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Towards a Unified Framework for District Heating Resilience

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Abstract **– Ensuring an uninterrupted supply of energy, electricity, and heat is becoming a pressing necessity. Resilience is the ability of a system to recover from adversity and in connection with the critical infrastructure – the ability to prepare for and adapt to changing conditions, and withstand and recover rapidly from disruptions. If energy resilience has not been well considered or even ignored in the planning, design, and operation stages in district energy communities can lead to system fragility and vulnerability. Therefore, the research assesses the different methods for resilience assessment in energy systems by focusing on district heating. Based on current studies, the energy resilience assessment is mainly considered for the electricity transmission system. The study on heat supply resilience is limited. During the research of the literature, it has been concluded that there is no consistent quantitative and quality approach to resilience because there is no consistent treatment of the concept of resilience. There is a need for a fundamental generic quantitative and quality approach for resilience, which can be used for the development of resilient systems and effective resilience strategies for district heating systems.**

Keywords **– District heating systems; resilience assessment; smart energy systems.**

1. INTRODUCTION

The decarbonisation of Europe’s energy supply relies on the expansion of district heating (DH) networks and increasing the share of renewable energy sources (RES) and waste heat [1]. This includes energy generation from fluctuating sources like solar and wind as well as integration of heat flows from industry, which the DH system can utilise and store [2]. The recent Russian Federation’s (RU) aggression in Ukraine (UA) has led to a significant energy crisis, emphasizing the need to accelerate the transition to RES-based energy systems to enhance the European Union's energy safety and independence [3]. The energy markets were already disrupted following the pandemic, but the following RU-UA conflict rapidly escalated the energy prices with natural gas and oil prices reaching the highest levels in recent history. As RU is a major contributor of these resources, the impact of sanctions from the EU and other countries, significantly reduced the availability of these resources to other countries. This lead to record high prices in European and Asian markets and overall increase in inflation, as well as significant changes in energy source distribution in different countries. This has made the energy systems more vulnerable to disruptions [4].

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The main advantages of a resilient DH system are the opportunity to use local renewable energy sources and waste heat to provide energy for a wider community, enhancing energy efficiency and costs due to independence from a single energy source and provision of reserves and energy storage systems in case of crisis. Additional benefits include stable energy supply, local economy boost, additional jobs and insurance against risks. The most important goal for a resilient DH system is to provide independence from fossil fuels with local energy sources. The main challenges for DH systems caused by global energy crisis are high costs of fossil fuels, fuel supply disruptions, climate change, decarbonization goals, available energy sources, the condition of existing and new networks, demand fluctuations, local risks and environments. Currently, some or even all of these challenges can be observed in existing DH systems [5].

The implementation of renewable energy technologies is an important task for emissions reduction and climate change mitigation in the EU and globally. However, this process is slow not just due to the costs, but also regarding the technologies themselves and society. The goal is to develop sustainable and resilient local energy systems, but environmental factors are studied the most, followed by technical, economic, institutional political and social aspects. These do include the reliability and security, but do not regard operational changes due to disruptions or risks that can affect the resilience of the energy systems with renewable energy technologies [6].

A switch to low-temperature DH networks is also a trend that has to be considered regarding resilience. It reduces grid losses and improves the operation and use of local heat sources. Resilient heat sources are just as important as market conditions, especially in cases where solar energy technologies, like photovoltaic systems, are added to DH and cooling systems. These kinds of systems have been studied more with regard to life cycle and environmental benefits, not really regarding resilience aspects [7].

Climate change has also exposed the DH systems to a critical aspect of energy system resilience that is presently underexplored and insufficiently considered in planning and redesigning DH systems to meet the regulatory frameworks' requirements [8]. This underscores the necessity of developing a scientifically rigorous DH system resilience assessment.

Any system operates at the optimal capacity in the range of set parameters and characteristic conditions; however, the conditions of the surrounding environment are not always close to optimally designed parameters [9]. Even the most stable systems have occurrences of operational parameter changes outside the planned ones. Systems are designed considering the limits of impact parameters [10]. Regular or directly irregular changes outside projected conditions rapidly increase the weariness of the system.

