A Review of Multi-Energy Systems from Resiliency and Equity Perspectives

Kathryn Hinkelman[a,*], Juan Diego Flores Garcia[b], Jing Wang[c], Saranya Anbarasu[b], Wangda Zuo[b,c]

[a] *Civil and Environmental Engineering, University of Vermont, Burlington, VT, USA*
[b] *Architectural Engineering, Pennsylvania State University, University Park, PA, USA*
[c] *National Renewable Energy Laboratory, Golden, CO, USA*

Abstract

Energy infrastructure systems need to maintain resilient operation in the presence of more intense and frequent disasters, which are disproportionately challenging for low-income and disadvantaged communities. Leveraging local natural resources with renewable energy sharing opportunities, multi-energy systems (MES) – or energy hubs – are technologically viable solutions to this challenge, but their wide-scale adoption for these purposes are not well understood. To this end, this paper comprehensively reviews MES literature from both resiliency and equity perspectives. The goal is to understand synergies and disparities among literature regarding these two perspectives, under a changing climate and a long-term goal of decarbonization. The results found that papers including equity are statically more likely to involve fully renewable energy systems (highly significant, $p < 0.001$), while middle income countries tend to adopt renewable/carbon-producing energy systems more frequently than high income countries (weakly significant, $p = 0.011$). Mobile storages are implemented independently of resilience and equity scopes, and it is increasingly common to integrate multiple storage types within a MES. Sector coupling with two energy types improved the resiliency index the most (73% difference between baseline and proposed MES), suggesting two-type systems are favorable compared to single-networks or more complex configurations. While some preliminary studies indicate lower operational costs and higher resilience can synergistically be achieved, more MES case studies are required to understand the life cycle costs of resilient design and operating schemes.

Keywords: climate change, energy hub, energy equity, interconnected energy system, resiliency, review, renewable energy

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1. Introduction

Energy systems are under pressure globally to be clean, resilient, and equitably serve community needs. The Intergovernmental Panel on Climate Change (IPCC) stated that it is

*kathryn.hinkelman@uvm.edu

"unequivocal that human influence has warmed the atmosphere, ocean and land", and there is "high confidence that human-induced climate change is the main driver" of hot extreme weather events (including heat waves) becoming more frequent and more intense and cold extreme events becoming less frequent and severe [1]. As such, climate-induced resilience and equity measures are major global concerns, which are reflected in the IPCC's top two climate action opportunities for energy systems of "energy reliability (e.g. diversification, access, stability)" and "resilient power systems" [1]. Further, the increase in climate- and human-induced disasters strain critical infrastructure systems in the built environment, of which energy is central. This has led to the formation of several international programs on resiliency [2] and energy justice [3].

To meet climate action targets while also providing reliable energy services for all, it is advantageous to recognize opportunities to interconnect multiple energy carriers through multi-energy systems (MES) with energy hubs (EH). While the scale, energy carriers, and equipment can vary significantly site to site, Figure 1 depicts an example of a MES and EH. Key features that distinguish MES from *hybrid energy systems* (HES) are the presence of multiple energy carrier sources and end uses. In contrast, HES typically have multiple energy sources or harvesting systems with fully electric distribution systems and end uses [4]. By integrating multiple electric, thermal, and mechanical energy sources, EHs can achieve a zero-carbon goal via deep renewable energy penetration and waste heat recovery while maintaining efficient, reliable, and flexible energy services [5]. Beyond decarbonization, MES can also provide financial and social benefits to communities by enabling pathways to integrate local resources, increase energy autonomy, and leverage economies of scale benefits through aggregation and resource sharing (e.g., higher systemic energy efficiencies through aggregation).

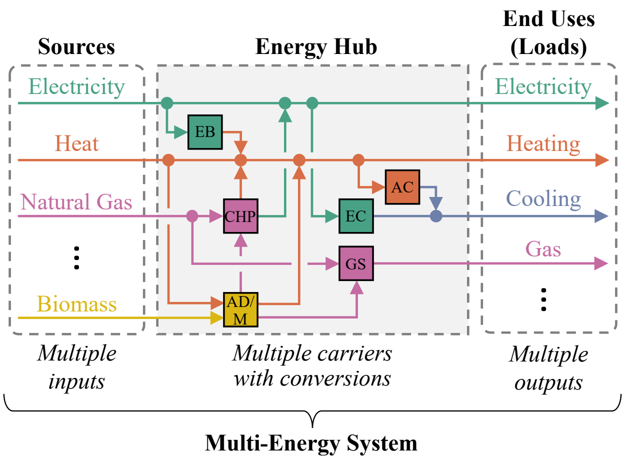

Figure 1: Example of a multi-energy system and energy hub that sources, converts, delivers, and sometimes stores more than one energy type. Conversion equipment shown are for representative purposes and are not present in all systems; these examples include an absorption chiller (AC), electric chiller (EC), electric boiler (EB), combined heat and power (CHP), gas storage (GS), and anaerobic digestion (AD)/methanation (M).

However, despite promising opportunities for MES to meet energy needs from both equity and resilience perspectives, they are seldomly implemented today for these purposes. In general, resilience remains an emerging topic for energy system engineering [2]. Meanwhile, most decarbonizing energy systems for low-income and developing communities to date have focused on lowest-cost electrification pathways [6, 7]; however, "the primary technical hurdles for [renewable energy] integration include the... design for *reliable and resilient operation* with intermittent high-penetration renewable generation" [7]. Addressing this hurdle among others, we aim to review MES literature from both resilience and equity perspectives to understand the extent to which previous literature has addressed these synergistic perspectives, what differences separate their approaches, and where technical gaps remain. In particular, this paper answers these questions through a lens of climate action and decarbonization for energy system engineering design and operation.

1.1. Resilience: Concept and Energy Applications

First introduced to the field of ecology in 1973, *resilience* is defined as "a measure of the ability of [ecological] systems to absorb changes of state variables, driving variables, and parameters, and still persist" [8]. In the context of *sustainability*, natural ecosystems must have sufficient flexibility to respond to disturbances – i.e., be *resilient* – to survive over long periods of time [9]. Since its ecological origin, the concept of resilience has been applied to a wide variety of fields, including safety and risk engineering [10], critical infrastructure systems [11], supply chains [12], and psychology [13], among others.

While the specific definitions and metrics for resilience vary across application domains [14], the fundamental concept can be explained through Figure 2. The three general classification stages of resilience include (1) *preparation*, (2) *resistance and response*, and (3) *recovery*. These three stages are consistent across numerous literature sources [14, 15, 16, 17]; although, the exact terms can vary slightly, and the middle *resistance and response* stage is at times further divided into two. In the first stage, corresponding with *normal operation*, the system can prepare for a future disturbance event δ occurring at time t_δ. This event can exhibit various levels of intensity, frequency, and predictability. Following the event, the time-varying system function $f(t)$ is pushed outside of its normal operating range. To return to normal operation, the system wants to resist the disturbance (limit Δf), respond quickly (limit Δt_1), and recover quickly (limit Δt_2). Generally, the shaded area under the curve represents the impact of δ on f; this is referred as the *total stability* [9] (e.g., ecological context) or simply the *resilience* [17] (e.g., power systems context).

