Principles and criteria for assessing urban energy resilience: A literature review

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A B S T R A C T
Between 60% and 80% of global energy is consumed in urban areas and given the projected increase in world’s urban population, this share is expected to further increase in the future. Continuity of energy supply in cities is affected by climate change and a growing array of other threats such as cyber attacks, terrorism, technical deficiencies, and market volatility. Determined efforts, acknowledging the interactions and interlinkages between energy and other sectors, are needed to avoid adverse consequences of disruption in energy supply. Resilience thinking is an approach to management of socio-ecological systems that aims to develop an integrated framework for bringing together the (often) fragmented, diverse research on disaster risk management. The literature on urban resilience is immense and still growing. This paper reviews literature related to energy resilience to develop a conceptual framework for assessing urban energy resilience, identify planning and design criteria that can be used for assessing urban energy resilience, and examine the relationship of these criteria with the underlying components of the conceptual framework. In the conceptual framework, it is proposed that in order to be resilient, urban energy system needs to be capable of “planning and preparing for”, “absorbing”, “recovering from”, and “adapting” to any adverse events that may happen in the future. Integrating these four abilities into the system would enable it to continuously address “availability”, “acceptability”, “affordability”, and “acceptability” as the four sustainability-related dimensions of energy. The paper explains different resilience principles associated with these abilities and sustainability dimensions. Also, different planning and design criteria were extracted from the literature and categorized into five themes: infrastructure; resources; land use, urban geometry and morphology; governance; and socio-demographic aspects and human behavior. Examination of the relationship of these criteria with the underlying components of the conceptual framework highlighted the complexity and multi-faceted nature of energy resilience. Exploration of the relevance of the identified criteria to climate change mitigation and adaptation revealed that most of the identified criteria can provide both mitigation and adaptation benefits.

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1. Introduction

Historically, cities have proved to be among the most surviving man-made products [1]. Over time, they have developed strategies to reduce the amount of damage caused by disasters [2]. However, climate change, which is largely driven by anthropogenic emissions of greenhouse gases (mainly CO2) [3], is expected to exacerbate hazards and increase the frequency and severity of extreme events. This limits the coping capacity of cities and can pose serious threats to their very survival. Adding non-climate-induced problems such as managerial mistakes [4], political conflicts and geopolitical instabilities [5], recurring economic crises, and terrorism [6] to the climate induced threats, may result in wicked problems with infinite repercussions for the structure and effective functioning of cities around the world.

Developed as a response to these dangers, the concept of resilience has gained prominence on the political agenda and is also rapidly gaining ground in the urban studies literature [7,8]. Over the past few years a substantial body of research has been published on urban resilience (e.g. see [9–11]). These, often, single-hazard oriented studies are mainly sector specific and focus on issues such as hazard mitigation [12], ecology [13–15], transportation [16], infrastructure [17], economy [18,19] poverty [20], diseases and pandemics [21,22], governance [23,24], and agriculture [25–27]. At the same time, few studies have focused on developing criteria and indicators for assessing urban resilience in different domains [6,8,28–33]. Unlike sustainability, for which comprehensive assessment tools exist that cover multiple aspects across different scales (e.g. see [34,35]), current tools for assessing urban resilience are mainly focused on single aspects. Engle and Bremond [32] have taken a first step toward developing a framework that covers various aspects.

Energy resilience is a strand of resilience that is not well-studied in the urban studies literature [36]. Of those studies addressing urban energy, only a few have discussed energy and resilience together [37–39]. This is despite the fact that 60–80% of global energy is consumed in cities [40] and, given the increasing rate of global urbanization, urban areas are expected to remain as the main loci of global energy consumption in the future [5,40]. By altering the CO2 concentration in the atmosphere, and thereby intensifying the greenhouse effect, increased consumption of energy in urban areas contributes to further warming of the climate and, therefore, can be considered as a major driving force of climate change. In turn, climate change and global warming can have negative impacts on energy sector through increasing energy demand [41] and intensifying extreme events that threaten the security of the generation, transmission, and distribution infrastructure. In addition, even under the most strict climate policy scenarios, the conventional proven oil and gas reserves, accounting for the largest share of global energy consumption, would be depleted before 2050 with adverse consequences for availability, accessibility and affordability of energy resources [42].

