Operationalization and Application of Resilience Enhancing Design Principles for District Heating Systems

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The energy transition from a fossil-based to a renewable sector-coupled energy system implies serious structural upheavals and uncertainties. Resilience management offers a guiding concept for this transformation process to handle with uncertain and unknown stressors as well as non-linear behavior of complex systems. Thus, a comparative assessment of the resilience of different future energy concepts is important in order to provide a basis for decision-making and implementation of resilient energy systems. Within the research project Urbane Wärmewende Berlin (Urban Heat Transition Berlin) the resilience of future heat supply concepts of two urban districts in the city of Berlin was analyzed. For this, certain resilience enhancing structures and functionalities (diversity, redundancy, loose- and optional couplings) were assessed by operational rating indices in order to enable a comparison of the degree of resilience of different heat supply scenarios. The analysis of the heat supply scenarios shows that local renewable heat sources are limited in urban districts. Hence, the majority of heat demand in future heat supply scenarios must be satisfied by electricity-based supply options fed by supraregional renewable electricity. The assessment has shown that the attributes diversity and loose- and optional couplings are decreasing due to a decarbonized changing of the local district energy system. In contrast, the redundancy in the system is increasing because of a higher installed capacity spread over a multitude of smaller decentralized renewable units.

Keywords: resilience, district heating, diversity, redundancy, loose and optional couplings, design principles, indicator-based assessment.

1. Resilience as a Guiding Concept for Energy System Transformation

In order to limit the increase of the global temperature below 2°C compared to preindustrial levels, a complete defossilization of the energy system should be pursued UNFCCC (2015). With a share of 15 to 17 %, the heating sector causes a significant part of the German CO_2 emissions Fraunhofer IWES/IBP (2017). Therefore a massive transformation of the heat supply is required. In order to achieve a realization of a regenerative heat supply in urban areas, a redesign of the existing structure and a integration of multiple renewable sources is necessary. This requires a high degree of digitization and automation of the underlying infrastructure. However, the more complex and automated the energy system becomes, the less traditional mechanisms are able to maintain system security. Consequently, the vulnerability to cyber-physic-attacks and other known and unknown stressors increases Fischer and Lehnhoff (2019). Stressors can affect the system from the outside or occur due to internal failure and can be differentiated in their characteristics of dynamics and degree of awareness. This means, they can occur either creeping or abrupt as well as in a known or unknown nature. Depending on the stressor's dynamics and its level of awareness, different resilience enhancing abilities (resistance, adaptability, improvisation capability, innovation and learning capacity) may counteract the disruptive event Gößling-Reisemann (Gößling-Reisemann).

Precautionary risk management (or more precisely the vulnerability analysis as an element of risk management) follows a preventive bottom-up principle by examining the behaviour of systems confronted with known and expected stressors to

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localize and rectify weak points (fail-safe) Linkov et al. (2014). Yet the structure-oriented or event-based vulnerability analysis has some blind spots. On the one hand, it only offers access to resilience that is focused on resistance and adaptability, while leaving out other resilience-enhancing system capabilities. On the other hand, possible unpredictable and unknown stressors (so called unkown unknowns) are not taken into account.

Risk management can therefore only preventively and adaptively protect the system against expected stressors. If the system performance is nevertheless disrupted, further routines are required to mitigate the intensity and duration of the disruption and to restore system performance. To address these demands, an approach to resilience is introduced, which originated in the ecosystem theory. This approach does not interpret resilience as a analytical tool, but rather as a guiding concept for the design of systems Brand et al. (2017). The hypothesis derived from this biomimetic approach is that the successful survival of biotic systems, even under changing and temporarily turbulent framework conditions, is based on identifiable evolutionary gained structures and functionalities. These structures and functionalities are the result of an optimization process of mutation, recombination and selection that takes millions of years and provide the system with possibilities to handle completely unknown and unexpected stressors Holling (1973); Brand et al. (2017). In resilience management, these structures and functionalities from biotic systems are used as a model for the design of socio-technical systems Gleich et al. (2010); Brand et al. (2017).