The resilience of engineered systems has been studied through absorptivity, adaptability and recoverability (see Fig. 1) aspects using the models regarding disruptive events and with a resilience factor [11]. Resilience assessment describes the ability of the system to combat disruptions while obtaining prevention measures and developing adjustments to provide effective responses to different impacts [12]. The framework of resilience assessment consists of:

- system identification, including the determination of goals and objectives;
- vulnerability assessment of the system to define appropriate response actions;
- an objective evaluation of resilience actions;
- coordination with stakeholders to ensure necessary solutions and knowledge to operate the system;

– determination of resilience capacities (absorptive, adaptive, recovery and restoration) [13].

A basic framework for resilience analysis of engineered and infrastructure systems has been shown in Fig. 1 [14]. Robustness and reliability are characteristics of the system that are important before disruptions occur and focus on mitigation of disruptive events [15]. Adaptive capacity describes the adjustment abilities of the system after disruptive events, including anticipation, recognition, preparedness, and reorganisation measures [16]. Recovery and restoration capacity describes the ability of the system to return to its originally defined or enhanced operation with a known level of reliability. In practice, recovery may be delayed by conflicts of interest and stakeholder opinions [13]. The National Academy of Sciences (USA) [17] defines the main components of resilience as 1) plan and/or prepare (the foundation of basic functions), 2) absorb (availability of basic functions), 3) recover (restoring pre-event operation conditions), and 4) adapt (implementing new knowledge for future solutions).

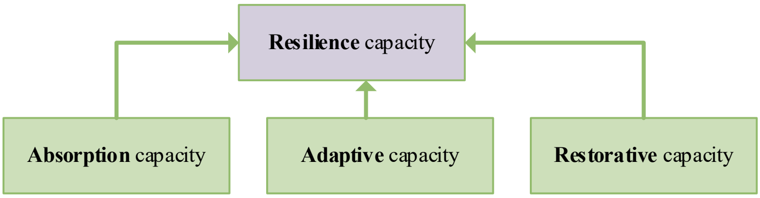

Fig. 1. The three major factors of systems resilience [14].

Several studies focus on the resilience of energy supply systems, where the influence sources are natural disasters [18], extreme weather conditions [19], mechanical damages [20], cyber-attacks [21], etc. The functions of the system must be considered for resilience assessment, including adaptability to different variations when faults occur. Resilience assessment of energy systems includes the improvements of robustness to enhance energy reliability, as well as different modelling approaches [22]. The main solutions studied for the improvement of energy resilience so far include choice of initial and emergency energy sources [23], transmission systems, alternative energy producers, an ability to separate subsystems, improved power distribution channels, and distribution of energy supply and prosumers [24]. The inclusion of transportation can promote the resilience of energy systems on a city scale if the source of energy is renewable [25]. Additional advantages of energy system resilience are increased synergies between involved parties, a possibility to decarbonize the system and improve energy security [26]. Energy resilience in power systems so far is described through the supply-demand chain in the following stages: energy supply-demand chain and power generation [27], power transmission network [28], energy storage [29] and power distribution networks [30]. Also, district heating infrastructure is continuously subjected to different inner and outer impacts which cause stress in the system and highlight its resilience of the system.

Based on current studies, the energy resilience factor for most is considered in the context of the electricity transmission system, and the DH infrastructure resilience study is limited. Therefore, the research performs qualitative and quantitative literature research on energy system resilience methods for resilience assessment in energy systems by focusing on DH. The aim of the paper is to establish the current “state-of-the-art” regarding DH resilience and establish a starting point for resilience assessment development for DH systems (see Fig. 2).