Disruptions in energy supply, as a vital component of economic systems at different levels of economic activity, may cost “up to 1–2%” of the annual development potential of nations and cause serious damage to the effective functioning of their economies [43,44]. A list of some of climate and non-climate induced threats and challenges associated with the functionality of urban energy systems is shown in Table 1 (note that this list is far from extensive). Each of these threats with exacerbated effects if two or more threats are combined) will have significant implications for energy security of urban communities and, given the tight energy-water-food-health nexus, may cause serious problems for the functionality of urban systems. Therefore, urban energy resilience warrants further investigation.

This paper seeks to integrate the existing knowledge on urban energy and resilience to elaborate on the concept of urban energy resilience and establish a theoretical framework that can serve as the foundation for developing tools for assessing urban energy resilience. It draws on material collected as part of a broader research project initiated in 2013 with the objective of developing criteria and indicators for measurement of urban resilience. The need for metrics and assessment tools for evaluating energy resilience has been mentioned in the literature [45]. Assessment tools can provide information about the baseline conditions and identify gaps that need to be filled using finite resources [34,46]. Results of the urban energy resilience assessment process can enable planners and decision makers to identify priorities, track achievement of goals, and make more informed decisions that facilitate transition to low-carbon and more resilient communities.

The primary objectives of this preliminary study are as follows: (1) to develop a conceptual framework for assessing urban energy resilience; (2) to introduce several categories of planning and design criteria that can be used for assessing urban energy resilience; (3) to explore possible associations between the selected criteria and the components of the energy resilience framework; and (4) to identify the selected criteria’s relevance to mitigation and adaptation to climate change.

The remainder of this paper is organized as follows: Section 2 gives a brief overview of the materials and methods used in this study. Section 3 elaborates on the definition of urban energy resilience and, through synthesis of related literature, presents a theoretical framework for assessing urban energy resilience. In the Section 4 planning and design criteria related to urban energy resilience are discussed. These criteria are organized into matrices showing how each criterion relates to the various components of the assessment framework introduced in the previous section. Section 5 explores the associations between the components of the resilience assessment framework and examines relevance of the selected criteria to climate change mitigation and adaptation. The last section discusses the implications of the research and makes some recommendation for future studies.
2. Materials and methods

2.1. Review questions and search strategies

This is a desktop research that involved content analysis of literature related to urban energy resilience. The literature review was conducted following the procedure described in Pullin and Stewart [69]. The specific review questions to be addressed were: “what is the definition of urban energy resilience?” and “what are the principles and criteria for assessment of urban energy resilience?”. In order to include the maximum possible number of relevant studies, a specific and broad review protocol was developed. The following electronic databases were searched to identify potentially relevant studies: Web of Science Core Collection under the Online Search dropdown menu of EndNote software (title/keywords/abstract) and Google Scholar (the first 200 hits). The search strings included terms related to energy resilience at the urban level (for more details see Appendix A, please click on the link provided at the last page of this manuscript to access the appendices).

The initial searches were conducted in January 2013 and yielded 347 matches, excluding duplicates. The abstracts of these papers were examined to determine if they are suitable for being included in the research. Papers that were not relevant to the above mentioned review questions were excluded at this stage. The 74 eligible papers, that address both energy and resilience, went under an in-depth study to identify the defining principles of urban energy resilience and distill criteria relevant to these principles. In order to add research published after the initial search, the alert system of Google Scholar was activated and used to update the article database. This system usually provides one to two series of weekly updates. Also, snowballing method was used to include other relevant studies in the study. In the snowballing process literature review starts with a number of selected articles. While reading the selected articles, relevant studies cited in their bibliography section are added to the review database. This helps including a larger number of studies in the review. Studies collected this way do not have the specified combinations of the search terms in their title/abstract/keywords, but are highly relevant to the review questions.

Overall, a total number of 245 studies from 1973 to 2016 were reviewed for the purpose of this paper. It should, however, be mentioned that except for seven papers, all studies reviewed here have been published since the turn of the century. This indicates a surge of interest in resilience (see Fig. 2 in Appendix A for more details). While mainly peer-reviewed articles, relevant grey literature, reports, and policy documents were also reviewed. Selected studies are published in English and span a variety of disciplines such as urban planning and design, civil engineering, housing studies, energy policy, energy security, food policy, transportation, geography, social studies, economy, public health, disaster management, and water management. This indicates the multidisciplinary nature and breadth of fields that the issue of urban energy resilience covers.