Resilience, as a guiding concept for the design of socio-technical systems[a], does not only address the resistance and adaptability of the system to prevent disruptive events. It also takes into account the ability of the system to innovate and improvise in order to counteract the disruptive event (safe to fail) Gößling-Reisemann (Gößling-Reisemann). These system abilities are enhanced by identified structures and functionalities. To identify these structures and functionalities and to develop corresponding design principles, the experience-based (a posteriori) approach from risk management is combined with the theoretical (a priori) approach from the evolution- and ecosystem-theory Brand et al. (2017). In the theoretical a priori approach, a bio-mimetic abstraction process is carried out (cf. Gleich et al. (2010)). Knowledge on resilience principles from evolution- and ecosystem-theory are summarized and examined for a possible adoption as resilience-increasing principles for the design of socio-technical systems. In the a posteriori approach, experiences from risk management and vulnerability analysis are evaluated and also examined for a suitable derivation as resilience-increasing design principles. The design principles derived this way are, amongst others, diversity, redundancy, loose and optional couplings, buffers, modularity, multifunctionality, subsidiarity, willing and capable actors Brand et al. (2017). Fig. 1 shows the classification of the contribution of the design principles redundancy, diversity and loose couplings to the four resilience-enhancing system capabilities regarding the disruptive events, which should be counteracted.

stressor	abrupt	creeping
known	**resistance** • redundancy • diversity	**adaptability** • redundancy • diversity • loose couplings
unknown	**improvisation capability** • diversity • loose couplings	**innovation capacity** • diversity

Fig. 1. Classification of the design principles redundancy, diversity and loose couplings to the four resilience-enhancing system capabilities regarding the disruptive events. Own graphic based on Brand et al. (2017)

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To provide a basis for decision-making and implementing resilient energy systems, a comparative assessment of the resilience of future energy concepts is important. Therefore, this article introduces an indicator-based assessment method of the resilience enhancing structures and functionalities diversity, redundancy and loose and optional couplings and shows their applicability by case studies of a model urban district heating supply system.

2. Indicator-based Resilience Assessment

Following resilience as a guiding concept raises the question of whether or to what extent resilience is actually enhanced by the structures and functionalities of ecological systems and if a transfer to social-technical systems is practically feasible. It is assumed that this question can be answered positively with regard to the formability of system-defining structures, elements and functions Gleich et al. (2010).

Within the research project Urban Heat Transition Berlin the resilience of future heat supply concepts of two urban districts in the city

[a] A detailed description of the approach "resilience as a guiding concept" on which this work is based can be found in the first three chapters of Brand et al. (2017).

of Berlin was analyzed. For this, the resilience enhancing structures and functionalities diversity, redundancy and loose couplings were assessed by operational rating indices in order to enable a comparison of the resilience of different heat supply scenarios. The project framework and the data basis of the assessment were economically and technically focused. This reduction in complexity to an economic-technical system allowed the application of the operationalization methodology for the mentioned design principles. Design principles that require a sociological data basis were not taken into account.

The following section provides the quantification method for measuring the design-principles diversity, redundancy and loose-couplings.

2.1. *Diversity*

According to Stirling, the diversity within a system can be described by three elements: the variety (number of option categories in the system), balance (distribution of the system elements over the option categories) and disparity (difference between the option categories) Stirling (2007). Diversity contributes to the evolutionary innovative ability of systems and thus reduces the sensitivity to stressors Peterson et al. (1998); Molyneaux et al. (2016), but at the same time complicates countermeasures and vulnerability localization by a more complex system architecture Fischer and Lehnhoff (2019). Furthermore, the variety of options of an appropriately designed system is helpful to avoid path dependencies Farrell et al. (2004). Functional and structural diversity is achieved through a corresponding selection and arrangement of generation, conversion, storage, distribution, control, and communication technologies and the associated resources. For the diversity of a system, certain assessment methodologies such as the Shannon-, Gini- or Stirling-index are established Stirling (2010); Binder et al. (2017). In this work the Stirling index (cf. (1)) is used as a suitable quantification metric. The Stirling index considers the variety of categories in a system, the balance of distribution of elements between the different categories and the disparity, meaning the dissimilarity between the categories Stirling (2010).

