high level of transparency to unfold potential bias, they face the complexity of energy systems and their quantitative number may facilitate the communication of the complex issue [33]. Following the assessment of economic, social and environmental parameters, some sustainability index methods weigh the criteria and provide a ranking as output. This can be done for technologies as well as whole systems.

2.4. Socio-Technical System Thinking

Systems thinking in general deals with interconnections and complexities [34]. It has been increasingly applied in policy theory and practice in recent years [35,36]. Using social science disciplines in energy system research has gained increasing attention [3]. Technology is always embedded in society and co-evolves with it. Social-technical system analysis arose from the challenge of describing this recursive relationship [37,38]. Conceptualizing energy systems as socio-technical systems has the advantage of pointing to their interrelations with the surrounding environment [2]. Transitions of energy systems are labeled 'socio-technical' because they not only entail new technologies, but also changes in markets, user practices, policy and cultural meanings [39]. The toolbox of innovation and transition research offers frameworks for analyses of energy system transitions [36].

The multi-level perspective on sustainability transitions [39,40] has been applied to energy systems. Niche innovations gradually link together. When landscape developments put pressure on the current socio-technical regime, windows of opportunity are created and new configuration can dominate the new socio-technical regime.

2.5. Socio-Ecological System Thinking

Socio-technical energy systems are always interconnected with social-ecological systems. On the one hand, they are dependent on services of social-ecological systems like raw material and fuel extraction. On the other hand, they are influencing social-ecological systems, for example through infrastructure. A social-ecological system is defined as a coupled system of humans and nature that constitutes a complex adaptive system with ecological and social components that interact dynamically through various feedback [41]. Socio-ecological system research analyses the interaction of ecosystems and social processes. It often has a definite spatial context, unit of analysis and is anchored in specific places. It does not explicitly follow normative goals, but it recognizes that extensive

system changes often hinder the desired long-term provision with system services [28]. In spatial context and normative goals, it differs from socio-technical system research, but both frameworks use multi-level perspectives since the systems are governed on processes of different levels [37,42]. Ideas of iterative learning and adaptability for analyzing complex dynamic systems are common in both domains. Foxon et al. [43] argue for a fruitful discussion between the domains of socio-technical and social-ecological frameworks for reaching long-term sustainable goals. Hodbod and Adger [28] show that a framework that gives insights in thresholds, benefit and risk distribution and ecosystem interaction is suitable to analyze energy system transitions.

Socio-ecological system thinking considers planetary boundaries. Thus, from this viewpoint, it is advisable to leave energy system trajectories that overstep these. This is possible with energy subsystems that are in dynamic feedback with socio-ecological systems without reducing the resilience of the adaptive cycle and endangering the continuous system service.

2.6. Challenge of Multi-Dimensionality

The described perspectives of different disciplines on energy transition make obvious that energy systems are complex, dynamic socio-technical-ecological systems, and each of these components as well as their interrelations have to be considered for sustainable transitions.

Knowledge about the dimensions of energy systems are widespread between engineers, economists, social scientists and ecologists. Applying the collective experience would probably lead to sustainable energy systems. Models for technical feasibility, external cost internalization for market signals, sustainability indexes for awareness are as important as multi-criteria analyses for innovation schemes and social-ecological system thinking for an energy system transition that leads to low-carbon systems with a fair sharing of costs without overusing resources and threatening ecosystems in the long-run. However, although they deal with related aspects, individual vocabulary and perspectives of the communities makes interdisciplinary research difficult [44] and different mental models hinder collaborative intelligence and thus synergy effects of expert knowledge combination taking effect.

Interdisciplinary concepts could be of help to give guidance for transition pathways. A concept that has proven helpful for analyzing ecological and social systems, which is also widely applied in engineering and economics and which is increasingly appearing for a wide range of aspects in energy system research, is resilience.