2.2. Data extraction and analysis

Analysis of the literature was conducted in two steps. The first step was focused on identifying different components of urban energy resilience. Results of this analysis are presented in Section 3,
The second step was to extract a list of energy resilience criteria and relate them to the components of the energy resilience framework, explore possible associations between the components of the energy resilience framework, and also discuss the relevance of the selected criteria to climate change mitigation and adaptation. An excel spreadsheet was developed for data entry. This resulted in a matrix where rows represent the individual criteria extracted from the literature and columns include a summary of information found in the literature on how each criterion is related to the components of urban energy resilience and to climate change mitigation and adaptation. Extracted criteria were later categorized into five groups that are discussed in Section 4.

To identify how each criterion relates to different components of the conceptual framework, opinions of 15 urban energy experts were also solicited. This was done in order to reduce the subjectivity of the procedure. All participants hold a PhD degree in fields related to urban energy. A package including a cover letter explaining the academic intent of the study and ensuring confidentiality and anonymity of the respondents, the description of urban energy resilience (Section 3) and Tables 3–7 (columns for which answers were sought were left blank) was sent to the experts and they were asked to identify abilities, sustainability dimensions, and principles related to each criterion. Nine completed forms were sent back. Comparing these forms with those completed by the authors showed a substantial amount of consistency. Differences were mainly related to the judgements on the relationship between the selected criteria and the principles of urban resilience. This could be explained by the fact that resilience is a normative concept and a certain amount of subjectivity will inevitably be inherent in the judgements. Each ability, sustainability dimension, and principle mentioned in Tables 3–7 was indicated by at least six experts. This measure was taken to reduce the subjectivity of the judgments.

These data were also used to determine if there are associations among the elements of the conceptual framework. Matrices were created showing the relationship of each criterion with each of the elements of the energy resilience framework (see Appendix B; 0, and 1 indicate absence and presence of relationship, respectively). When completed, all the files were aggregated and exported to IBM SPSS Statistics 22 to examine the existence of association between the elements (see Appendix C). The Phi and Cramer’s V Coefficients were calculated to determine the strength of association. The software was also utilized to calculate the percentage of criteria which are relevant to both elements in each pair of analysis (e.g. percentage of criteria that are relevant to both accessibility and acceptability).

3. Urban energy resilience

This section elaborates on resilience and abilities, sustainability dimensions, and principles that are related to urban energy resilience and are essential for conceptualizing and assessing it. Resilience is a polysemic concept defined and the way it has been defined and interpreted varies from one discipline to another [4,70]. Although a vast body of literature exists on resilience, there is still no consensus on how to define it [7]. Originated and developed in physics and psychology, resilience has been traditionally used as a measure of stability that indicates the ability of an object to survive a shock or trauma and return to the equilibrium state in a timely manner [7,71]. In 1973, Holling introduced resilience into ecology and emphasized the significance of a system’s ability to endure shocks by absorbing disturbance and not losing the pre-disturbance relationships governing the system components [71–73]. Holling’s definition indicates a multiple-equilibrium interpretation of resilience, as compared with the traditional single-equilibrium interpretation. Many other disciplines have borrowed the resilience concept from ecology [74]. Planning as a multi-disciplinary field, has seen an increasing interest in the study of resilience since the late 1990s. This has occurred in response to the increasing threats that modern cities need to deal with in order to keep the city, as a socio-ecological system, functioning [75].

Three approaches to urban resilience can be distinguished from the literature: “engineering” resilience, “ecological” resilience, and “adaptive” (“socio-ecological”) resilience [71,76].

Engineering resilience adopts a rigid approach to risk management and emphasizes the importance of enhancing resistance and robustness of the critical infrastructure in the urban system [28,77]. In case the critical thresholds are crossed, engineering resilience, as a static concept, requires a rapid recovery process that involves return to the equilibrium point [71,77]. This approach is based on the assumption that natural and man-made disasters are predictable and human-made prediction systems are reliable enough to predict them. This reliance may create a false sense of complacency that as Liao [77] argues only delays the hazards, accumulates the risks, and thereby...
Table 3 Criteria related to urban infrastructure and their relationship with the components of the conceptual framework.