Despite resiliency still being considered an emerging subject in many engineering fields [2], research in energy applications has made notable progress. With respect to MES and EHs, literature has been reviewed from various perspectives, including climate change adaption [18], modeling [19], microgrids including multi-energy microgrids [20], cyber-physical systems [21], and energy-transportation systems [22]. To summarize, previous reviews consider a wide variety of subsystems (e.g., electric grid, gas, cold/heat networks, transportation, water), conversion technologies (e.g., power-to-gas, power-to-heat, power-traffic), typologies (e.g., centralized/distributed, consumers/prosumers), failure events (e.g., equipment failure, natural disaster, supply shortage, cyber attack), and stages (e.g., preparation, resistance/response, recovery). Best practice suggestions are provided for modeling

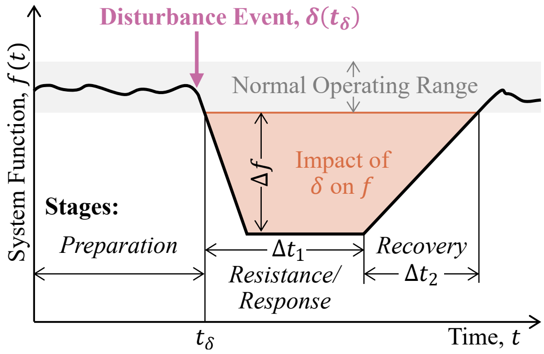

Figure 2: Functional system performance with resilience stages before, during, and after the occurrence of a disturbance event.

methods [19], resilience response strategies [20], and an overall qualitative assessment approach [21]. While indicating that existing research overall is still inadequate [19, 21], some of the identified future needs include resilience under extreme scenarios/high-impact low-probability events [18, 19], higher fidelity models [20], dispatch strategies of coupling components [19], assessment indexes and metrics [21], and interdisciplinary approaches [20].

Unlike previous studies, this work aims to understand resilience for MES applications in relation to equity considerations. From a complex systems perspective, resilience involves socio-economic factors as well as technical ones [2]; for example, the City Resilience Index [23] includes *economy and society* as a core dimension of resilience. In turn, socio-economic impacts due to energy service disruptions can be significant [24, 25]. However, literature reviews that address both resilience and equity perspectives for MES are lacking, to our knowledge.

1.2. Equity: Concept and Energy Applications

Representing the quality of being fair or impartial for all, *equity* is inextricably linked with energy as a universal human right to adequate health and well-being. However, energy systems inequitably serve disadvantaged and marginalized communities with respect to fundamental access and reliability, health and pollution, infrastructure funding and usage cost, and more [26]. Contributing to social injustice and equity problems [7], this lack of energy access directly impacts peoples' ability to obtain clean water, food, and good health. In 2021, 2.3 billion people still relied on dirty, inefficient cooking systems, while 675 million lived without electricity [27]. Lack of access to clean and reliable energy is primarily driven by affordability [7, 28] with the greatest vulnerabilities occurring for people who live in extreme poverty or rural places [6].

To improve clean energy access to billions of disadvantaged people across the world, most efforts to date aim to serve low-income areas by 100% electrified energy solutions with photovoltaic (PV) panels to decrease greenhouse gas (GHG) emissions [7, 6, 29]. These solutions are typically HES with PV and electric generators fed from another energy source, either renewable or fossil fuel based [7, 29]. As such, there is extensive literature on HES from energy equity perspectives [30, 31, 32, 33, 34, 35, 36, 37]. For example, Olówósejéjé et al. [29] found that integrated hybrid solar system with fossil fuel generators and no energy storage are the best solution in terms of financial cost and GHG emissions based on a commercial building case study in Nigeria. For case studies in Nepal, Peru, and Kenya, Yadoo et al. [6] found that microgrids powered by biomass gasifiers or micro hydro plants are favored for their reliability, sustainability, and low cost in rural and low-income regions.

Although HES have been most commonly implemented to date for low-income and remote communities, several open research challenges remain. First, while renewable sources powered 30% of electricity in 2021, heating and transportation sectors have been more difficult and seen less progress [27]. Second, electricity generated from solar PV and wind is highly stochastic, which frequently induces a need for either costly storage (e.g., chemical batteries) or flexible fossil-based generators (typically diesel) [30], posing both financial and environmental concerns. Without fossil fuels, it can be difficult for low-income and disadvantaged communities to achieve a reliable and resilient energy supply [38]. It is known that MES can help address these challenges by, for example, enabling multi-energy vector approaches that match source/delivery energy quality with end use energy quality demands [39], or by mitigating intermediate renewable generation through sector coupling, reducing or eliminating the need for storage [40]. However, it is unclear if MES are economically and technically viable for low-income, rural, and disadvantaged communities.

To this end, some insights are available from literature despite a general scarcity of MES research from an equity perspective. For high renewable energy systems, MES can have lower life cycle costs compared full electric systems with batteries, as Bartolini et al. [41] found when evaluating an MES with CHP and electric/hydrogen storages for a real residential community in Austin, TX, USA. While MES and district energy systems (DES) can be more affordable over their life cycle than other technologies, the shared infrastructure (e.g., DES piping networks) can be difficult to fund compared to individual building systems [42]. Also, MES can be more complex than single-energy network systems (e.g., HES), which poses technical as well as upfront financial challenges. This largely explains why MES have not been frequently implemented for energy equity to date. However with that said, more research is required to shed light on the economic and technical viability of MES for low-income and rural communities.

1.3. Existing Challenges and Objectives

The body of literature indicates several challenges for MES from resilience and equity perspectives that merit further investigation. First, it is important to recognize that both MES and resilience for engineering applications are newly emerging concepts [2, 43], while energy equity amidst the clean energy transition is a highly active and open research challenge [44, 45]. Within these larger domains, equity perspectives of MES are particularly lacking. Second, as an emerging technology, engineering challenges remain when designing and operating MES for various cultures and climates. Third, to our knowledge, there are no reviews on MES from both resilience and equity perspectives, which are highly interdependent and urgent subjects. As such, this study aims to address these important needs in order to understand the synergies, differences, technical challenges, and opportunities for resilient and equitable MES. In particular, our lens tends towards engineering solutions that meet decarbonization goals in the face of climate change.

The rest of this paper is organized as follows. Section 2 presents the methodology undertaken for the technical literature review from document searching through detailed analysis and synthesis. The results in Section 3 are first presented at a high level for the contextual overview, before divulging specifications across physical systems and research approaches. Lastly, Section 4 presents the final conclusions.

2. Methodology

The technical review methodology adopted in this work can be divided into three steps: (1) document identification, (2) document screening, and (3) analysis and synthesis. These steps are presents in their respective sections below.

2.1. Document Identification

All initial documents were collected from the Scopus database following a keyword search using terms listed in Table 1. The search was applied across the article title, abstract, and keywords. We included only document types of *Article* or *Conference paper* written in *English*, without any other restrictions.

Table 1: Keywords for literature search.

or	**and**	**or**
multi-energy		resilien*
multiple energy		vulnerab*
energy hub*		disadvant*
integrated energy		protect*
interconnected energy		secur*
hybrid energy		*equality
		equity
		justice
		developing countr*
		underdeveloped countr*
		low-income
		afordab*

Total number of documents: 2420.