3. Resilience

3.1. Emersion and Diversification of the Concept

The idea of resilience first arose in psychology, describing the psychological resistibility to survive difficult life situations without lasting derogation [45,46]. Holling [47] applied resilience to ecosystems not only to individuals and contested the traditional view of ecosystems as stable systems in equilibrium “Resilience determines the persistence of relationships within a system and is a measure of the ability of these systems to absorb changes of state variables, driving variable and parameters and still persist [47]” (p. 17). It has to be distinguished from stability. Systems only aiming at stability cannot react flexible to seldom, sudden, radical, surprising events and collapse due to the deterministic factors that enabled keeping the balance so far [47] (p. 21). Adger [48] points to the link between social and ecological resilience and defines social resilience as the ability of groups or communities to cope with external stresses and disturbances.

Extensive work on the resilience of social-ecological systems and the applicability of the concept for dealing with these systems has been done by the Stockholm Resilience Centre. They describe resilience of social-ecological systems as “The capacity of a system—be it a landscape, a coastal area or a city—to deal with change and continue to develop. This means the capacity to withstand shocks and disturbances such as financial crisis or use such an event to catalyze renewal and innovation” [41] (p. 18).

Engineers apply resilience to technical infrastructures, which implies the ability to keep functioning in case of catastrophic events. Thus, it has become an important characteristic in risk management where resilience is an approach for critical infrastructure [14].

In computer networking, resilience refers to trustworthiness, congestion and error tolerance and an acceptable level of service delivery when facing changes [49,50]. These applications built on different basic understandings of resilience, which will be discussed in detail in Section 3.3.

Being a rather observational science in the beginning, resilience is now discussed as a policy goal in different contexts, and resilience thinking is introduced in practice [28,51]. Considering resilience as the ability of a system to continue existing in a changing world, it addresses typical challenges in energy system transition research like uncertainty, iterative learning, complex structures and non-linearities.

3.2. Relevance in Energy System Research

Resilience in energy system research is widely applied in the context of energy security. Resilience of energy infrastructure is highlighted as an important characteristic and a beneficial property of power grids [52–54], especially due to their role as the critical network in a network of networks [55]. In this case, network resilience is characterized in terms of the “backup capacity” [55]. Furthermore, resilience of energy systems is referred to as the counterpart of energy demand and supply weaknesses on different scales [56]. For example, He et al. [57] present an energy import resilience index, while Chuang and Ma [58] analyze the impact of energy diversity in reducing risk of energy supply shortages and cost fluctuations. Ghanem et al. [59] conceptualize household resilience to power supply disruption during storm events. Resilience has also entered energy policy papers. The Energy Union Package of the European Commission is titled “A Framework Strategy for a Resilient Energy Union [...]” and resilience is mentioned as an desirable goal [60]. In addition, resilience here is understood as decreasing the risk of potential energy disruptions. A broader, although not further described meaning of the term is used in a study estimating infrastructure requirements for transition to renewable energy systems in the EU, pointing out that the scenario that may lead to a technically under-optimized solution with higher costs provides more resilience to the power sector from all points of view [61].

There are measures for energy system resilience that try to capture resilience meanings of different disciplines—engineering, risk assessment and social science resilience [14,62]. The latter suggest a resilience index as a composite of seven metrics concerning non-renewable fuel used, generation and distribution efficiency, carbon intensity, diversity, redundant electricity for use in GDP and reliance on imports.

While applications in energy system research is widespread, a differentiation in understanding of the term resilience can be observed.

3.3. Engineering and Ecological Resilience

As obvious in the energy applications of resilience, there are different understandings of the concept. Holling [63] distinguishes between engineering and ecological resilience. The first focuses on maintaining the underlying system functionality (e.g., keep the grid going), the latter considers more holistic concepts, emphasizing survival and adaption of the overall system. Engineering resilience operates near equilibrium with the underlying idea of the existence of an optimal state. This control of a single target variable independently of the larger ecosystem, economic and social interactions contributes to growing vulnerability to unexpected changes [63].