| Urban infrastructure | Ability | Sustainability | Principle | References |
|----------------------|---------|----------------|-----------|------------|
| Supply, transmission, distribution |         |                |           |            |
| In1 Fortification and robustness (physical security) | P, Ab | A1 | R | [43,44,62,74,82,92,101,109] |
| In2 Operational system protection (e.g. system relief, circuit breakers) | P, Ab | A1 | F, A | [56] |
| In3 Diversification of energy supply (fuel mix, multisourcing, type of generation) | P, Ab, A1,2 | D, Ad | [42,44,53,56,74,82,83,88,89,98,101,103,118,121,127–136] |
| In4 Spatially distributed generation (and critical facilities) | P, Ab, A1,2 | D, FSO | [36,47,50,53,56,74,83,114,126,137–139] |
| In5 Energy production near point of use (colocation of supply and demand) | P, Ab, R | A1,2,4 | E, I | [40,57,74] |
| In6 On-site energy production (photovoltaics, micro combined heat and power, tri-generation, thermal panels, small wind turbines mounted at the corners of the roof) | All | All | S, D, I, SO, E | [10,50,83,86,92,109,121–123,129,140–150] |
| In7 Solar absorption cooling | All | All | E, D | [151,152] |
| In8 Large wind turbines located outside the built-up area | P, Ab, A1,2,4 | D, FC, E | [137,153,154] |
| In9 Large solar thermal collectors | P, Ab, A1,2,4 | D, FC, E | [141,153] |
| In10 Smart micro-girds fed by micro-turbines and solar panels (photovoltaics, building integrated photovoltaics) and storage facilities | All | All | S, D, I, SO, E | [36,38,44,48,49,92,114,126,128,155–160] |
| In11 Building integrated photovoltaic/thermal for recovery of heat loss from photovoltaics and building integrated photovoltaics | All | All | E, D | [49] |
| In12 Ground source heat pumps | All | All | D, FC, E | [141,142,153,161,162] |
| In13 Waste heat or biomass-fueled combined heat and power plants | P, Ab, A | All | D, E, FC | [107,114,153] |
| In14 Biofuel energy (“food waste”, “second generation cellulosic biofuels”, “third generation using algae” etc.) | P, Ab, A1,4 | D, FC, E | [67,138,158,163–165] |
| In15 Biomass supply chain, wood pellet systems | P, Ab, A1,4 | D, FC, E | [118,138] |
| In16 Interdependency and interconnection of infrastructures and their networks | All | A1,2 | CC, In, A | [45,47,53,57,61,74,83,109] |
| In17 Regular maintenance | P | A1 | S, FC, Re | [56,74,98,166] |
| In18 Generation, transmission, and distribution efficiency (leakages, etc.) | P, Ab, A1,4 | E, S, Ad | [44,82,89,167] |
| In19 Age of the fleet (feeder lines, etc.) | P, Ab, A1,4 | R, S, E | [44,55] |
| In20 Phasing out obsolete and/or damaged assets and introducing new and more efficient technologies such as LEDs | P, Ab, A1,4 | E, Ad | [46,114,138] |
| In21 Type of feeder lines (overhead/underground cables; looped/interconnected or radial configuration) | P, Ab, R | A1 | S | [53,55,92,102,109,116,177] |
| In22 Natural gas distribution: continuous (grid) VS discontinuous (propane tanks) | All | A1,2,4 | E | [168] |
| In23 Alternative and safer energy sources for critical infrastructure such as parking gates, traffic lights, subways, etc. | All | A1,2 | S, F | [61,74] |
| In24 Intelligent ICT infrastructure and its cyber security for maintaining grid operation | P | A1 | S | [46,56,61,74,92,102,166,169,170] |
| In25 Flexible network architecture | All | A1,2 | F, FC, A | [56] |
| In26 Number and configuration of nodes and links in the transmission and distribution grid | P, R | A1, 2 | Rd, F, A | [17,134,171] |
| Backup and storage |         |                |           |            |
| In27 Back-up energy sources and stocks of energy | P, Ab, R | A1 | Rd, D, Re, FC | [74,134,166] |
| In28 Energy storage facilities (including electro-chemical batteries, flow batteries, hydrogen, etc.) | P, Ab, R | A1 | Rd, Re, FC | [48,86,88,102,114,117,119,126,129,133] |
| In29 Distributed storage | P, Ab, R | A1 | Rd, F | [53,92] |
| In30 Connectivity of generation and storage infrastructure | P, Ab, R, A1 | F, In | [60,98,101] |
| In31 Back-up data of the utility infrastructure (information networks, data sharing, etc.) | P, Ab, R | A1 | Rd | [56,62] |
| In32 “Spare capacity and reserve margins” (resources, transmission lines, etc.) | P, Ab, A1,3 | Rd, FC, Ad | [44,56,61,82,84,102,103,172] |
| In33 Installed/redundant components (generators, pumps, etc.) | P, Ab, A1,4 | Rd | [28,46,56,96,102,129,133,173] |
| In34 Vehicle to Grid and Vehicle to Community (selling surplus power) | P, Ab, A1,4 | D, I, In, Cr, E | [86,142,174] |
| Green infrastructure |         |                |           |            |
| In35 Parks and open spaces, bioswales, etc. (attention to regular trimming of trees) | P, Ab, A1,3,4 | E, Ad, SO | [55,175–189] |
| In36 Indigenous (native) vs invasive plants | P, Ab, A1,3,4 | E, Ad | [114,179] |
| In37 Deciduous trees for cold climates | P, Ab, A | All | E, Ad | [143] |
| In38 Xeriscape for hot and arid climates | P, Ab, A1,3,4 | E, Ad | [178,190] |
| In39 Urban agriculture (vacant lands, marginal lands, etc.) | P, Ab, A1,3,4 | E, I, Ad | [191] |
| In40 Green area ratio (building envelope) | P, Ab, A1,3,4 | Ad, E | [184] |
| In41 Green wall (vegetative covering, green façade) | P, Ab, A1,3,4 | Ad, E | [184,192–194] |
| In42 Green roof (living roof) | P, Ab, A1,3,4 | Ad, E | [114,177,186,190,195–198] |
Blue infrastructure