Overall, the objective of the search was to encompass a wide variety of literature without unexpected pre-filtering due to the exclusion of terminology variants. For example, "hybrid energy" at times is used to describe MES, but not always. To not miss publications that are within scope but adopt HES as the referenced system, we included this search term. After evaluating multiple term combinations, Table 1 produced the best results based on the intended scope of MES (system type) and resilience or equity (perspectives). In total, this search identified 2420 initial documents.

2.2. Document Screening

Following the database search, the documents were screened and selected for the detailed review following the PRISMA Statement [46]. Figure 3 shows the results of this process, and the major steps are as follows. After the document identification stage, the titles, abstracts, and keywords were first screened for the inclusion criteria. This first screening criteria required the document to present (1) original research and involve (2) multiple energy carriers (e.g., electric/heating, electric/gas, electric/heating/cooling); (3) the system level (e.g., not a material or one equipment only); (4) technical design (e.g., not policy); and (4) interdependencies (e.g., not separate, independent gas and electrical systems). Following the first screening, full texts for 802 documents were retrieved for secondary screening. In addition to the first screening criteria, the full text filtering also verified that the case study analysis and results included equity and/or resilience.

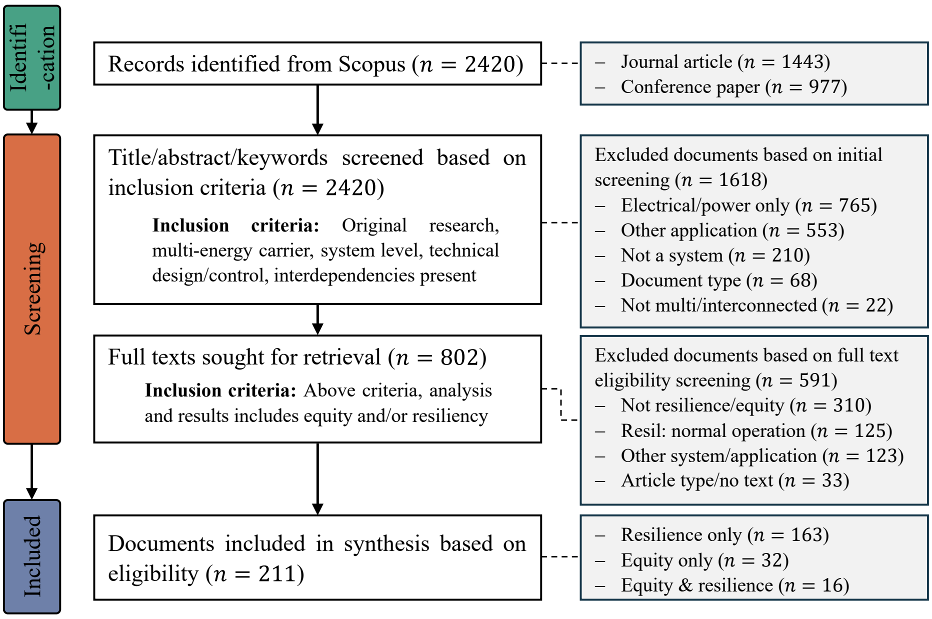

Figure 3: The review protocol to identify documents based on the PRISMA Statement [46].

In the screening steps of Figure 3, several common topics arose that were out of the scope of this work. Most frequently, 765 documents involved electrical/power systems only; while these were excluded because they are not MES, the relatively high volume of electric-only HES reflects the general popularity of this approach (as discussed in Section 1). Similarly, 553 documents involved other applications (e.g., communication only, energy policy, X-ray technology), while 210 documents were not at the system level (e.g., storage equipment, battery control, energy harvester). Further, in the second screening stage, 310 documents were excluded because the title/abstract/keywords mentioned resilience/equity terms, but the analysis itself did not pursue these goals. Additionally, some papers included resilience as part of the methods, but resilience was only assessed during normal operation without any faults/failures ($n = 125$), while other cyber resilience papers did not include information on the physical system infrastructure [47] and thus were excluded. Following the secondary screening, a final set of 211 documents remained for inclusion in the detailed review.

2.3. Analysis and Synthesis

The analysis and synthesis of results first involved a high-level contextual overview followed by detailed review of the full texts. For contextual analysis, we adopted the CorTexT Manager platform [48], an open digital platform for the analysis and visualization of textual data. To inform textual trends and correlations across the 211 documents, the corpus was first imported to CorTexT Manager, containing citation, bibliographic, abstract, and keyword information from Scopus. Then, a terms extraction algorithm identified the top 100 terms across fields of title, abstract, and keywords based on their specificity and frequency, excluding monograms. Specificity was computed as a chi-square (χ^2) score with the standard formula

$$\chi^2 = \sum \frac{(O_i - E_i)^2}{E_i}, \tag{1}$$

where O is the observed value and E is the expected value. Moore and McCabe [49] provides further information on this statistical method.

To identify textual correlations, a homogeneous network map based on the extracted 100 terms was created in CorTexT using the robust distributional proximity measure for edges. The network map involves nodes, clusters, edges, and country labels. Nodes represent commonly occurring terms with larger sizes indicating higher occurrence frequencies. Clusters represent thematic groupings based on the terms content with the size reflecting the number of terms. Edge lengths represent the regularity in which the terms co-occur. Lastly, the top three countries are presented for each cluster, where the country corresponds to first author affiliations.

For the in-depth analyses, classification categories were selected based on the study's objectives and refined based on the contextual overview results. Table 2 summarizes the discrete categories selected for classifying each document, including physical systems and research approaches. Across physical systems, we included six categories. For *energy class*, the systems were classified as nonrenewable/carbon-producing if fossil fuels were included; renewable/carbon-producing if all source energies were renewable, but at least one produces GHG emissions directly through its use (e.g., burning biofuel for heat/electricity); and renewable/carbon-free if all source energies were renewable and none produce GHG emissions directly through their use (e.g., solar PV, wind turbine). Source energies that are not primary sources (e.g., grid, district heat) were not included when determining energy class because the these sources may include any combination of renewable and nonrenewable inputs.

Research approaches included eight categories (Table 2). First, the *scope* was classified as equity only, resilience only, or both equity and resilience, where resilience papers included a fault, failure, or disruption beyond normal operation and equity papers address low-income, disadvantaged, rural, or island communities. For papers that included case studies involving real sites, we noted the geographical location of the case(s) as well as the scale, income, and climate classifications. The determination of "real" was set such that at least part of the system, loads, weather conditions, or failure scenarios involved location-specific information.

Table 2: Classification categories for all documents included in the detailed review with respect to physical systems as well as research approaches.

	Category	Variables
Systems	Energy class	nonrenewable/carbon-producing, renewable/carbon-producing, renewable/carbon-free
	Source energies	grid, natural gas, solar (thermal), wind, biomass, etc.
	Equipment	boiler, chiller, CHP, anaerobic digestion, mobile storage, etc.
	Networks	electric, heating, cooling, transportation, gas, etc.
	End uses	electric, heating, cooling, gas, etc.
Approaches	Scope	equity only, resilience only, equity and resilience
	Scale	building, district, region
	Location	Geographical coordinates representing the case study site
	Income	Country-level income classification of case study site
	Climate	Köppen climate classification of case study site
	Software	MATLAB, GAMS, Python, etc.
	Key metrics	life cycle cost, resilience index, total shifted load, etc.

