energies

MDPI

Article

Literature Review of Net Zero and Resilience Research of the Urban Environment: A Citation Analysis Using Big Data

Ming Hu [1,*] and Mitchell Pavao-Zuckerman [2]

[1] School of Architecture, Planning and Preservation, University of Maryland, College Park, MD 20742, USA
[2] Department of Environmental Science and technology, University of Maryland, College Park, MD 20742, USA; mpzucker@umd.edu
* Correspondence: mhu2008@umd.edu

Received: 25 March 2019; Accepted: 22 April 2019; Published: 24 April 2019

Abstract: According to the fifth Intergovernmental Panel on Climate Change (IPCC) assessment report, the urban environment is responsible for between 71% and 76% of carbon emissions from global final energy use and between 67% and 76% of global energy use. Two important and trending domains in urban environment are "resilience" and "net zero" associated with high-performance design, both of which have their origins in ecology. The ultimate goal of net zero energy has become the ultimate "high-performance" standard for buildings. Another emerging index is the measurement and improvement of the resilience of buildings. Despite the richness of research on net zero energy and resilience in the urban environment, literature that compares net zero energy and resilience is very limited. This paper provides an overview of research activities in those two research domains in the past 40 years. The purpose of this review is to (1) explore the shared ecological roots of the two domains, (2) identify the main research areas/clusters within each, (3) gain insight into the size of the different research topics, and (4) identify any research gaps. Finally, conclusions about the review focus on the major difference between the net zero movement and resilience theory in the urban environment and their respective relations to their ecological origins.

1. Motivation and Background

According to the Fifth Assessment Report (AR5) of the UN Intergovernmental Panel on Climate Change (IPCC), the urban environment is responsible for between 71% and 76% of carbon emissions from global final energy use and between 67% and 76% of global energy use [1]. Within the urban environment, buildings represent the greatest unmet energy savings and carbon emission reduction potential because existing and future buildings will determine a large portion of global energy demand [2]. As developing countries keep building and maintaining their standard of living by providing housing and infrastructure, the total energy use in urban environments, particularly use related to buildings, could triple by mid-century [3].

To date, primary research about the urban environment related to climate change has focused on energy efficiency or resilience. For energy efficiency, the ultimate goal is to realize the net zero energy (NZE) goal. NZE and resilience have overlapping origins in systems ecology [4,5] but have developed independently. Investigating how they differ allows us to see how they can inform each other's future development and potentially be integrated to create a more holistic framework for evaluating sustainable development. In 2010, buildings accounted for 32% of total global final energy use and 19% of energy-related greenhouse gas emissions [2]. The energy-centric approach is easy to understand and easily implemented in the building code. Large amounts of research have quantified building energy performance, and robust methodologies have been developed and established. The

number of net zero buildings increased by over 700% between 2012 and 2018 in the United States [6], and the steep upward curve can be expected to continue. On the other hand, resilience has a broad range of implications in the urban environment and includes the comprehensive measurement of performance rather than just energy performance. Methods have been implemented and tested to quantify the resilience of a single building, multiple buildings, or an entire city. For example, the city resilience index developed by the Rockefeller Foundation is used to understand and measure the resilience of a city. However, since resilience covers a wider range of issues than NZE, resilience research on the urban environment still lacks a consistent framework or definition that would prove helpful for communication among researchers and practitioners.

This paper's review of state-of-the-art studies regarding the NZE movement and resilience concept in the urban environment was based on a systematic screening of peer-reviewed articles by titles, keywords, and abstracts. The purpose of the review is to (1) identify the main research areas within each domain, (2) gain insight into the size of the different research focal points, and (3) identify any research gaps and trends. The paper is organized as follows. First, the intellectual origin of NZE and resilience is introduced in Sections 1.1 and 1.2. Then, the literature survey results of these two concepts are explained in Section 3. The analysis results are shown graphically and explained in this section as well. Following the analysis, current research gaps and future needs are outlined in Section 4. Conclusions based on Sections 2 through 4 are discussed in Section 5.

1.1. Origin of the "Net Energy" Concept

The concept of "net energy" has its origin in ecology and has continued to maintain a close relation to that field. In 1920, Frederick Soddy, an English chemist and Nobel prizewinner, first offered a new perspective on economics rooted in the law of thermodynamics in physics. Soddy drew attention to the importance of energy for social progress based on real wealth formation as distinct from virtual wealth and a debt accumulation process [7,8]. He suggested that detailed accounting for energy use could be a good alternative to the monetary system, as the conventional monetary system treated the economy as a perpetual motion machine, while in reality, as with any commodity, the actual wealth flow obeyed the laws of thermodynamics [9,10]. Soddy argued that real wealth was derived from the use of energy to transform materials into physical goods and services [11]. However, his theory was largely criticized and ignored in his time due to his standing as a critic—not a scholar—of orthodox economics. The contempt was mutual: in one review of his book called "Wealth, Virtual Wealth, and Debt," the Times Literary Supplement remarked that "it was sad to see a respected chemist ruin his reputation by writing on a subject about which he was quite ignorant . . . " [10]. The criticism of Soddy's theory contributed to the long-term silence in associated research development between 1930 and 1970.

In the 1970s, Romanian American mathematician and economist Nicholas Georgescu-Roegen further developed ecological economics or eco-economics based on Soddy's concepts, a field of research that is transdisciplinary and interdisciplinary, encompassing ecology, economics, and physics. Georgescu-Roegen proposed the application of entropy law in the field of economics, arguing that all natural resource consumption is essentially irreversible, a concept that had a profound impact on thinking about net energy flow or the lifecycle of natural resources. He was the first economist of some standing to theorize on the premise that all of Earth's mineral resources will eventually be exhausted at some point [12]; this concept of depletion of natural resources eventually led to the movement of sustainable development.

Another important development in the 1970s was the publication of the article "Energy, Ecology, & Economics" and the book "Environment, Power, and Society" by ecologist Howard Odum, who tackled the economic issue using ecological theories based on energy fundamentals. His energy economics concept was based on the understanding that energy is the foundation for all forms of life and is transformable. He stated that "the true value of energy to society is the net energy, which is that after the costs of getting and concentrating that energy are subtracted" [13]. His view of studying ecology

as large and integrative ecosystems paved the foundation for understanding how the different aspects of a whole ecosystem influence each other. In the latter part of his career, in the 1990s, he developed the concept of "emergy," which he defined as "a measure of energy used in the past and thus is different from a measure of energy now. The unit of emergy is the mjoule [14]. Emergy has attracted the attention of academic researchers and is being applied to research in the urban environment in addition to natural ecosystems [15,16]. Since the reemergence of the concept of net energy in the 1970s, energy-flow analysis and net energy simulation have been applied to many different fields beyond ecology and economics; the most visible increase of research and practice interest is in architecture, engineering, and the construction industry (AEC), and the most applicable translation of the concept is NZE building design and construction.