The current state of our energy systems may be one of resilience in the engineering meaning, but not in the sense of long-term resilience of an ecological perspective. The following observations underpin this assumption:

- Maintaining function in providing energy services is in the focus of our energy systems, which reminds one of stability. Slow variables changing of the larger system may not be recognized and give an appearance of stability [64].

- Focus on efficiency and functioning close to a fictive optimum state has decreased the adaptability of our energy systems. This results in inertia, a threshold for transformation ambitions.
- If one appraises the detection of the climate problem as a fundamental disturbance to the energy systems, a resilient system would adapt, eventually changing into a new state. Energy systems are, in most cases, static, eventually rather steering to collapse than adapting.

It is claimed that energy systems should be efficient in two different meanings. They should provide the energy service for as few societal costs as possible and also be efficient in the sense of not wasting resources or energy. Lietaer et al. [65] state that, for ecosystems, efficiency contradicts diversity and connectivity, which are important resilience parameters, and apply this to economic systems. Reaching sustainability has to find a balance between efficiency, which leads to brittleness of a system and diversity and connectivity which leads to stagnation of a system [65] (p. 94, Figure 2). Optimization and efficiency are accompanied by shrinking response redundancy, which reduces the leeway of adaptability and thus lowers resilience of a system.

In scenarios of sustainable energy systems, efficiency in both senses (cost and resource efficiency) is an important characteristic. As mentioned above, most energy system models utilize target functions for minimizing costs, thus the result reveals a system configuration, which provides the required energy system service, utilizing as few monetary resources as possible. Under the assumption that the relation between efficiency and resilience stated for ecological and economic systems applies to energy systems as well, it can be argued that reducing diversity in energy systems due to efficiency goals reduces the resilience of energy systems.

3.4. Dealing with Complexity

Looking at a social-ecological systems, if well-managed, they can provide a stable output while the underlying system is dynamic, complex and adaptive. A condition is the availability of functional diversity, providing robustness to the process and, as a consequence, great resilience to the system behavior [63]. If energy systems are shaped in a way that they inherit more characteristics of resilience like response diversity, it can be assumed that the probability of staying in case of unexpected disturbances is higher. Response diversity means that the system components can perform functional redundancy, thus multiple components can perform the same function, and if these are different in size and scale, it is more likely that they react differently to disturbances [41]. This adaptive capacity increases the probability that, in the case of unexpected disturbance, a system reacts flexibly, and maybe adapts, but keeps providing the same service.

In summary, existing energy systems demonstrate inertia and are unable to adapt, which is a signal of stability that is vulnerable to disturbances and inert to required changes. To cope with the challenges of climate change and so far unknown disturbances, adaptive resilient systems are required, providing stable energy services in the form of electricity, heat, and mobility. The aim of managing social-ecological systems is to receive system services while not undermining the complex system providing these. Resilience thinking can be understood as guiding principles to reach this goal. If we view energy systems as socio-techno-ecological systems, resilience thinking could help to shape and manage the transition to such energy systems. It can be understood as a supporting framework for guiding principles and does not reduce the relevance of different disciplines' methods for research on energy system transitions.

Experience in resilience thinking has been summarized in a publication of the Stockholm Resilience Centre [41] (summary of [66]). It explains seven principles for applying resilience:

- Maintain redundancy and diversity
- Manage connectivity
- Manage slow variables and feedback
- Foster complex adaptive systems thinking
- Encourage learning
- Broaden participation
- Promote polycentric governance systems

Some of these aspects of resilience thinking are emphasized across disciplines as important for energy systems: role of diversity [67,68], adaptability, interconnectedness, participation [24,69] and polycentric governance [2,69–71].