The system *scale* varied across locations, from single buildings to districts and entire countries/regions, all of which MES can serve [50]. The World Bank's public database on GNI per capita (most recent year) [51] provided country-level *income* classifications, while each *climate* classification reflected the Köppen-Geiger system [52]. Lastly, our analysis noted software tools and key metrics employed across the literature.

To discern correlations between various discrete categories in Table 2, we analyzed the findings using standard statistical methods. Pearson's χ^2 tests of independence [53] (Equation 1) were performed to statistically state the presence or absence of differences between categories (e.g., correlations exist between scope and energy class) and determine which parameters account for the differences (e.g., equity papers are more likely to use renewable systems). To determine the applicability of the χ^2 test for each categorical pair, minimum expected count frequencies followed the guidelines of Moore and McCabe [49] that 2×2 tables (i.e., degrees of freedom $df = 1$) require "all four expected cell counts to be 5 or more", while tables larger than 2×2 required "the average of the expected counts [to be] 5 or more and the smallest expected count [to be] 1 or more" [49, p.631]. As an indicator for statistical significance (i.e., whether the observed differences are real or only due to chance), $p-$values were calculated based on χ^2 and df. Alpha was set at 0.05 for all statistical analyses, with $p \leq 0.001$ for highly significant differences, $0.001 < p \leq 0.01$ for significant differences, and $0.01 < p \leq 0.05$ for weakly significant differences. As an example, $p \leq 0.05$ indicates that there is strong evidence that the observed differences are not due to chance (i.e., there is less than a 5% probability that the observed results are random).

3. Results and Discussion

In total, 211 documents were included in the detailed technical review, published from 1997 to 2023. Spanning lower-middle to high income countries, the document authors were geographically dispersed across predominately Asia, Europe, and North America, spanning 26 countries with 56 publications involving multi-national author affiliations. Top publication sources included *Applied Energy* ($n = 22$), *Energy* ($n = 13$), *Energies* ($n = 10$), and *IEEE Transactions on Power Systems* ($n = 10$). The following sections present the overarching contextual results (Section 3.1), followed by detailed summaries with respect to physical systems (Section 3.2) and research approaches (Section 3.3).

Several categorical pairs produced statistically significant differences across the variables listed in Table 2. For example, equity papers were statistically more likely to have case studies in lower income countries than resilience papers (significant, $p = 0.007$), which follows expectations. For other categories, statistical correlations are presented in their relevant sections below. Detailed results across all categories involving at least one statistically significant correlation are summarized in the Appendix (Table A1).

3.1. Contextual Overview

Of the 211 documents, 77% focused on resilience only, while 15% involved equity only and the remaining 8% covered both, with the overall number of publications increasing overtime (Figure 4). Resilience-only documents have seen considerable growth in publications per year since 2016. Meanwhile, equity only publications began to increase more recently (since 2021). The number of equity and resilience publications were greatest in 2021 but have yet to experience notable growth.

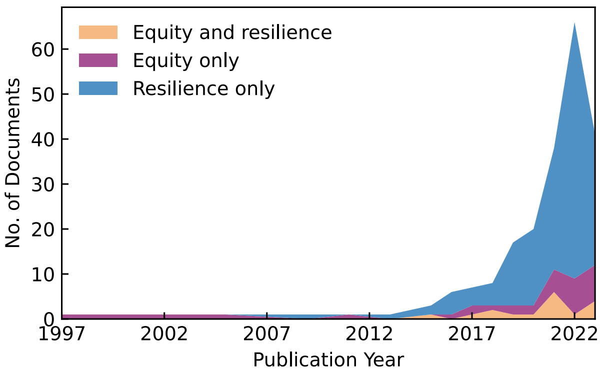

Figure 4: Number of documents published each year on equity, resilience, or both. Note that the final year (2023) is a partial year.

Table 3 presents the top ten most frequently occurring terms, beyond original search criteria (e.g., "energy system", "multi-energy system", "resilient operation") and common single energy system terms (e.g., "gas network", "energy sources", "energy flow"). Across all terms, "energy storage" was the most frequently occurring ($n = 41$). Common physical system references included CHP, "transportation network", and "distributed energy resources".

These terms also reflect an interest in control actions ("demand response"); failure types ("cascading" and "extreme weather"); and environmental considerations ("renewable energy", "environmental protection", and "CO2 emissions").

Table 3: Top ten frequently occurring terms excluding original search criteria and common single energy terms.

Term	Frequency	n
energy storage	56	41
demand response	26	20
combined heat and power	23	23
cascading failure	19	12
environmental protection	18	12
renewable energy sources	17	14
transportation network	16	9
distributed energy resources	13	10
CO2 emissions	12	8
extreme weather events	11	9

Further clustering the top 100 terms as a homogeneous network map, Figure 5 depicts ten thematic categories, their interrelationships, and common terms within and spanning each cluster. The three largest clusters by number of terms are "energy carrier microgrids & multiple energy" (16 terms), "system security region & energy system security" (15 terms), and "developing countries & rural areas" (15 terms). While the remaining analysis focuses on specific technical aspects, the bibliographic results here give a valuable picture of unbiased themes and common content across the full database.

3.2. Physical Systems

To understand the technical content in detail, the studies were first classified by the physical systems. Following the categorizations listed in Table 2, the review results are as follows.

3.2.1. Source Energies

While 32 source energy types spanned all studies, natural gas, solar, and wind were the most dominant primary sources, in addition to indeterminate electric grid connections (Figure 6a). While a grid source input was listed (just as heat and hydrogen), the source energies for electricity, heat, and hydrogen generation were not always documented. As such, these inputs have the potential to be from renewable or nonrenewable sources. Among all studies, solar (PV) and wind (turbine) were the most common renewable sources. For equity only studies, solar (thermal) and biomass were also common.

Interestingly, Figure 6(b-d) further indicates statistically significant differences in system classes for decarbonization goals. Papers including equity were statically more likely