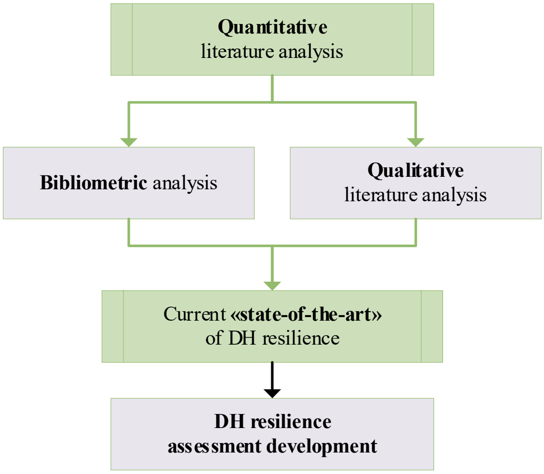

Fig. 2. The algorithm of the study.

2. METHODOLOGY

The quantitative and qualitative literature reviews have been carried out to answer three main research questions:

1. What are the focus areas, methods and impacting factors analysed in energy system resilience assessments?
2. How far the heat supply resilience is included in the energy system resilience analyses?
3. What are the focus areas in DH resilience, security, and flexibility assessments?

After identifying the main research questions, the collection of relevant papers for quantitative analyses has been done. The Scopus database is chosen for document retrieval as it includes the top 100 journals for the subject area "Energy" [31]. The document retrieval was performed in March 2024. Further, the selection of search criteria has been performed. For the initial keyword identification, a preliminary assessment of relevant research papers has been done, followed by backward and forward searching to improve the search criteria.

To answer defined research questions two separate paper selections have been performed. The first one was based on the keyword "*energy system resilience*" (search string: TITLE-ABS-KEY ("energy system resilience")) to identify the overall research trends in energy system resilience and its relation to heat supply systems. The second research paper selection was based on several keywords related to DH resilience: *"district heating system"* and *"safety"*, *"flexibility"*, and *"resilience"* (search string: TITLE-ABS-KEY ("district heating systems") AND TITLE-ABS-KEY ("safety" OR "flexibility" OR "resilience"). The keywords have been extended because when using only "*district heating resilience*" very few papers have been found. The addition of keywords "safety" and "flexibility" are included because they help describe the adaptive and the restorative capacities of systems.

The keywords *"energy system resilience"* found 77 research papers in Scopus with the first publication found in 2014 (see Fig. 3). The number of publications has increased significantly since 2021 highlighting the importance of this topic during the last years with extreme external conditions (pandemic, significant fuel price increase, lack of resources). The keywords *"district heating system"*, *"safety"*, *"flexibility"*, and *"resilience"* found 333 results starting from the year 1977 indicating that the secure operation of DH systems has been researched for a longer period. However, much more research has been published since 2015. It should be noted, that a significant share of these research articles (60) have been published in Denmark.

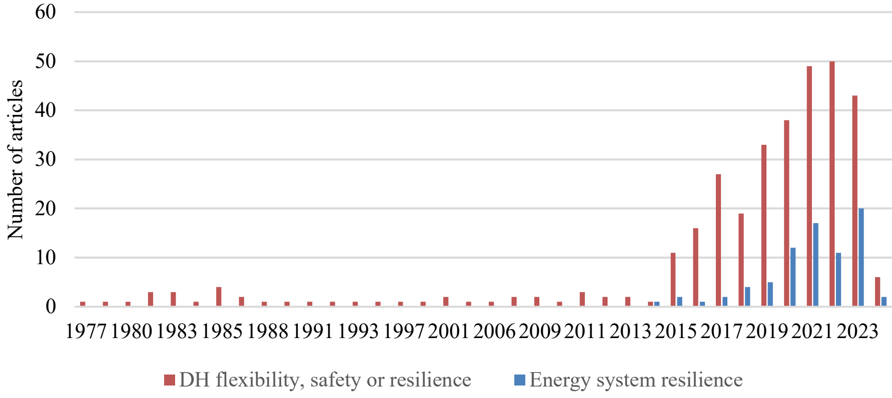

Fig. 3. Number of articles related to energy resilience and DH flexibility, safety or resilience.