4. Applying Resilience Thinking to Energy Systems

4.1. Idea

The seven principles of resilience thinking are taken as a guideline for assessing the resilience of energy system transitions. In the following, resilience refers to the target energy system itself, the pathway to reach it, and the process to develop and manage scenario and pathway process. Simonsen et al. [41] relate resilience thinking to socio-ecological systems and their management. Accordingly, for the energy viewpoint, it refers to socio-technical-ecological energy systems, specifically target systems defined in scenario processes and the transition to them. As an energy system and its transition touches the human, the technical and the natural environment system, social, technical and ecological aspects are included. The assessment is subject to the assumption that resilience of the target energy system and its pathway to it is a desirable goal, as it enhances the change that the provided system service (energy service) is continuously provided also in the face of disturbance and change.

4.2. Usage

The procedure can give guidance for integrating the resilience perspective in energy system transition planning and management. Figure 1 schematically illustrates an energy system transition process based on backcasting. In contrast to forecasting, which is more explorative, backcasting in energy scenario studies determines a target energy system that fulfills a certain aim. The derived pathway that leads to the target energy system in the future shows how and to which extent the defined aim and derived target energy system in the future can be reached [6,72,73]. Resilience thinking aspects add value and broaden the picture on different stages and aspects on the process, which is illustrated by the white boxes in Figure 1.

The following outline of a procedure targets researchers who want to access such a process from a holistic perspective. It can also be useful for decision makers having to make pathway decisions under high uncertainty. High levels of uncertainty inhere in far-in-the-future-looking backcasting approaches. The resilience conceptual framework then helps to get a better foundation for decisions that should lead to the targeted system with a higher probability despite uncertainty and unexpected changes. Applying the procedure adds resilience aspects to the process, to design the process of scenario making and following the pathway in a way that a resilient outcome is more probable. Furthermore, respecting the aspects can facilitate adaptation during the transition pathway, to reach the initial aim of a sustainable energy system providing a continuous energy service despite changing circumstances.

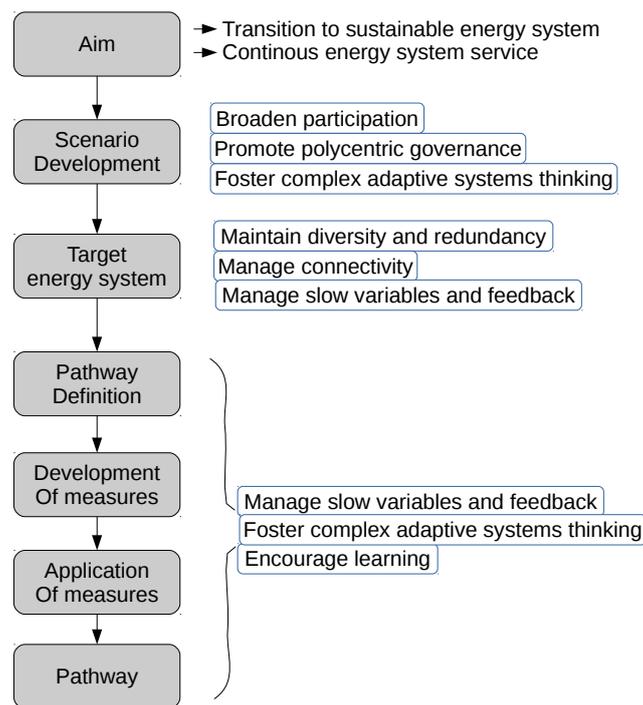


Figure 1. Energy system transition process (gray boxes on the left) based on backcasting and possible supporting resilience thinking principles (white boxes on the right) at different parts of the process.

4.3. Procedure

As illustrated in Figure 1, the seven principles of resilience thinking as named by [41] are applied for assessing the resilience of the target energy system, the pathway resilience and if the energy scenario process is designed in a way that a resilient outcome is probable.

If a chosen energy system transition process should be looked at following the procedure, it is recommended to first set soft boundaries (which can be later adapted during answering questions and parameters) by defining the focal system, main components, and the energy system service that should be continuously provided as well as the scenario development process including actors. The following questions derived from the resilience thinking aspects should be answered as a preparation for estimating the parameters listed in Tables 1–3.