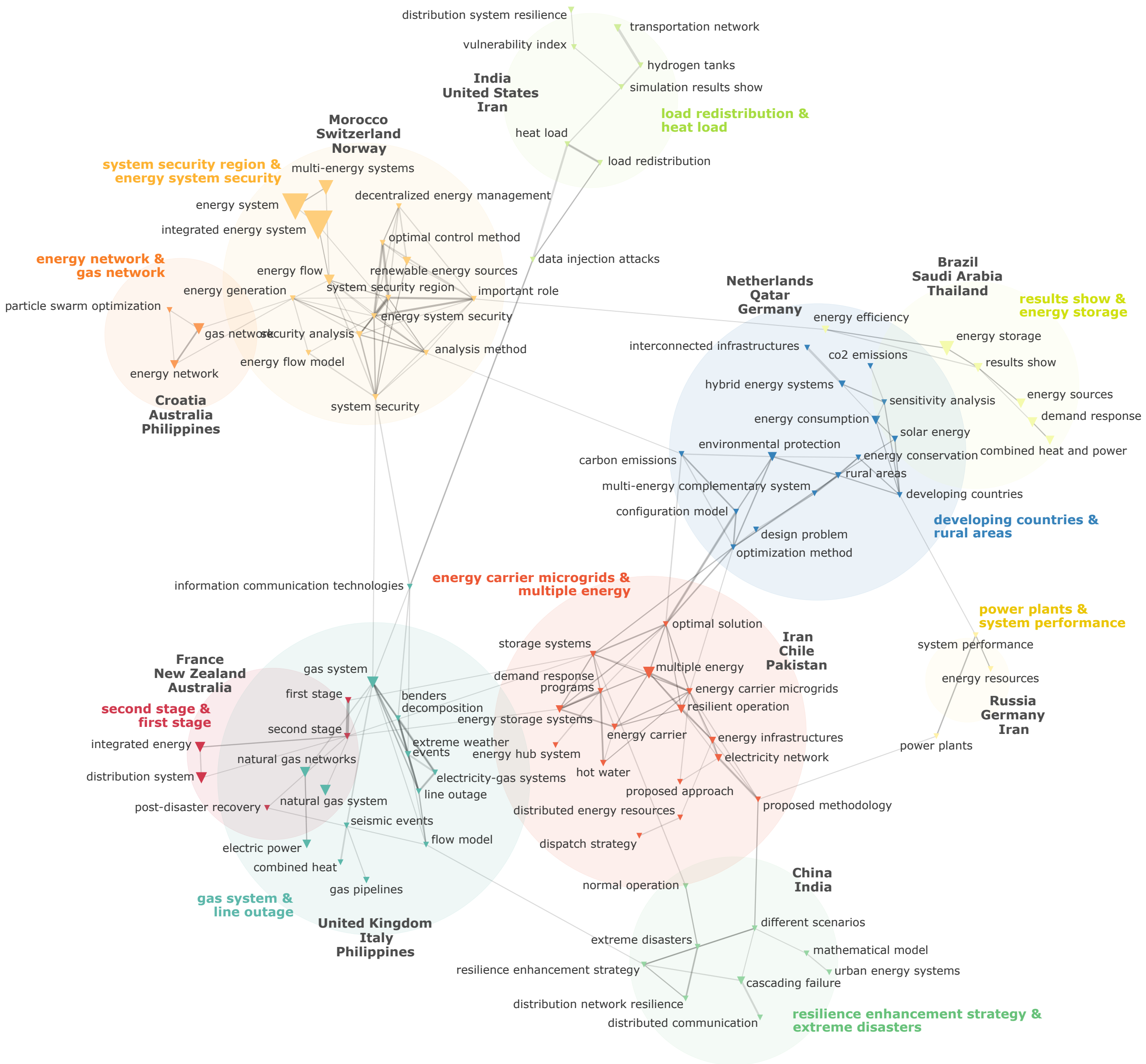

Figure 5: Homogeneous network map of commonly occurring terms across titles, abstracts, and keywords from all included documents. Top three countries from first author affiliations are listed for each cluster.

to involve fully renewable energy systems (highly significant, $p < 0.001$). In particular, the majority of renewable/carbon-producing systems involved equity; the majority of nonrenewable/carbon-producing systems involved resilience; and renewable/carbon-free systems frequently involved equity and not resilience ($p < 0.001$). Figure 6(b,d) shows these differences clearly, where 91% of case studies on resilience only involved nonrenewable/carbon-producing sources, while 59% of equity only studies were fully renewable (carbon-free and -producing).

Further, energy class produced statistically weakly significant differences with respect to case study scale ($p = 0.025$) and location income ($p = 0.011$). Specifically, renewable/carbon-

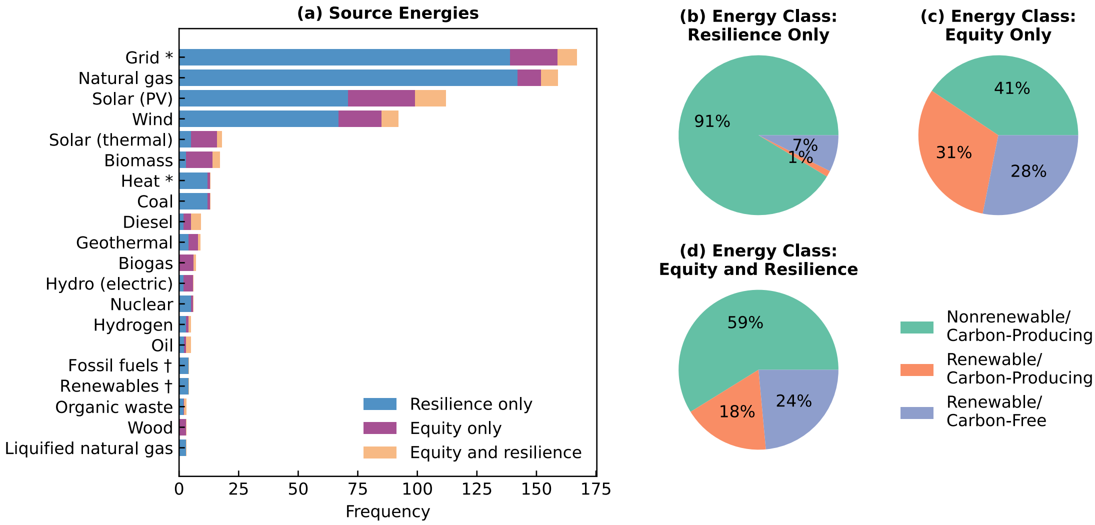

Figure 6: Adoption of (a) source energy types (20 most frequently occurring) and (b-d) energy class for decarbonization goals with documents focusing on (b) resilience only, (c) equity only, and (d) equity and resilience. In (a), energies with * are not primary sources (primary sources not specified in text). Energies with † are generic categories given in text without further details.

producing systems were more often considered for upper-middle and lower-middle income sites than high income sites. High income sites were statistically more likely to include either nonrenewable/carbon-producing or renewable/carbon-free systems.

3.2.2. Major Equipment

Researchers used a wide variety of multi-energy conversion and storage equipment that served gas, electric, heating, and cooling systems (Figure 7). Across all studies, 60% implemented at least one type of energy storage, and 53% involved CHP. More specifically, gas storage included natural gas/methane (CH_4) [54, 55, 56], biogas [57, 58, 59], hydrogen (H_2) [60, 61, 56, 62], oxygen (O_2) [63, 64], carbon dioxide (CO_2) [65], and gasoline [66]. Electric storage included chemical batteries [67, 68, 69] and fly wheels [70]). Heating storage included hot water [71, 72, 73], molten salt [74], and phase change materials [75]. Cooling storage included chilled water [76, 77, 78], ice [79, 73, 80], and molten salt [74]), while stratified thermal energy storage [81, 82]) served both heating and cooling. Of all storage types, electric batteries ($n = 88$), heating ($n = 68$), natural gas/methane ($n = 36$), cooling ($n = 30$), and hydrogen ($n = 18$) were most common. Regarding methane, some case studies included fossil-based natural gas while others were 100% renewable natural gas or a combination of the two.