$$S = \sum_{ij(i \neq j)} d_{ij}^{\alpha} \cdot (p_i \cdot p_j)^{\beta} \tag{1}$$

The Stirling index sums up the pairwise comparison of the categories i and j (with $i \neq j$). Here are p_i and p_j the shares of the categories in the heat supply. The parameters α and β govern the relative weightings on variety, balance and disparity. The disparity distance d_{ij} describes the distance between the categories i and j in the disparity space and is defined as:

$$d_{ij} = \frac{||D_L D_L^{-1} g_L||_1}{||g||_1}, \tag{2}$$

with

$$D = \sum_{k}^{n} b_k^T (x_i - x_j) b_k b_k^T. \tag{3}$$

To determine the distance of disparity between two categories, a classification tree is compiled to sort the considered categories. Each branch stands for another possibility to distinguish the different attributes in the categories. The construction of such a tree diagram helps to determine the possible attribute categories. The attribute categories are expressed in the distance vector x, independent from their previous position in the classification tree. For this purpose, a property vector x_i is created for every category. The encoding of the different possible properties ensures the numerical distinction and processing of the properties. Through the subtraction of two property vectors, x_i and x_j respectively, a difference vector $x_i - x_j$ is developed. This difference vector is transformed into a diagonal matrix D ($D \in K^{n \times n}$, with $n = dim(x_i, x_j)$) (cf. (3)), where the diagonal entries unequal to zero show a difference in the corresponding property. b_k is the kth orthonormal basis vector of the n-dimensional vector space ($b_k \in K^n$). To get rid of possible zero rows and columns, a submatrix D_L is generated, which has full rank ($D_L \in K^{r \times r}$, with $r = rang(D)$). Furthermore, the attribute categories can have a different weighting. For instance, to distinguish technologies to supply heat, the difference in fuel supply has a larger weight than the one of the installation site. Those different weights are represented in the weighting vector g, which is reduced to the vector, analogous to the difference matrix g_L.

2.2. *Loose Couplings*

In the energy sector, the grade of coupling of different infrastructures, generation and energy sources is rising – often referred to as sector coupling. Some examples of sector coupling between the heat and electricity sector are combined heat and power units (CHP) or heat pumps. In both cases, electricity grids and heat generation are coupled together, creating dependencies. In principle, all heat generation technologies currently dependent on a supply of electrical energy via electrical control and regulation, unless they are specially designed to be autonomous. With the design principle of loose coupling, a distinction between couplings is made, whether the system is able to separate (loose coupling) or the system is unable to separate (rigid coupling) Gößling-Reisemann and Thier (2019).

An advantage of loose couplings is that cascading continuations of disturbances can be avoided in case of failure. Loose couplings thus allow a fast isolation in case of damage Lovins and Lovins (1982); Gershenson et al. (2003). With rigid couplings, faults spread controlless through the system.

The assessment whether couplings are loose or rigid has been made by analyzing the dependencies of heat systems. Pipeline-bound energy carriers are to be regarded as more rigid than solid ones, since the distribution and storage of the latter can be carried out loosely and in many different ways. Heat generators that can be supplied by more than one energy source, one of which is independent of related infrastructures are referred to as being loosely coupled. Examples are heat pumps that are supplied with grid electricity as well as electricity from local photovoltaic (PV) systems or CHPs. Environmental heat and solar thermal energy (seasonal generation characteristics) in combination with decentralized control are self-sufficient and are considered as being loosely coupled. The number of possible options within the system is decisive for the type of coupling of a system.