Maintain Redundancy and Diversity

- What are the main components (technical, social (governance, users, managers), ecological) of the system?
- Which of these should be diverse and redundant?
- Can these components perform functional redundancy, which means multiple components can perform the same function, providing the same service?
- Can they perform response diversity? If they are different in size and scale, it is more likely that they react differently to disturbances.
- Are there key components/functions with low redundancy?
- For which components does diversity contradict/decrease efficiency?

Manage Connectivity

- Which kind of (technical, social, ecological) connections are important in the system?
- Does the level of connectivity of the important connections facilitate spread of disturbances?
- Does the level of connectivity facilitate recover possibilities after disturbances?
- Thus, which levels of connectivity are desired?
- Which factors increase technical connectivity, which decrease technical connectivity?
- Technical connectivity: Is the n-1 connectivity principle kept? The n-1 criteria means if one component breaks down, everything is still functioning.
- Which factors increase connectivity between actors?

Manage Slow Variables and Feedback

- Which are decisive slow variables in the system and which are the parameters changing these slow variables?
- Are slow variables of socio-ecological systems which provide service as a resource base to the energy system, steadily changed? Could this result in irreversible degradation of the respective socio-ecological system, reducing the ability of the respective system to keep providing the required service or resource in the future?
- Can the slow variables then be measured? How can they be monitored?
- Which positive and negative feedback loops exist? Do they support the original aim of the energy target scenario?

Foster Complex Adaptive Systems Thinking

- Which non-linearities exist in the energy system in transition? Are there warning signals of specified boundaries that should be seen as signals for early intervention to prevent deeper intervention?
- Which intended or non-intended side effects could appear due to the measures realized to pursuit the chosen energy system pathway? Are there critical thresholds of connected socio-ecological system that should not be overstepped?
- Which perspectives (technical, ecological, economical, social, local, national, international) are included in the scenario process, and which are not included yet?
- Is a multitude of perspectives acknowledged?
- Which methods to expect and account for uncertainty are applied? How do these uncertainty influence the pathway measures?

Encourage Learning

- How is improvement of the technical components encouraged in in the pathway process?
- Is there room for experimentation to develop new technologies?
- Is cross-scale learning possible?
- Are there technical infrastructural decisions that have to be taken at an early stage? Is adaptation of a pathway necessary due to new findings/learning nevertheless possible?
- Is adaptive co-management realized? Adaptive management is about testing out alternative approaches, adaptive co-management additionally focuses on knowledge sharing between different actors.
- Which monitoring processes are implemented, and how do their outcomes result in adaptation of measures?
- Is local and traditional knowledge integrated in the learning process?

Broaden Participation

- Who participates?
- Are all key actors/stakeholders involved? Which governance levels, and which interest groups are involved?
- Who takes which role? What are the rules of participation? Are they clearly defined?
- Which level of participation is necessary? Is this level reached?
- Could the level of participation be reduced, saving time and resources while keeping the participation still broad enough to include all relevant actors?

Promote Polycentric Governance Systems

- Which governance levels exist? Which governing bodies?
- How are the responsibilities shared? Does the authority and responsibility distribution match each other?
- Can the different governance levels communicate? How are they linked?
- Can problems/unexpected disturbances be addressed by the right people at the right time?