1.2. Origin of Concept of "Resilience"

Resilience emerged in the field of ecology at the same time that NZE studies started to catch researchers' and practitioners' attention. In the 1960s, the ecological resilience concept was introduced in studies of the stability of ecosystems. One of the pioneers in this area is C.S. Holling, who was considered by many to be the father of ecological resilience theory and who also introduced the word "resilience." Holling believed that extending the ecological framework to other fields would be useful for understanding how society, individuals, and community interact with natural ecosystems. The origin of this term has deeper roots that may be linked to the origins of ecosystem and systems ecology in the 1940s and 50s and their attempts to mathematically model dynamic ecosystems [17]. The idea that nature was composed of systems that may have properties like resilience set the stage for more formal conceptualizations of the term by Holling and colleagues throughout the 1970s and 80s [17]. Holling describes resilience as dynamic and complex in juxtaposition to other views of a stable and simple nature. The "stability" of ecological systems refers to their ability to return to an equilibrium state following a disturbance. Holling suggests that resilience "is a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables." In this early formulation by Holling, it is the instability of a system that conveys its resilience.

These ecological origins for the modern concept of resilience are in some ways at odds with notions of resilience from other disciplines. Engineering resilience applies to how a system responds to disturbances with respect to the system's stability in comparison to an equilibrium steady state [4,18,19]. Engineering resilience derives from notions of resistance to and recovery from disturbances and focuses on the ability and speed of a system to bounce back to its initial, equilibrium conditions following a disturbance event [18,19].

The ecological concept of resilience has seen an extension of its domain to include social-ecological resilience and a paradigm that is applicable to resource management [20,21].This parallels the organization of the Resilience Alliance, a collective of institutions and researchers that implement "resilience thinking" for the study and management of systems from an interdisciplinary perspective. Here, resilience extends from a concept focused on buffering stress and maintaining function to one where the focus is on the adaptive capacity to innovate and transform a system to sustain and reorganize in the face of stress and disturbance [20] These principles can be put into practice to manage a system for resilience [22–24].

2. Research Method, Materials, and Tools (Literature Review)

The literature review of these two related topics took two forms: quantitative and qualitative research.

2.1. Quantitative Research

The screening and review entailed three steps. First, key search terms on the NZE movement and resilience concept were used to scan the Web of Science and Elsevier's Scopus databases. The

screening excluded literature that was not peer reviewed, and multiple combinations of the search terms were used. Combinations of terms included (1) "resilience" with "city," "building," and "urban environment" and (2) "net zero" with "buildings" and "urban environment." Articles, conference proceedings, books, and book chapters were included. Terms appeared in titles, the abstract, and keyword lists. There were 1821 papers found from a variety of disciplines in the resilience research domain, and 592 papers were found in the NZE research domain, all from the period of 1970 through 2018. The different research fields include architecture, construction, engineering, environmental technology and science. After the initial papers were identified, the occurrence of the search terms was used as a filter to narrow down the literature: 20 occurrences were used for resilience papers and 10 were used for net zero papers to gain a comparable number of research domain clusters.

In the second step, citation analysis, co-citation analysis, and text data mining were carried out with the VOSViewer software to determine influential studies, thinkers, and concentrated research topics and their correlations. Citation analysis (CA) is the bibliometric method used to quantitatively evaluate scientific and academic literature to assess the quality of an article or the impact of study/research projects, authors, journals, or institutions. Co-citation analysis (CCA) is a bibliometric method used to measure the correlations among a variety of academic papers based on the rationale that shared references suggest an intellectual connection. This form of document coupling measures the number of documents that have cited a given pair of documents [25]; it is used in this research to trace origins and fields related to NZE and resilience studies in the urban environment. Text data mining (TM) is the process of deriving high-quality information from text-based documents (e.g., titles, keywords, and abstracts) to identify patterns and trends. Automated content analysis for text—which draws on techniques developed in natural language processing, information retrieval, and text mining—has boomed over the past several years in the social sciences and humanities fields [26,27] but is rarely used in scientific and engineering fields.

To analyze and interpret the results from CA, CCA, and TM, maps are often constructed to help visualize the data. Two types of maps are commonly used in bibliometric research: distance-based and graph-based maps [28,29]. In a distance map, the distance between two items generally indicates the relation and correlation. For representing literature review results, the degree of proximity of two research topics can be viewed as a representation of the intellectual connection of the research topics or areas. Graph-based maps indicate the distance between two items but do not need to reflect the strength of the relation between the items [30]. The relation between items is represented by a line. There is a variety of mapping techniques used in bibliometric research, such as multidimensional scaling. Van Eck's VOS mapping techniques [20,28], VXIrd, Pajek [31]. and Gephi. The most commonly used technique is multidimensional scaling.

For this project, VOSViewer was chosen for its two-dimensional distance-based map [32]. VOS, which stands for "visualization of similarities," aims to locate words in a low-dimensional space in such a way that the distance between two words reflects the similarity or relatedness of the words as accurately as possible [28]. The Pearson correlation has been the most popular indirect similarities measure in the literature review for a long time, and it is well known that the Pearson indirect similarities method is not completely satisfactory [33]. VOS is based on a more sophisticated indirect similarity measurement. More detailed technique information regarding how VOS runs the correlation analysis can be found in Van Eck et al. [28]. VOSviewer constructs a map based on a co-occurrence matrix using three steps. The first step is to obtain a similarity matrix; in the second step, a map is constructed by applying the VOS mapping technique to the similarity matrix; then, in the final step, the map is translated and reflected. The similarity or association strength between different words measured in VOSviewer depends on the total number of co-occurrences of words together and the number of occurrences of the terms separately. In a VOS-constructed map, different cluster maps represent different research foci; the sizes of the nodes indicate the relevance of the items—including research topics, authors, sources, or countries—and the distance between nodes illustrates the intellectual connections.

In this review, the following map types were created:

- Map of terms: we used all text data to generate a term map based on occurrence of texts to understand the researcher topics/clusters in one domain.
- Map of keywords: we used co-occurrence of keywords data to construct a map to understand the relation between knowledge groups and different research fields.
- Map of authors: we used citation data to construct a map to identify the influential thinkers in research domains.
- Map of countries: we used citation data to construct a map to identify the influential regions in research domains.

2.2. Qualitative Research

After creating an overview of research activities based on the map constructed with VOSviewer, the researchers identified the most active research areas, trending terms, and influential papers. Then, a qualitative review of all studies was conducted to reduce the articles to a total of 452 studies for resilience and 81 for NZE papers that were applicable to the scope of this study. After the initial VOS scan, the top 200 ranked studies for resilience and all 81 for NZE were reviewed separately by two authors to determine if they actually focused on resilience and NZE. According to the goal of this review, a paper was excluded if it (1) failed to define the term and (2) did not identify the research gaps and trends. This analysis unveiled 20 top-ranked influential papers in each area (40 papers in all). Lastly, a focused review was carried out on the 20 most influential papers in each area as a means of gleaning findings and identifying research gaps and needs. Sections 3 and 4 highlight and discuss the main results from the NZE and resilience literature review, respectively.

3. Findings: Research Clusters, Topics, Gaps, and Trends

3.1. Research Clusters on Resilience (Map of Terms)

First, in order to identify the research clusters and origin, a term map was created based on the occurrence of texts within a corpus of 1821 scientific publications. The terms (texts) appeared in titles, abstracts, and keywords. The occurrence frequencies of terms (texts) of journals were determined based on a minimum number of 20 occurrences of a term. (The default and recommended number of occurrences is 10, according to the program manual. In order to narrow down the research, we doubled the default number.).