The share of the heat energy E_L provided by the previously defined loosely coupled system units in the total annual heat energy supply E_{total} serves as an indicator for the assessment of the design-principles loose-couplings:

$$L = \sum \frac{E_L}{E_{total}}. \tag{4}$$

2.3. *Redundancy*

Redundancy means the duplication or multiple existence of similar system components. If one component fails, operation is not impaired because another component effectively replaces the function (n-1 principle) Biggs et al. (2012). Physical redundancy thus increases resistance to a (disturbance) event and primarily promotes system resilience, since stable and safe system performance can be guaranteed even if one or more relevant components fail. At the same time, redundant provision of system components multiplies the exposure of the system to external stressors, since the assailable surface of the system has equally increased as the redundancy. For the evaluation of the redundancy of a system, a probabilistic risk analysis under the consideration of a stepwise failure of units is conducted. For this purpose, the risk of supply R_i under progressive failure of units is considered. The risk of supply results from the product of supply deficit in the combination of failing units and the probability of occurrence of this default combination. The following equation (5) describes the risk of not supplied energy of one failure combination i:

$$R_i = p_i \cdot \sum_{\substack{t=0 \\ (\Delta P_{S,t,i}<0)}}^{T} \left(|\Delta P_{S,t,i}| \cdot \tau_t \right), \tag{5}$$

with p_i representing the probability of the failure combination i and the second multiplicand representing the expected energy loss due to lower supply capacity, which is the sum of all times of power deficit ($\Delta P_{S,t,i} < 0$). The probability of the failure combination i is calculated by the product of probabilities of running and not running units:

$$p_i = \prod_{v \notin I_i} (1 - p_v) \cdot \prod_{w \in I_i} (p_w). \tag{6}$$

The combination of failing units is consolidated in the set I_i. The probability of failure of a single generation unit is represented by p. In this sense, the index v refers to all running units and the index w to all not running units of the failure combination i.

The total risk R is calculated by summing up all individual risks R_i of determined failure combinations:

$$R = \sum_{k=0}^{n} \sum_{i=1}^{\binom{n}{k}} R_i. \tag{7}$$

R is the total risk of the failure of up to k units of a total number of n units ($n - k$, with $k \in \{1, \ldots, n\}$). In each step the supply risk for every combination i of failing units is calculated and added up. The number of all combinations of failing facilities is defined by the binomial coefficient of k failing units out of n units in general. If k is one and the total risks R results in zero, the $n - 1$-criterion is satisfied. This means, that there is still enough power available regardless of which unit fails and regardless of the time of failing.

3. Application of the methodology to case studies of model districts in Berlin

In the research project Urban Heat Transition Berlin, the indicator-based assessment method was applied to case studies of two urban model districts in Berlin. It should be mentioned that due to the conciseness of this paper, the results of only one model district are shown here. However, there were no different conclusions drawn from the analysis of the not exemplified model district. The case studies considers the status quo of 2018

(A), as well various transformation paths, outlined by snapshots of the energy supply of the district in 2030 and 2050.

The shown transformation paths outline the edges of the examined spectrum. Scenario B presents a very ambitious development, which, in a long-term perspective, aims at an integration of all technically feasible regenerative heat sources on a local level. These are the utilization of solar-thermal potentials and of heat pumps which are supplied by waste water, industrial waste heat, surface water or waste heat from the CHP. The remaining supply deficit is compensated by resistance heating units, fed by supraregional renewable electricity. In the medium-term the supply will focus on biogenic and synthetic fuels used in CHPs next to local heat sources, connected with heat pumps.

The other side of the spectrum is flanked by a conservative development (C), which will continue to be characterized by fossil fuels in the medium-term, but will increasingly feature CHPs. Long-term development continues to be dominated by CHPs, but substitutes fossil fuels with biogenic and synthetic ones.

Fig. 2 shows the share of each technology category in the annual thermal energy supply. The share of individual technology categories and the associated units in the installed capacity of the heat supply is shown in Fig. 3.