Table 1. Target energy system resilience. Parameter derived from the following resilience thinking aspects: *Maintain diversity and redundancy, Manage connectivity and Manage slow variables and feedback.*

Parameter	Type	State or Trend If...	..Effect on Resilience of Target Energy System
Supply technologies	number	high	increase
Energy sources	number	high	increase
Response diversity	boolean	present	increase
n-1 technical connectivity	boolean	present	increase
Suitability of actor communication channels	boolean	present	increase
Degradation of resilience of resource systems	number or boolean	high or present	decrease

Table 2. Energy pathway resilience. Parameter derived from the following resilience thinking aspects: *Manage slow variables and feedback, Foster complex adaptive systems thinking and Encourage learning.*

Parameter	Type	State or Trend If...	..Effect on Pathway Resilience
Existence of positive feedback loops supporting the aim	boolean	present	increase
Potential of the system for acquiring complexity in terms of numerosity (e.g., number of relevant actor networks)	number	high	increase
R&D activities in energy technology	number	high	increase
Monitoring in place	boolean	present	increase
Coverage of main indicators by monitoring	percentage	high	increase
Types of knowledge considered	number	high	increase
Methods account for uncertainty	boolean	present	increase

Table 3. Scenario process resilience. Indicators derived from the following resilience thinking aspects: *Foster complex adaptive systems thinking, Broaden participation and Promote polycentric governance.*

Indicator	Type	State or Trend If...	..Effect on Probability of a Resilient Outcome
Perspectives acknowledged	number	high	increase
Diversity of involved actors	number	high	increase
Disciplines involved	number	high	increase
Relevant stakeholder involved	percentage	high	increase
Authority-responsibility correlation	correlation	high	increase
Clear participation rules	boolean	present	increase
Governing bodies-components	correlation	high	increase

5. Discussion

Facing a multitude of resilience understandings for energy systems, it is important to stress the long-term sense of it. Valuing resilience as an important characteristic of energy systems aims at a joint existence of energy- and social-ecological systems that exceeds the sometimes understood meaning of keeping function. The latter rather refers to stability. Energy systems are always to some extent dependent on resources from social-ecological systems. For a long time, an energy system can provide a stable service, keeping its function while steadily changing slow variables of the social-ecological systems providing the input. This gives an impression of stability, but slow variables can, in the long-run, bring the systems providing service for the energy systems out of balance. A resilient energy system would not bring the underlying socio-ecological systems out of balance. If it does, the system itself is not resilient. When the underlying systems stop providing service, the energy system itself loses balance. Thus, in the long-term sense of resilience, most of our current energy systems and subsystems are not resilient because they rely on resources that do not recover and substantially change social-ecological systems that provide the services they depend on.

Resilience thinking as such is not a method to define energy system pathways from a social, technical, economical or ecological point of view. It can provide a good framework to capture aspects that are usually worked on in different procedures, partly leading to competing solutions. Basic understanding is touched since it is not about controlling system components but helping to refine a mental model of systems that encourages change, variability and diversity.

When talking more concretely about how resilience of a sustainable energy system can be reached, it is helpful to not only look at a targeted energy system itself but to take the scenario process, pathway and derived measures to reach the targeted system into account. If the design of the scenario process is supporting broad participation, involving relevant stakeholder and social, technical, ecological perspectives, involving local knowledge, it has a higher probability that the derived energy target system is of higher resilience.

For following resilient pathways leading from the current state to a targeted energy system, monitoring and learning are important. A difficult question is infrastructural decisions, if they have to be taken at an early stage of following such a pathway. Some energy systems have decisive infrastructural requirements, like e.g., the electricity grid for power systems. Due to long investment cycles, the decision of which infrastructure to build has to be taken early in the process, which can hinder future adaptation to other system configurations. To keep options open, but still proceed in a direction, it is important to find and pursue “no-regret options”.

Learning and participation are important cornerstones of managing resilient socio-ecological systems. The whole complexity cannot be understood by one single mind. Knowledge gain for different characters is crucial for further learning, thus sharing knowledge openly is a cornerstone for a resilient process. When transferring this principle to the scenario and pathway process of energy system transformation, an important part of knowledge sharing as a basic condition for learning and participation is the open provision of data and tools for research on energy systems. If models utilized

to access complex energy systems and data describing the system are openly available, conditions for learning and broader participation are improved. The upcoming trend of open data and open source in energy system research [74] supports scenario processes that are designed to meet these conditions.