Out of the 39,855 terms, 496 met the threshold. For each of those 496 terms, a relevance score was then calculated. Based on those scores, the most relevant terms were selected, using the program's default of the top 60% most relevant terms. Altogether, 275 terms were selected for the resilience research study; the result is shown in Figure 1. Based on the VOSviewer clustering technique, the terms in the data set were divided into four clusters, with a different color for each research cluster.

- Cluster 1 (red): technology, application, energy efficiency, performance, event (left)
- Cluster 2 (blue): factor, finding, relationship, health (right)
- Cluster 3 (green): urban resilience, governance, understanding/theory, ecosystem/eco service (middle)
- Cluster 4 (yellow): disaster, hazard, mitigation (upper)

These clusters show four separate focus areas across different disciplines, which may be referred to as techniques and application of resilient practice (cluster 1), cause and relation of resilient factors (cluster 2), the understanding of the mutual influence of urban resilience and ecosystem (cluster 3), and disaster and hazard relief (cluster 4). The clusters are closely related to the three predominant definitions of resilience in an urban environment emerging from its ecological origin: engineering resilience, ecological resilience, and social–ecological resilience [34]. Engineering resilience is defined

as a system's speed of return to equilibrium following a shock, indicating that a system can have only a single stability regime [35].Ecological resilience emphasizes conditions far from any equilibrium steady state, where resilience is the measurement of the magnitude of disturbance that can be absorbed before the system changes its structure [4]. Social–ecological resilience is defined by Adger as the "Ability of communities to withstand external shocks to their social infrastructure" [36,37]. Cluster 2 is derived from ecological resilience; cluster 3 is the continuation of social–ecological resilience; and cluster 4 is related to engineering resilience. Lastly, cluster 1 is about the translation or transformation of resilience theory to practice.

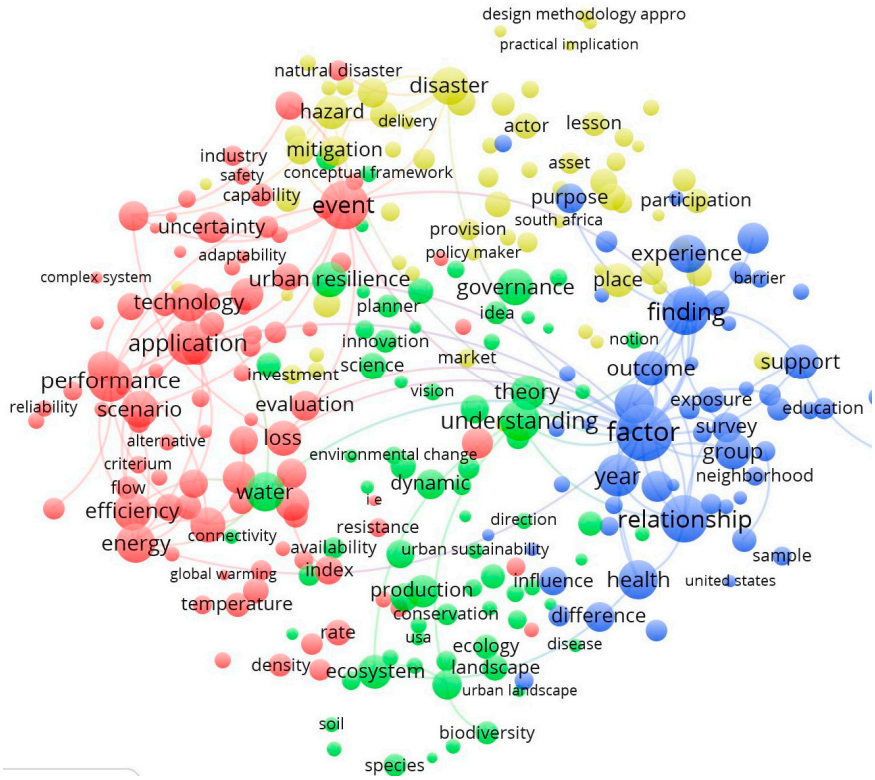

Figure 1. Term map representing the main research areas on resilience in the built environment.

The four research clusters are not of equal size and density. Cluster 1 has the most research activities and impact, while cluster 4 has the least number of studies and relevance. Clusters 2 and 3 are of very similar size. Within cluster 1, there are four sub-clusters: technology application, energy efficiency advancement, performance in different scenarios, and individual disastrous events. Among those, technology application is closely linked to energy efficiency advancement, as well as performance in different scenarios. The disastrous events sub-cluster, which is associated with damage and uncertainty, is relatively remote from the other three sub-clusters. Cluster 2 has three clear sub-clusters: finding/program, factor, and relationship. This cluster mainly represents social and community resilience, as other associated terms include family, health, culture, intervention, and education, and they can be seen as a further development of the socio–ecological resilience definition. Cluster 3 is the second-largest cluster, but unlike clusters 1 and 2 it does not have clear sub-clusters. Instead, it is interwoven into cluster 1 and cluster 2.

The connection between "event" under cluster 1 and "urban resilience" under cluster 3 appears to be very strong, even after pulling them away from the cores of their respective areas. This close connection might indicate the rising risk of shocks from natural disasters and the demand to find techniques with which to build robust urban resilience. "Understanding" under cluster 3 is connected to "finding" in cluster 2; the finding about the factors that determine the resilience of a system help to establish an understanding of what drives the transformation of an existing system into a more

resilient one. There is almost no connection between cluster 4 and cluster 3, and "disaster", "natural disaster", and "hazard" are located far from "ecosystem/ecosystem service" and "green infrastructure". This weak link could indicate a substantial gap between disaster mitigation and ecosystem service and green infrastructure development. "Understanding" (cluster 2) is situated in the center of the diagram, equally remote from both ecosystem (cluster 3) and natural disaster (cluster 4). "Understanding" also has almost no linkages to technology/application and performance/energy (cluster 1). Together, these may indicate that the current application of engineering resilience needs more scientific support, as without an in-depth understanding of the resilient factors, the performance and technical application of resilience theory cannot be improved and verified.

3.2. Research Focus/Topics and Relations on Resilience (Map of Keywords)

A keywords map was created, based on the co-occurrence of keywords, to study the underlying structure of the different research clusters explained in Section 3.1 and their relationship with knowledge groups and different research fields. In general, the closer keywords are located to each other on a map, the stronger the relation between them. Out of 2359 keywords taken from all the papers, where a minimum of 10 occurrences of a keyword was used to identify the most related knowledge and research fields, 36 keywords met the threshold. The 36 keywords came from the four research clusters identified in Section 3.1.

As can be seen in Figure 2, among all research topics, there are three linked research concentrations. The first is the linkage between "climate change" and "management" and "adaptation", which together could represent environmental science research rooted in ecology with a focus on adaptation to climate change in the urban environment. Biodiversity and the ecosystem are viewed as trending techniques for realizing climate change management and adaptation. The United Kingdom, Canada, China, and South Africa appeared as having the most research objects of interest. The second set of coupled topics is sustainability and system management, where concentrations appear around energy efficiency and buildings. The third set of coupled topics is vulnerability and urban resilience, which can be interpreted as the connection between existing urban environmental conditions and the difficulty of adapting to future conditions under climate change.