Further, *VOS viewer* software has been used for the visualisation of the timely dynamics of keywords used in both research sets. The software allows visualization of co-citations of all indexed keywords by using the colour scale of average time of the documents including a particular keyword. Therefore, it is possible to indicate which keywords are used more often and their relations. The minimum number of keyword mentions was set to 5 to acquire a representable set of keyword clusters, and close duplicates were combined by providing a replacement thesaurus (e.g., keywords "*alternative energy*", "*renewable energy*", "*renewable energy source*" were replaced by "renewable energy sources").

3. Results

3.1. Quantitative Literature Review

Figure 4 indicates the keyword relationship for the searching results under *"energy system resilience"* keywords. It is not surprising, that the keywords with most often occurrence was general ones "*energy systems*" (27 occurrences and 138 link strength), "*system resilience*" (22 occurrences and 135 link strength) and "*resilience*" (19 occurrences and 69 link strength). However, they were followed by keywords "*climate change*" (13 occurrences and 67 link strength), "*energy policy*" (11 occurrences and 72 link strength) and "*energy security*" (27 occurrences and 138 link strength) indicating the main aspects driving the increased focus on energy system resilience research. The energy system resilience key-word mapping also shows that the keywords related to heat supply ("*thermal energy*", "*thermal energy systems*" and "*air conditioning*") are connected to "*buildings*" and "*environmental technologies*". However, they are poorly linked to the general energy system resilience keywords. It approves that most of research of energy system resilience are power system oriented without including DH systems. District heating has not been identified as a keyword for *"energy system resilience"* among the identified research set.

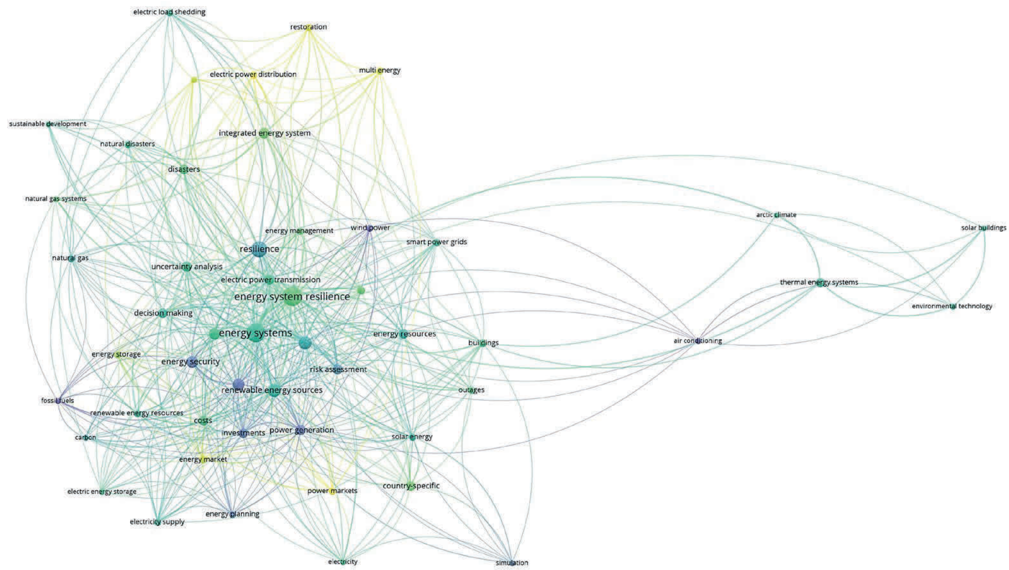

Fig. 4. Key-word relation network for "*energy system resilience*" research set.

Figure 5 shows the key-word interlinkage for the second research set by using "*district heating system*" and "*safety*", "*flexibility*" or "*resilience*". Within this research set the most common general keywords are "*district heating*" (282 occurrences and 2759 link strength), "*district heating system*" (214 occurrences and 2109 link strength) and "*heating equipment*" (155 occurrences and 1588 link strength). However, they were followed by keywords "*heat storage*" (85 occurrences and 1113 link strength), "*wind power*" (58 occurrences and 700 link strength) and "*combined heat and power*" (52 occurrences and 643 link strength). Also "*renewable energy sources*", "*optimization*" and "*heat pumps*" are among often occurring keywords in relation to district heating flexibility and security assessments. Several keywords indicate the interlinkage among heating and power systems (e.g., "*power generation*", "*electric storage*", "*electric power transmission*"). Several keywords are related to cost optimisation, operation and regulation of the system and uncertainty analyses, however, there are no keywords related to security or safety of heat supply systems. There are no keywords related to district heating system and security or safety of heat supply systems, showing that the restorative and adaptive capacity of resilience assessment for district heating systems is insufficient to be considered as a direct application of resilience assessment for DH systems.