Inputs and parameters that make an energy system itself resilient are diversity, redundancy and response diversity of the technical components. Furthermore, a level of connectivity that does not spread disturbances to a critical extent, but is connected enough to support recovery after disturbances, is helpful. Regional modularization, a diverse ownership structure and functional diversity are important for reorganization of energy systems after disturbances like natural disasters, price shocks or detection of previously unknown environmental problems. Additionally, a target energy system can only be resilient if it does not change its natural resource systems to an extent that change the slow variables of these to an extent that critical thresholds of the socio-ecological systems are met and cannot provide the service necessary for energy systems on the long run. This is also part of sustainability, but the resilience aspect of managing slow variables and feedback add the non-linearities of the underlying systems, which requires additional attention.

Another important insight that resilience thinking offers is the relativization of the efficiency target. Pursuing sustainable energy system often includes efficiency targets in the sense of cost and resource efficiency. Whereas efficiency is important to reduce resource consumption, at some points, it contradicts resilience as it is often attended reducing redundancy. If this really is a trade-off, or can be solved consistently, has to be carefully looked at.

When determining a sustainable target energy system and measures resulting in a pathway resulting in that target system, this is based on several assumptions and uncertainty. Furthermore, energy systems are complex, as they are embedded in social, ecological and technical interdependencies, which are difficult to survey completely. Thus, making decisions about measures to reach a certain aimed-at energy system has to be done under uncertainty to some extent. Complex adaptive systems thinking is necessary in managing socio-ecological systems because it expects and accounts for uncertainty. Becoming aware of knowledge gaps (in the sense of uncertainty about complex energy systems) in energy pathway definitions is a first step for choosing “no regret” options. Here, encouraging learning (trial and error, room for experimentation, keeping up progress) and fostering complex adaptive systems thinking are helpful principles to account for complexity and uncertainties.

Looking through the glasses of resilience will not lead directly to a quantified definition of the technical composition of future energy systems that are sustainable and resilient against disturbances. However, the procedure outlined above gives guidance for comparative resilience assessment of energy target scenarios and pathway resilience based on parameters.

The following research steps could include a refinement of the questions and parameters to energy systems of different scope (local, regional, national, international) and different sectors (mobility, heat, electricity). Resilience parameters, for example for the global freight system, differ from the ones of a village heating system or a national power system, although they follow the same foundation described in the paper.

6. Conclusions

The thoughts described above are another explorative step in interdisciplinary energy system research. Resilience thinking can help to lay foundations for a different mindset of a more holistic view on energy systems that is necessary for sustainable solutions. The multitudes of methods of different disciplines researching the energy system are important. However, resilience principles can be a good additional guiding principle for a pragmatic but complexity-accepting compromise between the challenging sustainability claim and the need for policy action under uncertainty. The main advantage of resilience thinking is that options are kept open and that it helps to avoid lock-ins. This is essential for complex energy system transitions that are mostly characterized by a complex network of social, technological and ecological matters. As a process of different connected

matters, with many stakeholders, energy system transitions can also gain from complex adaptive systems thinking, as this approach suggests that one does not need to know all—and nobody alone needs to know all—but gives hints on how to shape the process to reach goals everybody agrees on now.

For an energy system transition, it is decisive to distinguish between resilience and stability and to find a practicable degree. The antagonism between efficiency and resilience points to the trade-off between efficiency (cost and resource) and diverse flexibility for energy systems. Being aware of this trade-off is decisive for sustainable energy transformation pathways.

Applying the seven principles (maintain diversity and redundancy, manage connectivity, foster complex adaptive systems thinking, manage slow variables and feedback, encourage learning, broaden participation, promote polycentric governance) of resilience thinking to energy system transformation processes is a good starting point for a more integrated, interdisciplinary view. This perspective can help with decisions on how pathways are designed, configured and managed to cope with variations and disturbances. If resilience is high, continuing to exist in a changing world is more probable.

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