3.3. Research Gaps and Future Trends on Resilience

Overall, the term map indicates the gap between social–ecological resilience and engineering resilience. Although there are some studies that discuss future and past views of the two types of resilience, to a large extent, social–ecological resilience focuses on the understanding and interoperation of potential development (forward thinking), while engineering resilience mostly relies on what happened and responses to extreme events [4,37]. From the keywords map, despite the closely connected major topics, there is quite a large number of uncoupled research interests, such as health, information, consumption, operation, networks, heat-island, urban regeneration, and design. Those topics represent potential research gaps that require further development and study, as well as integration with existing resilience frameworks. For instance, the disconnect between ecosystem/green infrastructure and building and energy efficiency is evidence of some reluctance in the building and construction industry to consider the urban environment as part of a large ecosystem. Some fundamental thinking and knowledge could be brought into the planning and design phase. For example, the quality of ecosystem services and green infrastructure could protect urban dwellers from natural hazards. The robustness and continuity of such services under conditions of shock or stress are important.

Overall, the intellectual connection of research topics indicates potential research trends. After a focused and in-depth qualitative review of the most influential studies and articles, we categorized the resilience of urban environment research into three future research trends: urban resilience, risk management, and sustainable development.

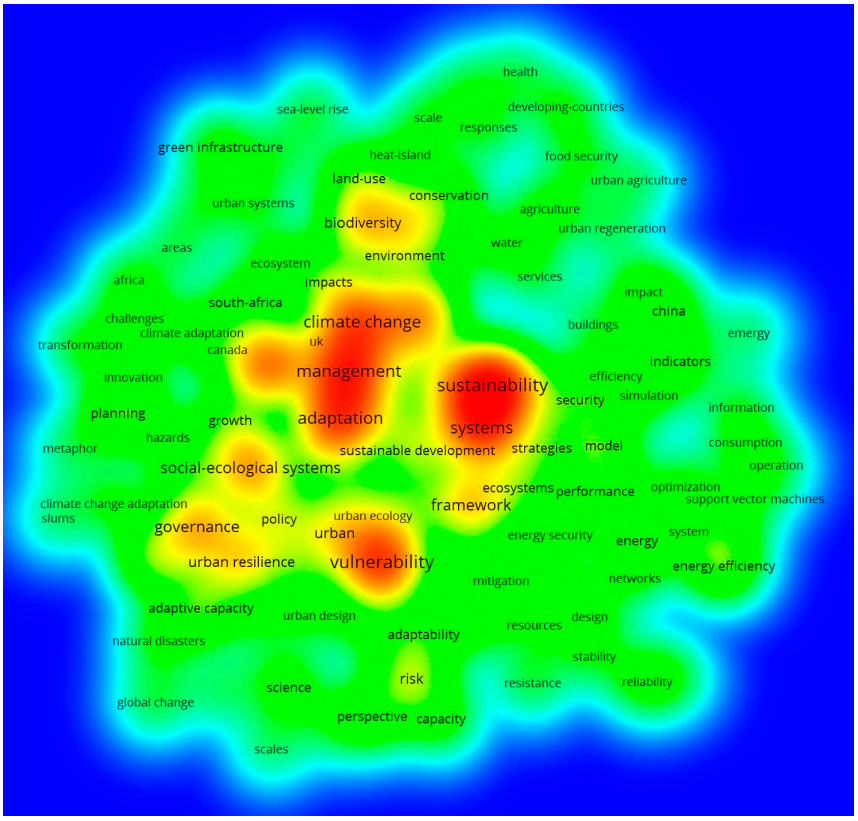

Figure 2. Keywords co-occurrence map (by linkage), showing the relationship between research areas.

Urban resilience studies are closely related to adaptation, vulnerability, and community building, and many of the research studies are written from a social–ecological perspective. There are also quite a few technical reports produced by government and not-for-profit foundations and organizations [38]. This domain represents the fusion between ecology and social science. Risk management is closely related to climate change, which has the potential to bridge the gap between disaster risk reduction and climate change adaptation, as well as re-establish the connection between green infrastructure building and urban design principles. In this domain, the research related to disaster reduction has moved away from traditional disaster risk management, which mainly focuses on specific hazards such as floods and other natural disasters. Instead, it has been expanded to a wide range of disruptive events and social disturbance and stress, both stresses and shocks that could influence governance and policy making. The third domain is sustainable development, which is mainly rooted in the engineering, building, and construction fields. It does appear to have more frequent co-occurrence with other critical terms, as the concept and practice of sustainability has a much longer history in comparison to resilience; the two terms often appear as paired concepts. Through this exercise, we could observe the evolution of the concept of sustainability.

3.4. Research Clusters on NZE (Map of Terms)

The process used in studying research domains within resilience was reapplied to the net zero research domain, first creating a term map from 519 documents (articles, book chapters, and books). This number is much lower than the quantity of research activities in the resilience domain. Therefore, the occurrence frequencies of terms (text) of journals were determined based on a minimum number of 15 occurrences of a term, which is lower than the minimum used for resilience research. Out of the 15,438 terms—only half of the number of terms associated with resilience—167 met the threshold. For each of those 167 terms, a relevance score was then calculated. Based on this score, the most relevant terms were selected using the program's default of the top 60% most relevant terms. Altogether,

100 terms were selected for NZE research; the result is shown in Figure 3. Based on the VOSviewer clustering technique, the terms in the data set were divided into four clusters, with a different color for each research cluster.

- Cluster 1 (yellow): effect, rate/period (left)
- Cluster 2 (red): project/standard, net zero energy/practice, home (right)
- Cluster 3 (green): emission, energy source, water (middle)
- Cluster 4 (blue): zero energy building, heating/cooling/temperature, ventilation (upper)