The quantitative analyses of key-word mapping indicated that current research of energy systems resilience have not been directly applied on the DH system analyses. Therefore, a more detailed qualitative assessment has been performed for the identified most relevant research.

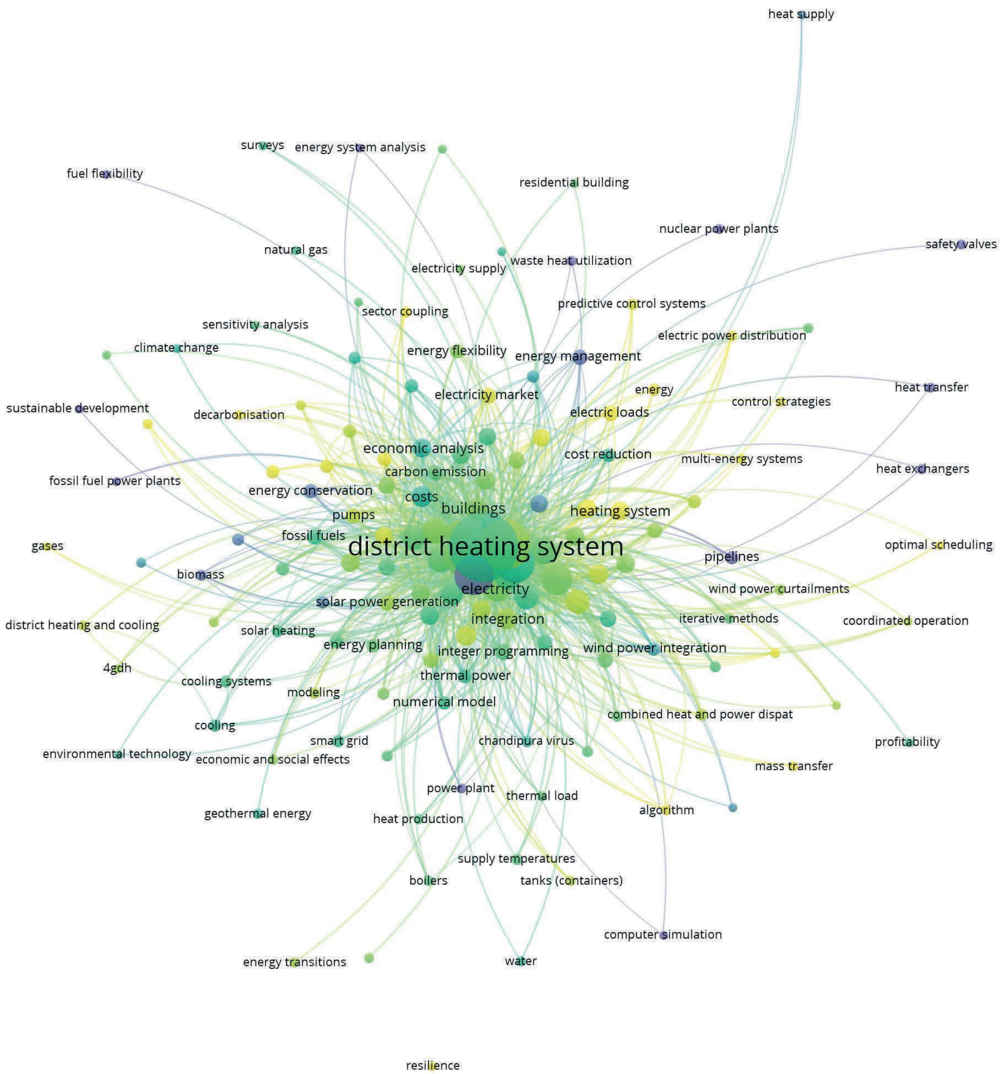

Fig. 5. Keyword relation network for "*district heating systems*" and "*flexibility*", "*safety*" or "*resilience*".