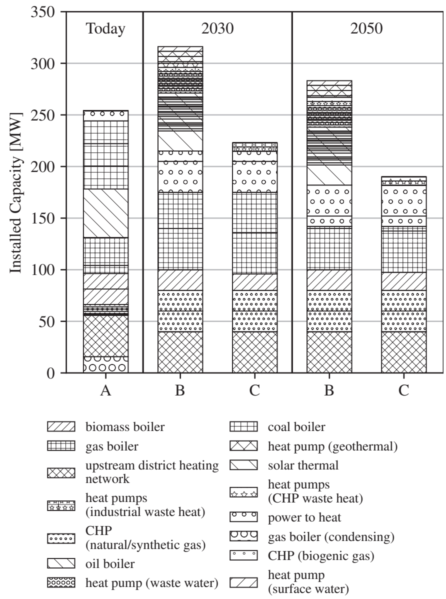

Fig. 3. Installed capacity of individual heat generation units. Uniform pattern belong to a technology class.

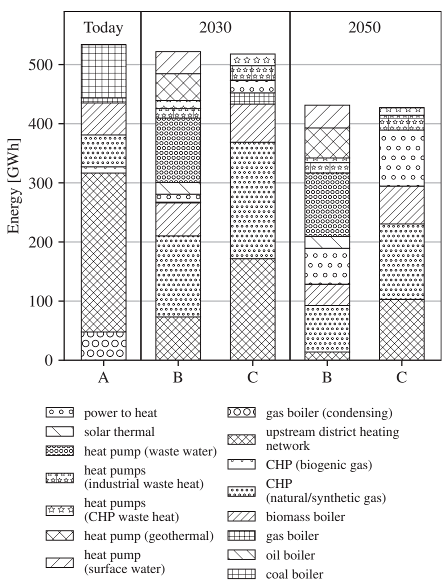

Fig. 2. Energy share of annual thermal energy supply of each heat generation technology.

The analysis of the case studies shows that if the ambitious transformation path is pursued, the diversity within the model district will increase in the medium-term, as it is shown in Fig. 4. This is due to the partially preceded substitution of fossil combustion technologies to biogenic and synthetic ones, as well as to electrified supply technologies. As transformation continues, the balance shifts to electricity-based heat supply, reducing the diversity of the system. For the conservative transformation path shown in scenario C, there is a continuous increase in diversity. Due to a broad resource base of the assessed heat supply systems, the diversity of the conservative transformation path significantly exceeds that of the ambitious scenario B in 2050.

A similar trend results from the quantification of the shares of loose and optionally coupled units in the heat supply of the model district, as shown in Fig. 5. Equivalent to the diversity assessment, the ambitious transformation path shown in scenario B achieves a higher value compared with the conservative one in the medium-term view. With the progressing transformation and thus the electrification of the heating sector up to 2050, the picture shifts and the conservative transformation path C will perform better. In contrast to the diversity indicator, the examined transformation spectrum shows a continuous deterioration in relation to the status quo regarding the share of loose and optionally coupled units in the heat supply of the model district.

Fig. 6 shows the results of the redundancy analysis. Since as indicator for the redundancy is the total risk of supply deficit, higher values

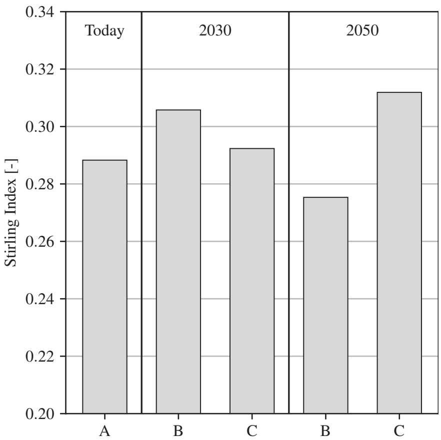

Fig. 4. Results of the Stirling index as indicator for diversity for the heat supply scenarios of the case study.