In43 Rainwater harvesting, decentralized water harvesting systems
P, Ab, A A1,4 E, SO, I [123,175,199,200]

In44 Water conservation
P, Ab, A A1,4 E [123,190]

In45 Heat recovery and energy generation from sewage
P, Ab, A A1,4 D, E, FC [54,175]

In46 Separation of used water into grey and black flows
P, Ab, A A1,4 E, FC [190]

In47 Removing and recovering ammonium and phosphate from wastewater
P A1,4 E [190]

In48 Waterscape as a natural heat sink
P, Ab, A A1,3,4 E, Ad [180,186,201]

In49 Roof pond
P, Ab, A A1,3,4 E, Ad [83,157,202,203]

Buildings and neighborhoods

In50 Redesign and refurbishment (retrofit)
P, Ab, A All E [40,47,58,138,140,156,178,190,204–207]

In51 Glazing
P, Ab, A All I, E [139,140,207,208]

In52 Net-zero and net-positive energy buildings
P, Ab, A All E [36,109,123,126,128,138,140,141,143,151,159,185,190,205,207,209–212]

In53 Insulation and dynamic insulation of buildings
P, Ab, A A1,3,4 E [194, P663]

In54 “Cut-off of air conditioning waste heat discharge”
P, A A1,4 E [194, P663]

In55 Net zero energy neighborhoods
P, Ab, A All I, E [140]

In56 Pooling of the built environment (shared walls)
P, Ab, A A1,3,4 SO, E [140,188]

In57 District energy systems (“using low-temperature heat from renewable sources” and “industrial waste heat”)
All A1,2,4 I, E, D [91,114,156,161,199]

Transportation

In58 Infrastructure for active transportation modes
P, Ab, A A1,3,4 D, Ad, E, Eq [40,114,143,157,169,191,213–217]

In59 Modal split
P, Ab, A A1,3,4 D, Ad, E, Eq [89,214]

In60 Size of cars
P, A A1,3,4 Ad, E, Eq [169]

In61 Fuel efficiency of cars
P, Ab, A A1,3,4 E [47,169,216]

In62 Supporting promotion of hybrid vehicles and installing electric vehicle plug-ins in locations where multiple use can be achieved.
All A1,2,4 Cr, D, E [56,83,86,114,157,199]

Innovation

In63 Enhancing energy efficiency through innovation and technology (building, industry, transportation)
P, Ab, A A1,3,4 E, Cr, Ad [40–44,48,49,56,57,74,83,107,123,142,161,200,209,214,216,218,219]

In64 Fuel flexibility of the grid, appliances, automobiles, etc.
P, Ab, R A1,2 F, S, D [56,83,157,199]

P, Preparation; A, Absorption; R, Recovery; Ad, Adaptation; A1, Availability; A2, Accessibility; A3, Affordability; A4, Acceptability; R, Robustness; S, Stability; F, Flexibility; Re, Resourcefulness; CC, Coordination Capacity; Rd, Redundancy; D, Diversity; FC, Foresight Capacity; I, Independence; In, Interdependence; C, Collaboration; A, Agility; Ad, Adaptability; SO, Self-Organization; Cr, Creativity; E, Efficiency; Eq, Equity.
exacerbates disasters. Acknowledging the unpredictability of many disasters, the ecological and adaptive approaches to resilience adopt a more flexible and dynamic approach.