3.2. *Qualitative Literature Review*

3.2.1. External Impacting Factors and their Potential Impacts

Disturbances or disruptive events are individual events or a set of events that, acting on a system, make it sensitive or cause a disturbance in its operation. In most sources of scientific literature, the circumstances of damage to the electricity infrastructure are reviewed. Zhou [32] divides the energy system security elements into threats affecting infrastructure, operational continuity, data management security and government regulation. In turn, these security aspects are affected by various sources: cyber-attacks, terrorism, technical failures, natural disasters, climate change, market fluctuations, and governmental decisions. Natural conditions are one of the most common causes of infrastructure damage-disruptions. According to research, lightning accounts for 10–35 % in the Nordic countries, and other natural conditions (e.g., storms, floods, icing, etc.) account for 4–25 % of disturbances [33].

Otuoze *et al*. [34] have categorized the main security threats of smart grids into technical and non-technical. The technical threats include infrastructure, technical operational and system data management security. Non-technical threats are environmental and government regulatory policies and implementations.

The threats analysed in relation to the security of DH systems are more related to heat prices [35], fuel availability, physical failure of components or faulty operation. Olsson *et al*. [36] have identified key supply chain risks for biomass-based heating systems. Risks associated with potential local fuel shortages (biomass and peat) have been also assessed by Karhunen *et al*. [37]. Mao *et al*. [38] have focused on the vulnerability of DH networks by assessing the potential failure scenarios of pipes. Also, other research [39], [40] identifies the leakages in DH pipes due to corrosion or mechanical impacts and reduced thermal insulation performance as important damage type. Additionally, cyber-security is also one of the possible threats for the continuous heat supply [41].

Based on the previous research, the more specific threats associated with secure DH supply have been summarized in Fig. 6. Different treats have been identified for the overall DH system operation and main elements – heat source, heating network and consumers.

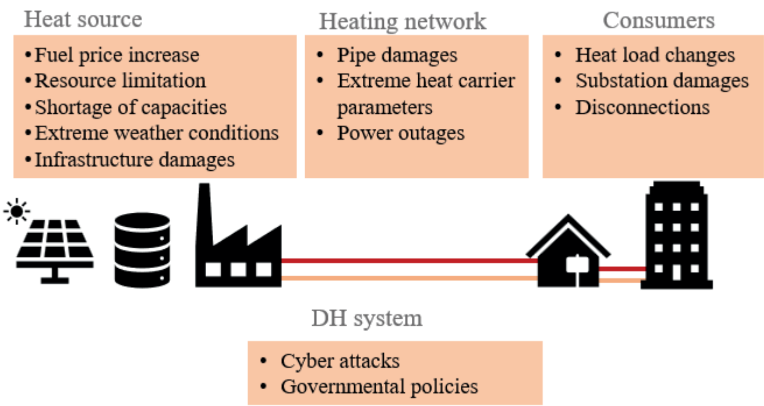

Fig. 6. DH system threats and resilience aspects.

3.2.2. *Quantification Methods of Energy System Resilience*

There is no clear method for energy resilience quantification. Studies have tried to quantify:

1. Energy resilience with absorptive capacity [13];
2. Additional costs to improve the productivity of a system and ensure recovery [42];
3. Recovery ratio [43];
4. Adaptability ratio [44];
5. Performance difference between stable and disrupted operation [45];
6. Sum of energy costs and energy lost due to disruption [46];
7. Stability index of a system [47];
8. Resilience index [48];
9. The utilization ratio of available capacity [49].

The summary of the reviewed case studies and the systems studied there is given in Table 1.