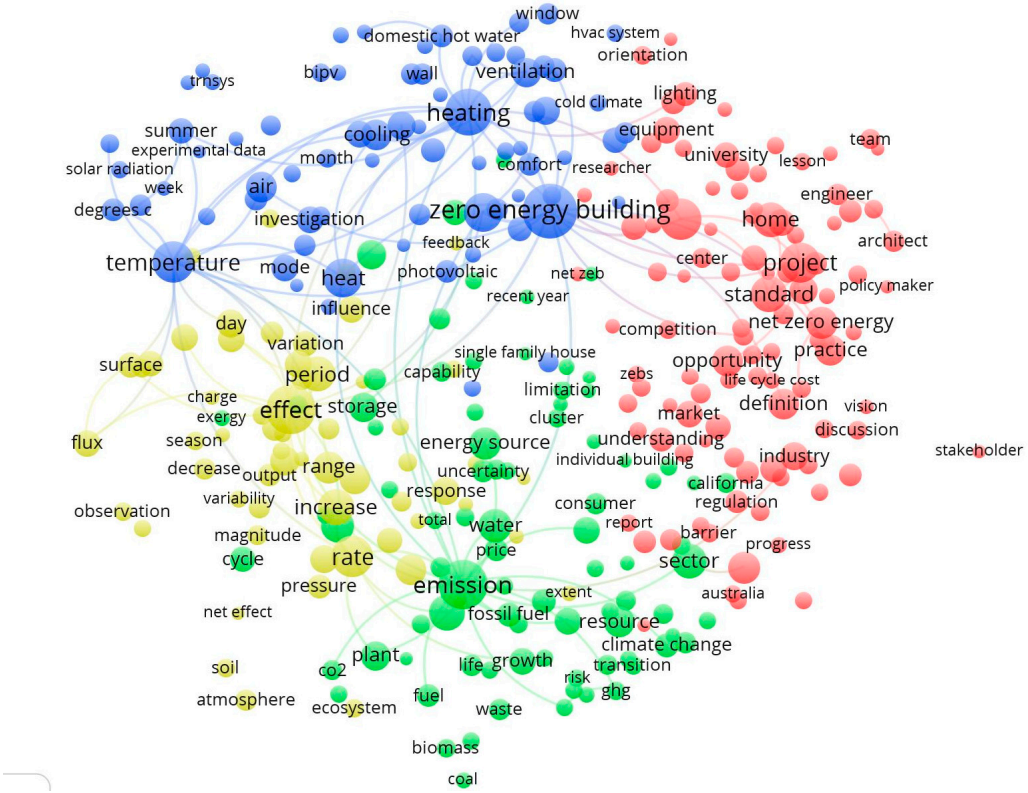

Figure 3. Term map representing the main research areas on net zero in the built environment.

These clusters show four research areas across different disciplines related to NZE research activities, which may be referred to as net zero impact (cluster 1), net zero energy practice in industry (cluster 2), net zero emission (cluster 3), and techniques to achieve net zero energy building (cluster 4). Cluster 4 has the greatest number of research activities, which center around NZE building and temperature control. It is commonly known that NZE building mainly focuses on operating energy reduction. Heating and cooling together account for more than 50% of overall operating energy consumption, and the outside ambient temperature has a large influence on building heating and cooling loads. Those facts could explain why heating, cooling, and temperature appear as critical sub-topics in cluster 4. Cluster 2 and cluster 3 are of almost equal size, with cluster 2 containing more items and cluster 3 having items aggregating toward one major focus area, "emission." Cluster 1 has the fewest research items and is connected to clusters 3 and 4, but has no connection to cluster 2. The disconnection between clusters 1 and 2 indicates the limited verification and measurement of the effectiveness of net zero development, particularly in the building industry. Such lack of verification and measurement caused some concerns about the validity of the NZE building design and approach, which presents a challenge and a gap as well as opportunities.

3.5. Research Focus/Topics and Relations on NZE (Map of Keywords)

A co-occurrence map was created, using keywords, in order to study the underlying relationship of research areas and then to predict future research trends (refer to Figure 4). Out of 2028 keywords from all the papers, where a minimum of 10 occurrences of a keyword was used to identify the most related knowledge and research fields, 43 keywords met the threshold. The 43 keywords came from the four research clusters identified. As can be seen in Figure 4, strong relationships emerged among the topics of design, system, efficiency, and performance.

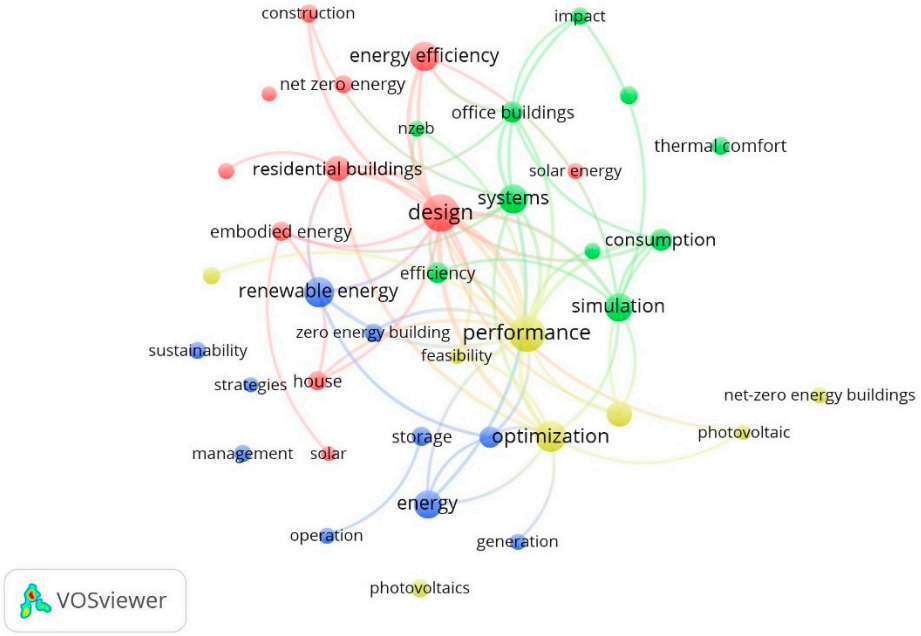

Figure 4. Keywords co-occurrence map representing the relationship between different research topics on NZE.

Among all research topics, there are two linked research concentrations. The first is the linkage between "design" and "efficiency" and "system," which reflects awareness of the important role of design and systemic consideration in energy efficiency. The second linked research concentration is "performance" and "simulation." Office buildings, residential buildings, and embodied energy are popular research topics associated with those two concentrations.

3.6. Research Gaps and Future Trends in NZE

As shown in Figure 4 (keywords map), there are two research gaps in NZE research. Firstly, current research is primarily around renewable energy sources. Only one specific renewable energy technology is present: photovoltaics. Limiting the focus to photovoltaics could hinder the search for other alternative renewable energy resources for future net zero building development. Alternative renewable energy resources such as hydro energy and biomass energy were not active in the urban environment, but are more widely studied and applied in other fields, such as industry ecology. The second research gap is identified by some important keywords that are missing, such as insulation, standards and regulations Most of those missing keywords are associated with the practicality and feasibility of NEZ. This might be explained by most studies found in the Web of Science database and Elsevier's Scopus database being academic research focusing on system, method, and framework studies. But it does show that more future studies and research could be undertaken in the areas of technology, techniques, and practical standards of NEZ. The lack of technique keywords might also indicate a disconnection between academia and practice. The lack of research indicates gaps in both knowledge and opportunities for future work.

Based on the quantitative and qualitative research from previous sections, we then categorized future research on NZE into four directions: office building; residential building; sustainability management/strategies; and design. NZE research activities in office building have largely been related to operating energy efficiency and environmental impact. With respect to residential building, NZE research activities are mainly focused on embodied energy reduction and achieving an overall net zero energy goal. Another difference between the first and second trends is the fact that in residential building, design is a focal point, and the active research and practice activities involve design practitioners such as architects, planners, and engineers. In contrast, in the office building field the focus is around system and simulation, due to the large scale and complexity of office building. Also, the inputs from numerous stakeholders demand a more systematic and high-level approach in achieving a net zero goal in office building. The third and fourth trends are not associated with any particular building types; instead, the focus is around the optimization of energy performance and research on renewable energy production.