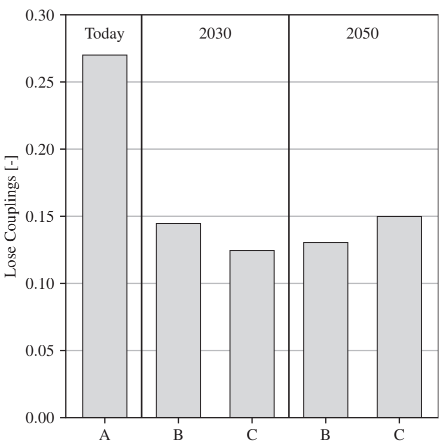

Fig. 5. Results of the shares of loose and optionally coupled units in the heat supply scenarios of the case study.

mean a higher risk and indicate a lower redundancy. Based on the current composition of the heat supply units in scenario A, the additional installation of heat pump capacities (waste heat and CHP low-temperature heat) leads to an increase in redundancy. In this case, the risk of a supply deficit is reduced (see Fig. 6). In the medium-term perspective of the supply scenarios of the year 2030, the redundancy in scenario B improves, while the redundancy in scenario C deteriorates, which is indicated by higher values of the total risk of supply deficit (see Fig. 6). This is due to the additionally installed wastewater and surface water heat pumps in B, while there are no plans to develop decentralized heating capacities in scenario C. In the long-term perspective of the supply scenarios of the year 2050, the redundancy increases in all scenarios compared to 2030, since taking a renovation rate of 2% into account reduces the heat requirement. The relative differences between the supply scenarios remain.

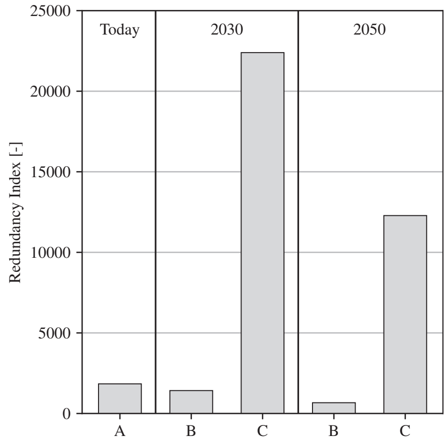

Fig. 6. Results of the redundancy index for the heat supply scenarios of the case study.

4. Conclusion and Outlook

There are many assessment methods for resilience in the literature. Jesse provides an overview of a large number of different resilience theories and associated assessment methodologies in his review article (cf. Jesse et al. (2019)). A distinction is made between qualitative and quantitative assessment. Jesse notes that, given the multitude of definitions, resilience is often equated to the opposite of vulnerability and so often quantified as a reversal of a vulnerability analysis. The resulting resilience assessment is therefore only an indicator of how the system would react to the known and tested disruptive events, but does not provide any information about the behavior of the system in the case of completely unknown and unexpected stressors. The evaluation method used in this work focuses on the resilience-increasing structures and functionalities of the system and tries to assess the resilience by quantifying those. This approach has already been followed with regard to diversity and connectivity in a system (cf. Stirling (2010); Binder et al. (2017)). With the work on which this article is based, the structural and functional assessment method was expanded to include the dimensions of redundancy and loose couplings and refined to the specific case of heat supply in urban districts.

The application of the operationalization methods to the case studies of the model districts shows that the evaluation indicators are able to produce plausible and comprehensible results. Thus, the indicator-based assessment seems to allow a quantitative comparison between different options of technical energy systems in regard to their resilience. In addition to the assessment of the resilience of energy systems, the method presented in this paper also offers potential opportunities for creating and varying scenarios for the modeling and simulation of energy systems for a comprehensive resilience analysis.

However, just as resilience competes with other objectives in the transformation of energy systems, such as defossilation and cost-effectiveness, there are trade-offs with the implementation of resilience enhancing functionalities and structures. For example, with an increasing diversity in the system, the complexity increases as well, which adversely affects the design principle of simplicity. To assess the resilience comprehensively, it is necessary to develop a methodology to quantify further design principles and to derive an overall assessment framework considering all design principles taking into account a more socio-technical focus rather than only a technical view.

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