TABLE 1. THE SUMMARY OF REVIEWED CASE STUDIES

No.	Studied system	Impact	Resilience evaluation	Source
1.	Petrochemical supply chain and other supply systems	Hurricane	Resilience costs Characteristics for improvements Absorptive capacity Adaptive capacity	[50]
2.	Water and power systems	Earthquake	System performance The system repair efficiency and impact	[51]
3.	Electric power system	Hurricane	Quantified resilience Economic losses	[43]
4.	Power grid resilience	Extreme weather intensity Grid exposure Vulnerability Impact levels	Reliability evaluation Grid resilience enhancement and grid resilience assessment Restorative measures	[44] [52]
5.	Engineered and community systems	Seismic event	Seismic resilience (technical, organizational, social and economic dimensions)	[45]
6.	Energy system	Disruptions	Energy security criteria evaluation based on fuel supply, electricity production and DH operation analysis	[46]
7.	Energy system	Disruptions and risks	Improvement of adaptive capacity measures (ecological resilience, psychological resiliecnce, energy security, disruption impacts and risk assessment)	[47]
8.	Engineered energy systems	Disruptions Varying operation modes	Performance-based resilience assessment (functionality loss and associated financial losses)	[48]
9.	Shipboard power system	Distributed energy management	Grid resilience Energy storage system evaluation	[49]
10.	DH system elements	Vulnerability	Failure simulation models Feasible life service method Hydraulic analyses Functional reliability index (for pipe and pump damages)	[38] [39] [53] [54]
11.	Thermal energy community	Energy security	Agent based modelling	[55]

Absorptive capacity is related to the design and main operation of the system, providing robustness to minimize the impacts of disruptions. The management of the system is the main feature to define the absorptive capacity offering abilities to better control and operate systems.

An example of resilience evaluation for a petrochemical supply chain operation after a hurricane is given. It looks at the additional resilience costs and the characteristics for developing improvements related to changes in the function of a system due to disruption. To determine recovery-dependent resilience costs (RDR), two variables are needed – influence the productivity of a system (SI) and total recovery effort (TRE). SI is the difference between the target and actual performances of the system, while TRE describes the recovery efficiency of the system after disruption. These variables lead to a unified variable - RDR, which is dimensionless and best used for the comparison of different systems influenced by the same disruption. The relations between the different variables adding up to the resilience costs are displayed in Equation (1) [50].

$$RC = SI + MRE + TRRE/TMVP, \quad (1)$$

where

RC	resilience costs, unitless;
SI	influence productivity of a system costs, currency;
MRE	market recovery effort costs, currency;
TRRE	transportation recovery effort costs, currency;
TMVP	target market value of production costs, currency.

The characteristics framework includes the improvement of the main capacities of the system. Examples of absorptive capacity for supply systems are additional storage, robustness of the system and redundancy, like dispersed supply of raw materials. Adaptive capacity is enhanced by emergency generators in power supply systems, the ability to replace system components with alternatives and change production technologies to obtain the same output. Dynamic repairs such as investments and outsourcing leading to permanent changes in the system improve restorative capacity [50].

Resilience analysis with a focus on performance in case of an earthquake has been carried out for water and power systems with related infrastructure in Los Angeles. Modelling was used for system development and change in 47 different scenarios. The main outputs were curves for system performance, power supply reduction, reduction in gross regional product and households without power supply. To combat possible damages, a restorative model was developed to analyse the system repair efficiency and impact [51].

The resilience of an electric power system in the event of a hurricane has been analysed using a set of models – a hurricane hazard model, models of component fragility, a performance model and a restoration model for an electric power system. The main outputs of these models are quantified resilience and economic losses. The power system was based on an existing system using real data for outages and actual restoration data after a hurricane in 2008 [43].

Jufri *et. al.* [44] studied another example of power grid resilience changes in extreme weather conditions. The main characteristic of a resilient grid is reliability, which is mostly used in the evaluation of system performance. It examines the frequency and duration (>5 min) of outages caused by common disturbances that are more local and impact smaller areas (high probability – low impact events). Disturbances caused by extreme weather conditions are assessed separately from reliability evaluation. An active operation of the grid in extreme weather conditions is expected. Therefore, grid resilience focuses on adapting complex restorative measures after extreme weather events to improve the system after long outages (low probability – high impact events) [52].