Beyond static storage equipment, 21 papers leveraged mobile storage (e.g., trucks, buses, electric vehicles) to allow fewer resources to access more locations. Mobile storages were implemented independently of resilience and equity scopes. Of studies with mobile storage, electric vehicles were most common ($n = 13$) [83, 84, 85], followed by plug-in hybrid electric vehicles ($n = 3$) [86, 71, 87] and hydrogen gas trucks ($n = 3$) [64, 88, 89]. Finally, two papers

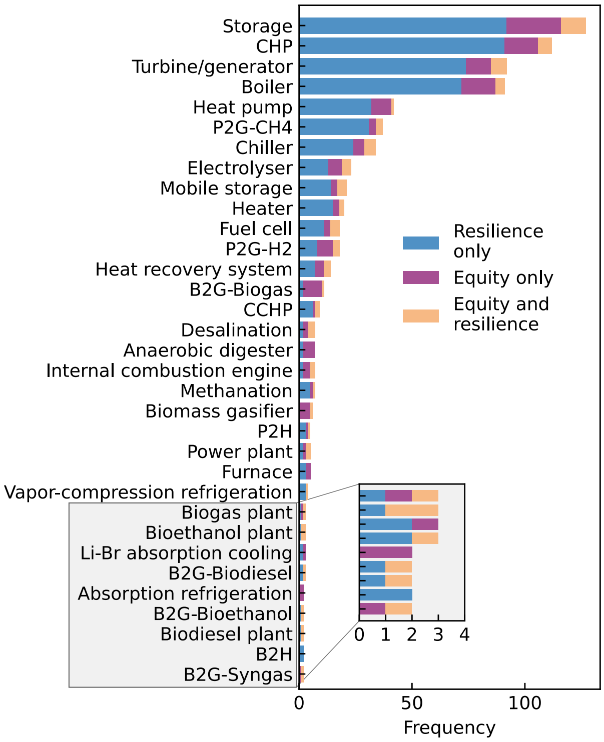

Figure 7: Occurrence frequency of multi-energy conversion equipment and systems with more than one occurrence. Sector couplings include biomass-to-gas (B2G), biomass-to-heat (B2H), power-to-gas (P2G), and power-to-heat (P2H).

used more than one type of mobile energy storage. Sui et al. [80] implemented electric, ice, and water mobile storages in a post-disaster self-sustaining operational strategy for islands, while Tao et al. [90] evaluated the vulnerability of MES involving fuel cell vehicles and plug-in hybrid electric/hydrogen vehicles.

Further, the relative number of documents that include storage are increasing over time (Figure 8). Since the number of publications per year started increasing in 2015, the percentage of papers including either (1) any storage or (2) two or more storages have increased over time. For documents published in 2023 ($n = 41$), 71% included storage, while 49% included two or more storage types. Prior to 2018, no documents included more than one storage type. Mobile storage has not seen significant growth to date and is included in 7.7% of the documents on average.

Spanning both equity and resilience perspectives, 31% of studies integrated sector coupling via *power-to-X* or *biomass-to-X* processes into the system design. Of all variants, *power-to-gas* with the gas as CH_4/natural gas was most common ($n = 38$), followed by power-to-gas producing H2 ($n = 18$). Studies also captured heat through *power-to-heat* [61, 91] and *biomass-to-heat* [92, 93] processes, which may have been wasted otherwise. Across all *biomass-to-gas* studies ($n = 21$), the “gas” included biogas [75, 92, 94], biodiesel [92, 95], syngas [96, 97], and others [92, 93, 95], such as bioethanol, biochar, glycerol, and methanol.

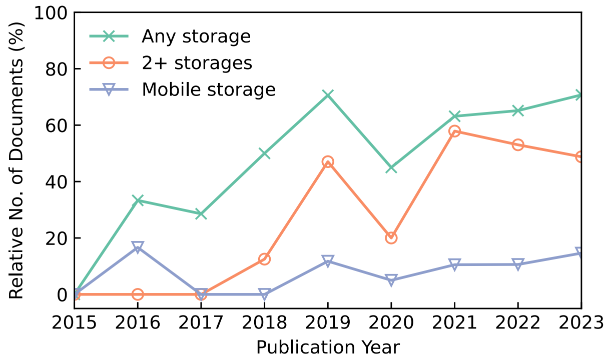

Figure 8: Relative number of documents published each year since 2015 that include storage equipment.

While further information regarding the various bio-fuels are available in [98, 99], a brief description is as follows. A typical process to create CH_4, the main component of natural gas, is to first produce H_2 from electricity via an electrolyser, and then convert H_2 to CH_4 via methanation. Anaerobic digestion produces biogas, which is mostly CH_4 and CO_2. In contrast, syngas, produced via a biomass gasifier with wood chip [96] and straw [97] feedstocks, is mostly H_2 and carbon monoxide (CO), conventionally.

3.2.3. Networks and End Uses

Each paper included between two and seven network types (Figure 9), representing the complexity of the MES. While the networks and end uses represented a wide variety of energy types, the most dominant were electric ($n = 207$), heating ($n = 138$), and natural gas/methane ($n = 122$), followed by cooling ($n = 42$) and hydrogen ($n = 18$). Across networks, the case studies included 24 different energy types overall. Providing fuel for building, industrial, and transportation applications, gas-based networks beyond natural gas included hydrogen [100, 101, 60], biogas/biodiesel/bioethanol [95, 92, 59, 58], and oxygen [64, 63]. Beyond energy, some integrated transportation [80, 89, 102] and information [103] networks for multi-infrastructure perspectives.

3.3. Research Approaches

After classifying physical systems, the studies were evaluated for their research approaches. The review scope included case study locations, software tools, and key performance metrics, while emphasizing both resilience and equity perspectives. The results are as follows.

3.3.1. Case Study Locations

For the case study, 43% ($n = 90$) of the papers studied real geographical locations, from a specific building to multi-country regions. Figure 10 depicts the geographical distribution of these 90 studies with respect to country-level income classification. One of the most notable findings was that the income level of the case study location and energy class

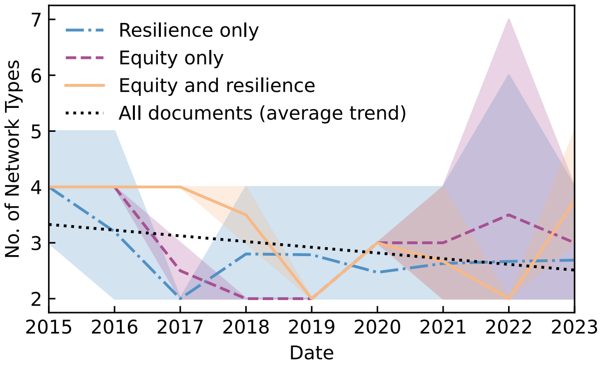

Figure 9: Number of network types included in each case study. Lines are annual averages for each category. Shaded regions are the annual minimum and maximum for each category. The dashed black line is the linear fit of the annual average number of networks for all categories.

(i.e., renewable/nonrenewable, carbon-free/producing) produced statically weakly significant results ($p = 0.011$). Lower-middle and upper-middle income countries tended to adopt renewable/carbon-producing energy systems more frequently than high income countries. Renewable/carbon-free systems were statistically favored by high and lower-middle income counties. Meanwhile, nonrenewable/carbon-producing energy systems most frequently involved high income countries. None of the case studies involved low income countries.