3.7. Most Influential Studies and Active Regions

The most influential studies of resilience, based on the citations and connections to others, are Pickett's "Resilient Cities: Meaning, Models, and Metaphor for Integrating the Ecological, Socio-economic, and Planning Realms" [39] (ecology), which has been cited 490 times since 2003, and Head's "Suburban Life and the Boundaries of Nature: Resilience and Rupture in Australian Backyard Gardens" [40], which has been cited 103 times since 2006 (refer to Figure 5). These studies cover diverse fields that include ecology, economics, environmental science, geology, landscape architecture and regional planning. Generally, they could be categorized as social-ecological research and studies. To date, there are no influential studies about engineering resilience.

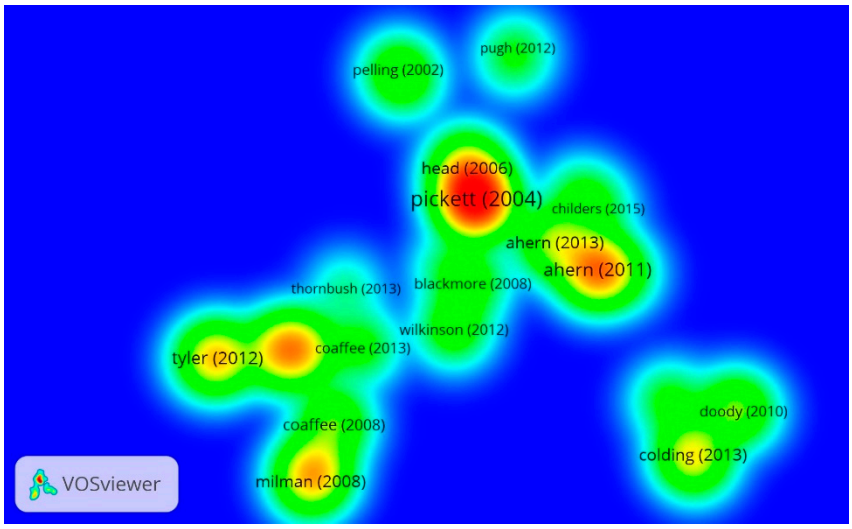

Figure 5. Citation map representing influential studies (resilience).

The most influential studies of NZE are Hernandez and Kenny's "From Net Energy to Zero Energy Buildings: Defining Life Cycle Zero Energy Buildings" [10] (engineering), which has been cited 332 times since 2010, Marszal and team's "Zero Energy Building: A Review of Definitions and Calculation Methodologies" [41] (engineering), which has been cited 598 times since 2011, and Sartori and team's "Net Zero Energy Buildings: A Consistent Definition Framework" [42] (architectural engineering), which has been cited 375 times since 2012. These studies are mainly from the architectural engineering field; research activities accelerated from 2011 and reached a peak in 2015 (refer to Figure 6).

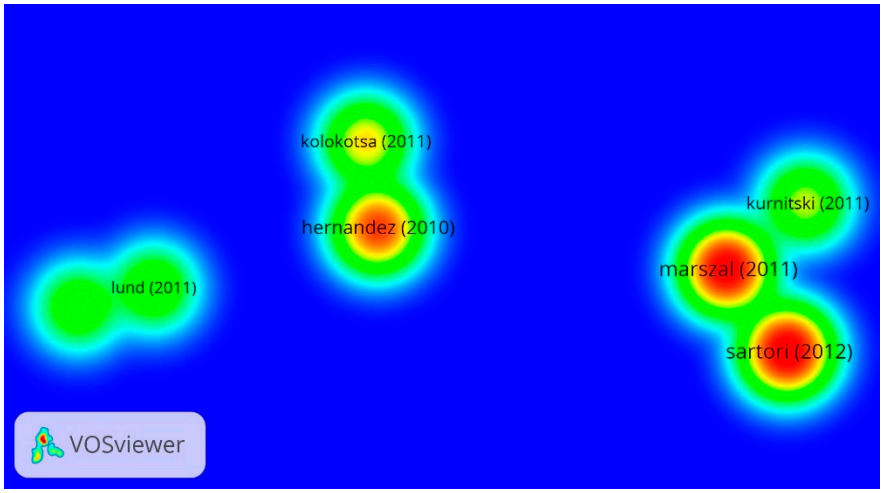

Figure 6. Citation map representing influential studies (net zero).

The most influential countries in the research domain of NZE in the urban environment are: the United States, with 156 research documents and 814 total citations; Italy, with 49 documents and 891 total citations; and Norway, with 24 documents and 615 total citations. China is the only developing country on the list and ranks fifth, after Canada, with 44 publications and 320 citations. This is likely due to China's rapid urbanization and the demand for the control of pollution caused by excessive emissions (refer to Figure 7).

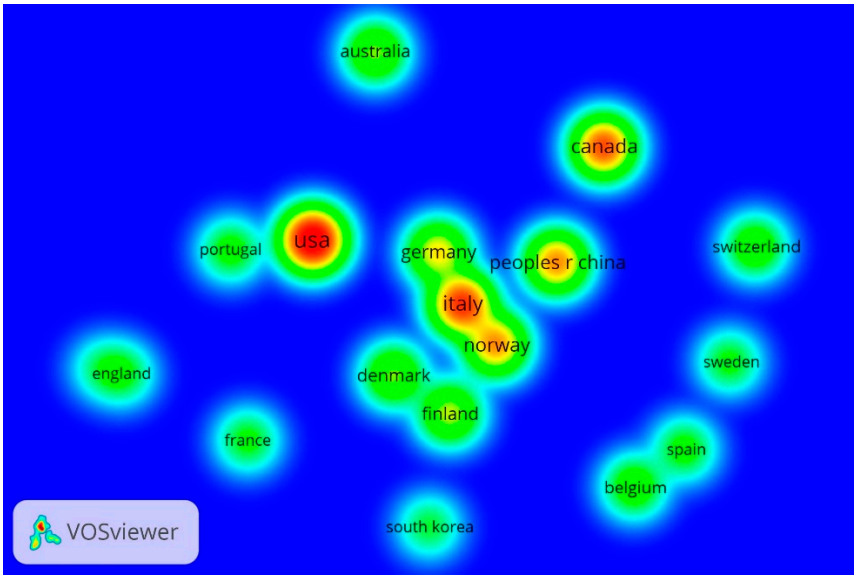

Figure 7. Citation map representing influential countries (net zero).

4. Discussion: Difference and Divergence of Research Activities

The concepts of net zero and resilience are both rooted in ecology, originally looking at the built environment from a systematic perspective [4,7,8,15–19]. However, the two disciplines have taken quite different approaches and directions in recent years. Resilience studies were promoted due to the urgency of severe climate change events such as flooding, wildfire, and extreme temperatures. The three research focus areas of urban resilience [38], risk management [43], and sustainable development recognize the vulnerability of the urban ecosystem [39,44]. and the necessity to adapt to climate change [37]. In general, resilience studies in the urban environment take a more holistic and comprehensive approach and take into account long-term strategies. In comparison to resilience, the research around

NZE has limited scope. Unlike resilience studies, the research activities on NZE have moved away from its ecological origin, to focus on particular building types [42] and design applications [41]. The lifecycle approach of the original net energy concept, which developed from ecology, was replaced by a performance-driven, building-types-driven engineering approach [10]. This relatively narrow focus might be seen as a deviation from the original ecological roots, which used energy flow to measure the sustainability, accessibility, and efficiency of a system. The narrowed focus was driven by multiple market needs, industry preference, and political incentives. Among many factors, the search for a consistent and common definition of net zero building has been a singular focus over the past five years due to strong interest and the quantity of new construction projects around the world [42].