Grid resilience considers weather intensity, grid exposure, vulnerability and impact levels. A more detailed grid resilience framework consists of two parts – grid resilience enhancement and grid resilience assessment. The enhancement includes cost-benefit analysis, stakeholder engagement evaluation, physical hardiness and operational capability of the system. The assessment summarizes weather data, grid information, hazard modelling, grid resilience index, and different states describing prevention, degradation, restoration and adaption measures [44].

Seismic resilience evaluation is considered for both engineered and community systems. It is enhanced by improving the infrastructure of the community to make it able to perform the necessary measures during a seismic event and lead a successful recovery effort. The concepts of resilience can also be defined by technical (performance), organizational (management of measures), social (reducing negative consequences on communities) and economic (financial losses) dimensions [45].

A case study of the Lithuanian energy system is analysed, regarding fuel supply, electricity production and DH operation to justify the use of resilience in this case and demonstrate the advantages of the developed methodology. The main advantage of this methodology is the expansion of traditional tools of energy system modelling by adding disruptions offering an ability to model scenarios by energy security criteria [46].

Another evaluation of the energy system's resilience focuses on enhancing economic stability by improving adaptive capacity measures, including ecological resilience, psychological resilience, energy security, disruption impacts and risk assessment [47]. The key components of adaptive capacity in this case are diversity, additional capacity, structure and efficiency of the system.

Performance-based resilience assessment is a different option offered for the evaluation of engineered energy systems [48]. The resilience of the system is based on functionality loss and associated financial losses. The methodology was tested in an integrated energy system of an office building. The proposed methodology gives a quantified outcome for resilience considering system responses to disruptions and varying operation modes. All the components of the system are analysed through the consequence matrix and resilience matrix regarding different scenarios.

Resilience measures have been applied to a shipboard power system, which can also be considered as an isolated electric microgrid system. These measures were implemented in a distributed energy management system. The system was divided in different zones with assigned operators and cloud operators for the energy storage system [49].

When focusing on secure operation of DH systems, several authors have quantified the vulnerability of separate DH system elements trough failure simulation models [38], feasible service life method [39] and hydraulic analyses [53]. Cao *et al*. [54] have introduced the functional reliability index to evaluate the impact of building internal parameters when pipes and pumps are damaged. Fouladvand [55] have used the agent-based modelling to analyse the energy security in thermal energy community with focus on consumer behaviour. However, a comprehensive quantification methodology for DH resilience assessment has not been developed yet.

4. CONCLUSION

The transition to carbon-neutral energy systems and extreme external conditions are forcing to investigate different aspects related to the secure and continuous operation of energy systems. With wider integration of renewable energy sources and sectoral interlinkages, the energy sector becomes more complex. Therefore, the research on optimal operation of energy systems, associated risks and potential solutions has been significantly increased.

The quantitative literature review shows that current research on energy systems resilience is focusing mainly on the secure operation of power systems. The thermal energy supply has not been fully integrated into the overall energy resilience assessment. On the other hand, there is a wide range of research focusing on the flexible, vulnerable, cost-optimal, and secure operation of DH systems. However, current heat supply research is mainly analysing the operation of separate heating system elements and a clear definition of overall DH system resilience is missing.

During the research of the literature, it has been concluded that there is no consistent quantitative and qualitative approach to resilience because there is no consistent treatment of the concept of resilience. The available literature sources about energy resilience are limited in their scope and usability and hence are not amenable for use outside the scope where they have been developed. The metric and formula used for calculating resilience, if any, and the input data required for such calculations are also dependent on the research scope. There is a need for a fundamental generic quantitative and qualitative approach for resilience that would be usable and useful across various scopes or sectors in a consistent manner, which can be used for the development of resilient systems and effective resilience strategies for DH systems.

Further research should focus on merging the energy resilience frameworks with the research on optimal operation of DH systems. Such an approach would allow analysis of the heat supply technologies, operation conditions and efficiency measures that could increase the overall resilience of energy systems.

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