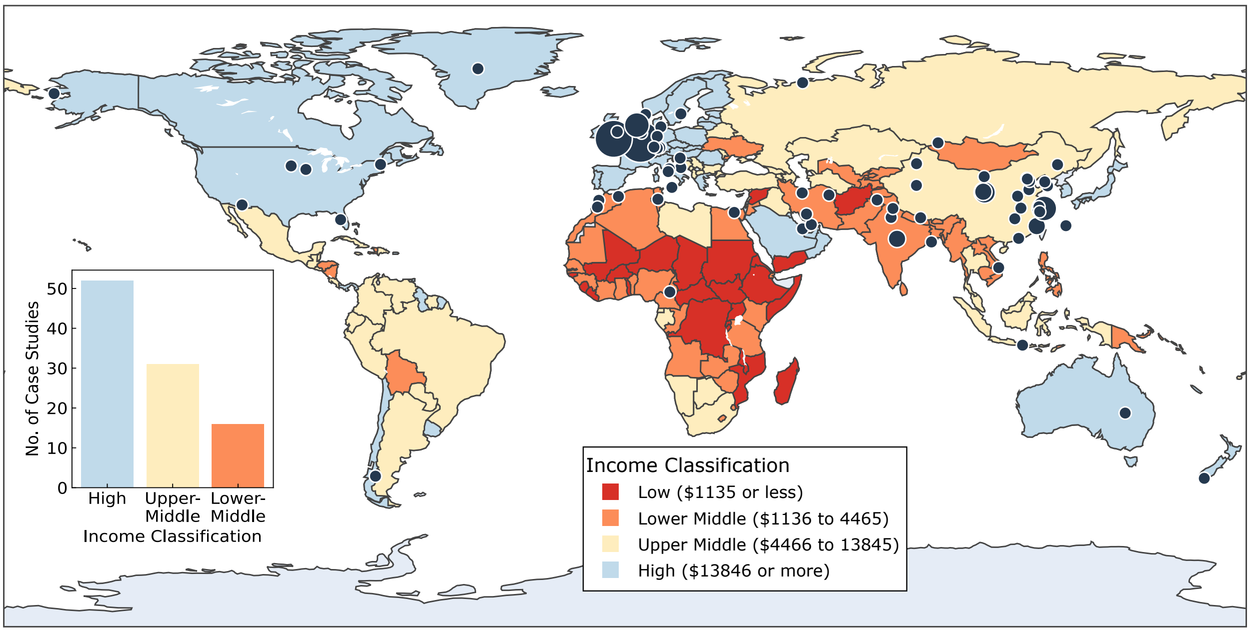

Figure 10: Geographical distribution of case study locations with respect to country-level economic statuses. Size of dark blue circles indicate number of documents.

Based on the Köppen-Geiger Classification [52], the case study locations spanned all major climate groups, with 61% involving moderate *warm temperate* climates (Table 4). In contrast, case studies in the extreme Climate Groups A (Tropical) and E (Polar) were generally lacking ($n = 7$). Among these seven studies, all involved nonrenewable/carbon-producing energy systems except Iniyan and Jagadeesan [104], which considered renewable/carbon-producing systems. Equatorial case studies included Thailand [54], an isolated low-latitude island in the South China Sea [105], India [104], Vietnam [106], and Bali [107]. Polar case studies included several Arctic countries [70] and Patagonia, Chile [108].

Table 4: Total number of occurrences of case studies across major climate groups in Köppen-Geiger [52].

Climate Group		n
A	(Tropical)	5
B	(Arid)	13
C	(Warm temperate)	56
D	(Snow)	16
E	(Polar)	2

3.3.2. Mathematical Models and Simulation Tools

A variety of mathematical models were solved across this review's body of research, including both steady state and dynamic models with continuous, discrete, and hybrid systems of equations. Most commonly, 29% of studies described the mathematical problem as a variant of mixed integer programming (MIP), with mixed integer linear programming (MILP) algorithms as the most dominant. To solve these models, researchers employed 24 different software environments and programming languages. Among commercial software, MATLAB ($n = 62$), HOMER ($n = 4$), PowerFactory ($n = 3$), and Engineering Equation Solver ($n = 2$) were most common. The most common open-source software included YALMIP ($n = 15$), Python ($n = 9$), and Julia ($n = 2$). Additionally, the literature also implemented GAMS ($n = 39$) and Modelica ($n = 3$), which are generic programming languages with both commercial and open-source environments available.

3.3.3. Key Indicators and Metrics

From an equity perspective, cost-based metrics dominated across the body of literature. Financial metrics were calculated on several bases, including investment cost [109, 15, 110], operational cost [54, 60, 82, 111, 58, 86, 112, 113], investment and operations [114, 106, 77, 115, 116], maintenance/repair [64, 117, 118], taxes [68, 119, 58], penalties [80, 57, 120, 121, 122, 69, 123], life cycle cost [124, 125, 126, 127], net present value [128, 61, 125, 129, 68], levelized cost of energy [94, 85], and payback period [125, 130].

From a resilience perspective, several important metrics recurred across the literature. These include loss of power supply probability (LPSP) [97, 61, 131] and loss of load probability (LOLP) [132, 133, 134, 135]; expected energy not supplied (EENS) [133, 134, 73] and expected energy unserved (EEU) [132, 136]; System average interruption frequency index (SAIFI) [134, 73, 137] and system average interruption duration index (SAIDI) [134, 73]; and Conditional Value-at-Risk (CVaR) [71, 83, 137, 138]. While interested readers can find more information on the above metrics, their equations, and how to solve them in Billinton and Li [139], a brief description is as follows. First, LPSP gives the ratio of energy not supplied by a generation system over the total energy demand [114], LOLP is the probability that load demand will be higher than the capacity of a generation system [140]. Second, EENS (or EEU) represents the expected amount of energy that all the generating units (multi-energy or stand-alone) cannot provide for the end users during a period of time due to insufficient capacity (i.e., deficit) or unexpected power outages [141]. Third, SAIFI indicates how many interruptions a customer experiences during a period, while SAIDI quantifies the amount of time the interruption lasts in a period (usually a year) [142]. Lastly, CVaR quantifies the expected loss in system performance beyond a given threshold of extreme events (i.e., the tail risk events) [143] and is used for both renewable energy uncertainty and low-probability-high-impact events. In their implementations, these resiliency metrics are used as design indicators for reliability, as optimization constraints, and in optimization objective functions.

In addition to these resilience and reliability metrics, several researchers adopted a *resilience index* (R) as a high system-level performance metric. Typically, the R used in literature is a normalized ratio that reflects the ability of a system to respond to and recover from a disturbance. Literature evaluates R on both power (R_P) [144, 145, 146, 147] and energy (R_E) [72, 118, 16, 148, 149] bases, which can be represented as

$$R_P = \frac{\sum_i w_i P_{i,\text{actual}}}{\sum_i w_i P_{i,\text{undisturbed}}} \quad \text{and} \tag{2}$$

$$R_E = \frac{\sum_i \int_{t_0}^{t_f} P_{i,\text{actual}} dt}{\sum_i \int_{t_0}^{t_f} P_{i,\text{undisturbed}} dt}, \tag{3}$$

where i is a component index, P is the power at time t occurring over the time horizon $t \in [t_0, t_f)$, and w is a weighting factor for component i. The powers are summed over all components (e.g., consuming devices, generation units, storage devices) in the system. At times, equal weights are assumed across all components [144], eliminating the w terms. Quantitatively, $R = 1$ indicates ideal, uncompromised performance despite a disturbance event (i.e., high resiliency); $R \to 0$ as systems fail or under-perform (i.e., worsening resiliency); and $R = 0$ for complete failure.