Unlike research related to resilience, the three most influential papers for NZE focus on net zero building measurement and application, and the most influential thinkers, researchers, and institutions are primarily in the building and construction industry. Those net zero studies only address CO_2 emissions from buildings that affect climate change, and do not consider the influence of climate change on urban environments at a higher level. They pay only limited attention to the effects of climate change or ecosystem change on net zero building design strategies.

Another main difference between net zero research and resilience research is coverage. It appears that resilience not only covers a wide range of fields, but also has research contributions from both developed nations (such as the US, the Netherlands, and Sweden) [4,35,36] and developing countries (such as China and India) [18]. This might be because resilience is in more emergent need in developing countries, since they are more vulnerable to natural disasters due to their lack of robust infrastructure and prevention methods. On the other hand, net zero research is mostly undertaken in developed countries, including the United States and some of the western European countries.

Resilience and net zero are two primary research focus areas in the urban environment related to sustainable development, and bridging them could potentially yield rich results. Recently, there have been some studies that integrated the holistic and multi-disciplinary resilient approach in energy development. Sharifi and Yamagata [45] used a resilience framework to measure the sustainability of an energy system. They suggest that the energy system could be evaluated based on availability, accessibility, affordability, and acceptability, which is more holistic than the current efficiency-centric criteria. Torcellini et al. [46] identified metrics useful for implementing guidance for energy-related planning, design, investment, and operation. The metrics include energy reduction, energy resource diversity, energy storage, preventive maintenance on energy systems, and other metrics in physical, information, and human interaction categories. Beheshtian et al. [47] created a model to measure the long-term resilience of transportation energy infrastructure in Manhattan, NY.

5. Conclusions

This paper presents findings from a literature review of two topics with shared ecological intellectual roots. The literature review was conducted with both quantitative and qualitative approaches. It scanned 1821 papers in the resilience research domain and 592 in the NZE research domain, all from the period of 1970 through 2018. Citation analysis, co-citation analysis, and text data mining were carried out using new data mining software, VOSviewer, to determine influential studies, thinkers, and concentrated research topics and their correlations. Based on the findings, conclusions can be drawn as follows. This paper provides an initial step in understanding the research activities of the past five decades in these two areas and their connection to their ecological roots.

'Net zero' and 'resilience' have overlapping origins in ecosystem and systems ecology. 'New zero' stems from Georgescu-Roegen's application of entropy to ecological economics and Odum's systems ecology and development of the emergy concept. 'Resilience' stems from Holling being influenced by developments in systems ecology that drew together a more formal mathematical approach to systems analysis of ecological cases. Developments in systems ecology in the 1960s largely forms the connection between the two research fields through Holling and Odum. However, despite the richness of research on both NZE and resilience in the urban environment, and despite the shared ecological

roots of NEZ and resilience, the literature on both energy resilience and comparisons between NZE and resilience is very limited, almost non-existent. Unlike resilience studies, NZE research has relatively narrow coverage and has moved away from its ecological origin. The transformation of current NZE practice and concept will be crucial for climate change stabilization. Applying the existing resilience ecological framework to NEZ research could shift the focus on application and individual buildings to broader systematic consideration.

Author Contributions: Conceptualization, M.H. and M.P.-Z.; methodology, M.H. and M.P.-Z.; software, M.H.; validation, M.H. and M.P.-Z.; formal analysis, M.H.; investigation, M.H. and M.P.-Z.; data curation, M.H.; writing—original draft preparation, M.H.; writing—review and editing, M.H. and M.P.-Z.; visualization, M.H.

Funding: This research received no external funding.

Acknowledgments: We would like to acknowledge the support given from School of Architecture, Planning and Preservation, and Department of Environmental Science and Technology in the University of Maryland.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Seto, K.C.; Dhakal, S.; Bigio, A.; Blanco, H.; Delgado, G.C.; Dewar, D.; Huang, L.; Inaba, A.; Kansal, A.; Lwasa, S.; et al. *Human Settlements, Infrastructure and Spatial Planning*; International Institute for Applied System Analysis: Laxenburg, Austria, 2014.
2. Lucon, O.; Ürge-Vorsatz, D.; Ahmed, A.Z.; Akbari, H.; Bertoldi, P.; Cabeza, L.F.; Eyre, N.; Gadgil, A.; Harvey, L.D.; Jiang, Y.; Liphoto, E. *Buildings*; Cambridge University Press: Cambridge, UK, 2014.
3. Allen, M.R.; Barros, V.R.; Broome, J.; Cramer, W.; Christ, R.; Church, J.A.; Clarke, L.; Dahe, Q.; Dasgupta, P.; Dubash, N.K.; et al. *IPCC Fifth Assessment Synthesis Report-Climate Change 2014 Synthesis Report*; IPCC: Geneva, Switzerland, 2014.
4. Holling, C.S. Engineering resilience versus ecological resilience. In *Engineering within Ecological Constraints*; National Academies Press: Washington, DC, USA, 1996; p. 32.
5. Yi, H.; Srinivasan, R.S.; Braham, W.W.; Tilley, D.R. An ecological understanding of net-zero energy building: Evaluation of sustainability based on emergy theory. *J. Clean. Prod.* **2017**, *143*, 654–671. [CrossRef]
6. New Building Institute. Getting to Zero Status Update and Zero Energy Building List, 2018. Available online: https://newbuildings.org/resource/2018-getting-zero-status-update/ (accessed on 5 January 2018).
7. Rapoport, A. (Ed.) *The Mutual Interaction of People and Their Built Environment*; Walter de Gruyter: Berlin, Germany, 1976.
8. Spash, C.L. (Ed.) *Routledge Handbook of Ecological Economics: Nature and Society*; Taylor & Francis: Milton Park, UK, 2017.
9. Hassler, U.; Kohler, N. *Resilience in the Built Environment*; Taylor & Francis: Milton Park, UK, 2014.
10. Hernandez, P.; Kenny, P. From net energy to zero energy buildings: Defining life cycle zero energy buildings (LC-ZEB). *Energy Build.* **2010**, *42*, 815–821. [CrossRef]
11. Soddy, F. *Wealth, Virtual Wealth and Debt*; George Allen and Unwin Ltd.: London, UK, 1933.
12. Boulding, K.E. *Ecodynamics: A New Theory of Societal Evolution*; SAGE Publications, Incorporated: Thousand Oaks, CA, USA, 1978.
13. Odum, H.T. Energy, ecology, and economics. *Ambio* **1973**, *2*, 220–227.
14. Odum, H.T. *Environmental Accounting: Emergy and Environmental Decision Making*; Wiley: Hoboken, NJ, USA, 1996.
15. Pulselli, R.M.; Simoncini, E.; Pulselli, F.M.; Bastianoni, S. Emergy analysis of building manufacturing, maintenance and use: Em-building indices to evaluate housing sustainability. *Energy Build.* **2007**, *39*, 620–628. [CrossRef]
16. Pulselli, R.M.; Simoncini, E.; Marchettini, N. Energy and emergy based cost–benefit evaluation of building envelopes relative to geographical location and climate. *Build. Environ.* **2009**, *44*, 920–928. [CrossRef]
17. Lindseth, B. The pre-history of resilience in ecological research. *Limn* **2011**, *1*, 1.
18. Liao, K.H. A theory on urban resilience to floods—A basis for alternative planning practices. *Ecol. Soc.* **2012**, *17*, 48. [CrossRef]