Across all studies that calculated R, Figure 11 shows the distribution of results with respect to the number of network types and system version (i.e., a baseline vs. a proposed model with improvements). Across all network sizes, the mean R increased between baseline and proposed MES, with the largest improvements occurring in two-network (72.7% improvement) and three-network (38.2% improvement) MES. Across all studies, R increased 31.6% on average between baseline and proposed MES.

Further, some studies evaluated both R and financial performance. As shown in Figure 12, four studies found correlations between financial metrics (operating cost, profit, or total cost) and R. With increasing R (more resiliency), operating costs decreased and operating profits increased. In contrast, total cost - which included both initial investments and operating costs - tended to increase with respect to R. For studies that found mutual

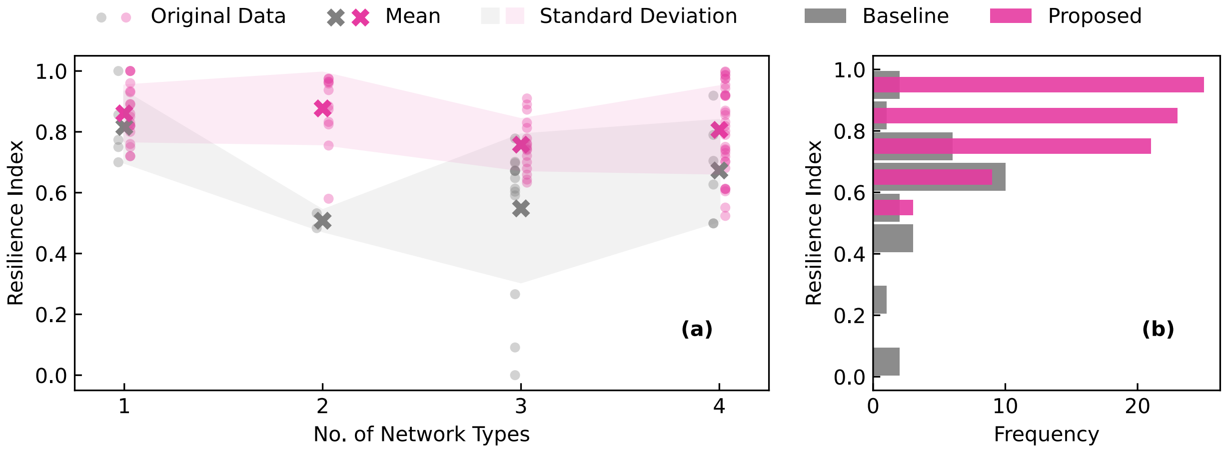

Figure 11: Distribution of resilience index results for baseline and proposed model systems with respect to (a) the number of network types and (b) the overall frequency distribution.

benefits between resilience and operational costs, Javadi et al. [145] optimized energy hub scheduling, while Yodo and Arfin added microgrids to the MES under cost constraints [118].

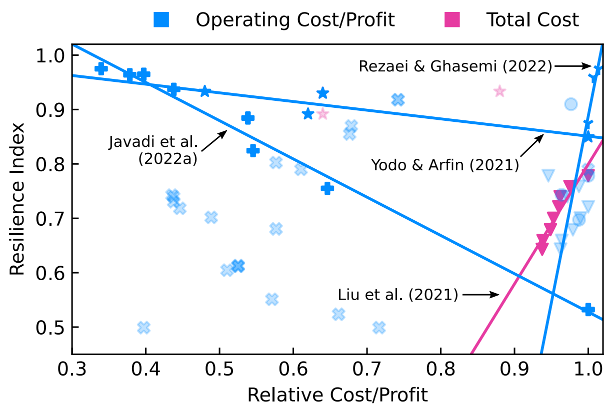

Figure 12: Resiliency index with respect to relative total and operational costs/profits (profit if greater than one). Linear regression trend-lines are included for publications exhibiting $R^2 > 80\%$.

4. Conclusion

Amidst anthropogenic climate change, energy systems around the world need to identify technologically and financially viable pathways for a sustainable future. Multi-energy systems – integrated energy networks that exchange and deliver two or more energy types via energy hubs – present promising solutions to this sustainability challenge; however, their applications at the intersection of resiliency and equity are not well understood. From these two perspectives, this comprehensive review analyzed scientific literature on MES, including system technologies, applications, computational tools, and evaluation metrics. The findings encourage future MES research to adopt an equity perspective, indicated by these systems' tendency to eliminate fossil fuels much more frequently than research focusing on resiliency alone (highly significant). Despite being encouraging, equity-based MES research remains sparse. Similarly, future case studies in tropical and polar climates (Köppen-Geiger Groups A and E, respectively) as well as low-income countries are merited based on existing research gaps and a need to innovate MES technology under extreme design conditions.

While revealing critical literature gaps, this review also serves as a comprehensive reference on MES energy types, equipment, and evaluation methodologies. For example, the results summarize MES applications that include 32 source energy types, a growing utilization of multiple and mobile storages, and effective sector coupling via power-to-X or biomass-to-X processes. Among system configurations, MES with two energy types produced larger resilience gains (72.7% improvement in R) compared to both single-energy type and larger networks. Opportunities exist to decrease operational costs and increase R with MES, yet future research is required to better understand payback periods with various MES technologies. In all, this review aids the advancement of MES for sustainable, resilient, and equitable energy infrastructures by synthesizing past applications, identifying research gaps, and proposing future directions.

Data availability

The data that support the findings of this study are openly available at the following URL: `https://doi.org/10.5281/zenodo.13741787`.

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Appendix A. Statistical Results

Table A1 summarizes the results of the statistical test results for all pair-wise combinations of categorical variables included in this study.

Table A1: Statistical results from chi-square tests of independence. Asterisks indicate statistical significance with *** for highly significant ($p \leq 0.001$), ** for significant ($0.001 < p \leq 0.01$), and * for weakly significant ($0.01 < p \leq 0.05$).

Category 1	Category 2	n	df	χ^2	p	
Scope	Energy Class	228	2	44.122	< 0.001	***
Scope	Scale	208	2	6.803	0.033	*
Scope	Climate Group	106	4	8.924	0.063	
Scope	Location Income	103	2	9.836	0.007	**
Scope	Demand-Side	228	1	0.477	0.49	
Scope	Mobile Storage	228	1	0.705	0.401	
Energy Class	Scale	193	4	11.122	0.025	*
Energy Class	Climate Group	92	8	†	†	
Energy Class	Location Income	90	4	13.037	0.011	*
Energy Class	Demand-Side	211	2	0.049	0.976	
Energy Class	Mobile Storage	211	2	1.715	0.424	
Scale	Climate Group	91	8	†	†	
Scale	Location Income	88	4	6.004	0.199	
Scale	Demand-Side	193	2	1.817	0.403	
Scale	Mobile Storage	193	2	0.689	0.709	
Climate Group	Location Income	90	8	†	†	
Climate Group	Demand-Side	92	4	†	†	
Climate Group	Mobile Storage	92	4	†	†	
Location Income	Demand-Side	90	2	3.655	0.161	
Location Income	Mobile Storage	90	2	2.277	0.32	
Demand-Side	Mobile Storage	211	1	12.488	< 0.001	***

† Minimum required frequency not met.

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