19. Wang, C.H.; Blackmore, J.M. Resilience concepts for water resource systems. *J. Water Resour. Plan. Manag.* **2009**, *135*, 528–536. [CrossRef]
20. Berkes, F.; Folke, C. Linking social and ecological systems for resilience and sustainability. In *Linking Social and Ecological Systems: Management Practices and Social Mechanisms for Building Resilience*; Cambridge University Press: Cambridge, UK, 1998.
21. Folke, C. Resilience: The emergence of a perspective for social–ecological systems analyses. *Glob. Environ. Chang.* **2006**, *16*, 253–267. [CrossRef]
22. Adger, W.N.; Hughes, T.P.; Folke, C.; Carpenter, S.R.; Rockström, J. Social-ecological resilience to coastal disasters. *Science* **2005**, *309*, 1036–1039. [CrossRef] [PubMed]
23. Biggs, R.; Schlüter, M.; Biggs, D.; Bohensky, E.L.; BurnSilver, S.; Cundill, G.; Dakos, V.; Daw, T.M.; Evans, L.S.; Kotschy, K.; et al. Toward principles for enhancing the resilience of ecosystem services. *Annu. Rev. Environ. Resour.* **2012**, *37*, 421–448. [CrossRef]
24. Walker, B.; Salt, D.; Reid, W. *Resilience Thinking: Sustaining People and Ecosystems in a Changing World*; Island Press: Washington, DC, USA, 2006.
25. Small, H. Visualizing science by citation mapping. *J. Am. Soc. Inf. Sci.* **1999**, *50*, 799–813. [CrossRef]
26. O'Connor, B.; Bamman, D.; Smith, N.A. Computational Text Analysis for Social Science: Model Assumptions and Complexity. Available online: https://people.cs.umass.edu/~{}wallach/workshops/nips2011css/papers/OConnor.pdf (accessed on 28 March 2019).
27. Zhai, C.; Massung, S. *Text Data Management and Analysis: A Practical Introduction to Information Retrieval and Text Mining*; Morgan & Claypool: Rafael, CA, USA, 2016.
28. Van Eck, N.J.; Waltman, L.; Dekker, R.; van den Berg, J. A comparison of two techniques for bibliometric mapping: Multidimensional scaling and VOS. *J. Assoc. Inf. Sci. Technol.* **2010**, *61*, 2405–2416. [CrossRef]
29. Garfield, E. From the science of science to Scientometrics visualizing the history of science with HistCite software. *J. Informetr.* **2009**, *3*, 173–179. [CrossRef]
30. Van Eck, N.J.; Waltman, L. Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics* **2010**, *84*, 523–538. [CrossRef] [PubMed]
31. Davila, C.C.; Reinhart, C. Urban energy lifecycle: An analytical framework to evaluate the embodied energy use of urban developments. In Proceedings of the BS2013: 13th Conference of International Building Performance Simulation Association, Chambéry, France, 26–28 August 2013; pp. 26–28.
32. Moed, H.F. *Citation Analysis in Research Evaluation*; Springer Science & Business Media: Berlin, Germany, 2006; Volume 9.
33. McCain, K.W. Mapping authors in intellectual space: A technical overview. *J. Am. Soc. Inf. Sci.* **1990**, *41*, 433–443. [CrossRef]
34. Quinlan, A.E.; Berbés-Blázquez, M.; Haider, L.J.; Peterson, G.D. Measuring and assessing resilience: Broadening understanding through multiple disciplinary perspectives. *J. Appl. Ecol.* **2016**, *53*, 677–687. [CrossRef]
35. Borg, I.; Groenen, P.J. *Modern Multidimensional Scaling: Theory and Applications*; Springer Science & Business Media: Berlin, Germany, 2005.
36. Adger, W.N. Social and ecological resilience: Are they related? *Prog. Hum. Geogr.* **2000**, *24*, 347–364. [CrossRef]
37. Colding, J.; Barthel, S. The potential of 'Urban Green Commons' in the resilience building of cities. *Ecol. Econ.* **2013**, *86*, 156–166. [CrossRef]
38. Schipper, E.L.F.; Langston, L. A Comparative Overview of Resilience Measurement Frameworks. Available online: https://www.odi.org/sites/odi.org.uk/files/odi-assets/publications-opinion-files/9754.pdf (accessed on 28 March 2019).
39. Pickett, S.T.; Cadenasso, M.L.; Grove, J.M. Resilient cities: Meaning, models, and metaphor for integrating the ecological, socio-economic, and planning realms. *Landsc. Urb. Plan.* **2004**, *69*, 369–384. [CrossRef]
40. Head, L.; Muir, P. Suburban life and the boundaries of nature: Resilience and rupture in Australian backyard gardens. *Transact. Inst. Br. Geogr.* **2006**, *31*, 505–524. [CrossRef]
41. Marszal, A.J.; Heiselberg, P.; Bourrelle, J.S.; Musall, E.; Voss, K.; Sartori, I.; Napolitano, A. Zero energy building—A review of definitions and calculation methodologies. *Energy Build.* **2011**, *43*, 971–979. [CrossRef]
42. Sartori, I.; Napolitano, A.; Voss, K. Net zero energy buildings: A consistent definition framework. *Energy Build.* **2012**, *48*, 220–232. [CrossRef]

43. Tyler, S.; Moench, M. A framework for urban climate resilience. *Clim. Dev.* **2012**, *4*, 311–326. [CrossRef]
44. Ahern, J. From fail-safe to safe-to-fail: Sustainability and resilience in the new urban world. *Lands. Urban Plan.* **2011**, *100*, 341–343. [CrossRef]
45. Sharifi, A.; Yamagata, Y. A conceptual framework for assessment of urban energy resilience. *Energy Procedia* **2015**, *75*, 2904–2909. [CrossRef]
46. Torcellini, P.; Pless, S.; Leach, M. A pathway for net-zero energy buildings: creating a case for zero cost increase. *Build. Res. Inf.* **2015**, *43*, 25–33. [CrossRef]
47. Beheshtian, A.; Donaghy, K.P.; Geddes, R.R.; Gao, H.O. Climate-adaptive planning for the long-term resilience of transportation energy infrastructure. *Transp. Res. Part E Logist. Transp. Rev.* **2018**, *113*, 99–122. [CrossRef]