Ecological resilience focuses on the tenacity of the system (in contrast to its stability). Here, resilience is interpreted as possessing a certain level of tolerance to absorb change and disturbance and retain the main architecture, function, and character of the system [71,72,77,78]. This implies that a system may shift to a new regime (new equilibrium state(s)), as long as its structure and function is unchanged.

A more recent, and slightly different, conceptualization of resilience is adaptive resilience that is developed based on the recognition of cities as complex and dynamic socio-ecological systems. According to this approach, a system undergoes change continuously and will not necessarily return to an equilibrium state (either old or new) after a disaster. Adaptive resilience seeks to embed the following characteristics in a socio-ecological system: (1) system integrity that enables the system to undergo shock, withstand and absorb it, and maintain the same character, function, and architecture; (2) capability of “self-(re)organization to accommodate external changes”; and (3) ability to learn from the disaster and seize it as an opportunity for self-improvement and enhancement of the coping capacity [11,31,32,70,71,76,98,88]. Therefore, adaptive resilience advocates for “short-term coping” and “long-term adaptation” [32, P1302], that enables the system to bounce back and also bounce forward. The adaptation and learning features are particularly important given the fact that small-scale, recurring disasters account for the bulk of disaster damages [79], indicating that little has been learnt from the event.

Because of the wide range of uncertainties associated with the supply and demand of energy, as a critical resource for effective functioning of cities, and since adaptation and learning from experience are key for enhancing the coping capacity in the face of increasing adverse impacts of climate change, this paper adopts and adaptive approach to urban energy resilience. The defining elements and the main principles of a resilient urban energy system are respectively described in Sections 3.1 and 3.2.

### 3.1. A synthetic approach to defining urban energy resilience

In the context of urban energy, resilience is strongly connected to the concept of sustainability as a guiding principle. In this study sustainability is envisioned as being broader than the concept of resilience. As specified in the frequently used definition proposed by World Commission on Environment and Development, sustainability entails meeting “the needs of the present without compromising the needs of the future” [80, P8]. As explained in Table 2, broadly speaking, achieving sustainability requires taking an integrated approach that covers multiple, inter-related environmental, social, and economic dimensions. Precautionary measures to respect uncertainty, promoting inter- and intra-generational equity, minimizing adverse impacts on the environment, maximizing efficiency and economic benefits through resource

### Table 4
Criteria related to resources and their relationship with the components of the conceptual framework.

| Resources | Ability | Sustainability | Principle | References |
|-----------|---------|----------------|-----------|------------|
| Energy    | P       | A1,4           | E         | [44,82,89,102,134,136,204] |
| Re1       | Energy/Carbon intensity of generation |               |           |            |
| Re2       | Efficient resource use                | Ab, A         | A1,4      | E, Ad      | [41,86] |
| Re3       | Energy conservation                   | P, Ab, A      | A1,4      | E, Rd      | [138] |
| Re4       | Energy self sufficiency                | All           | A1,2      | I, S       | [45,83,136] |
| Re5       | Energy cycling                        | P, Ab, A      | A1,4      | E, In      | [39,86] |
| Re6       | Waste management and waste incineration| P, Ab, A      | A1,4      | E, D       | [88,123,135,161] |
| Re7       | Environmental and socio-economic impacts of energy system| P | A4 | FC, Eq | [82,83,88,135] |
| Water–energy nexus |            |               |           |            |
| Re8       | Reducing energy footprint of water production, treatment and distribution| P, A      | A1,4      | E         | [52–54,114,125,167,200,221] |
| Re9       | Using water saving shower head         | P, Ab, A      | A1,3,4    | E, Ad      | [52,54,190,209] |
| Re10      | Installation of low-flush toilets      | P, Ab, A      | A1,3,4    | E, Ad      | [125] |
| Re11      | Using low-energy cloth washing and dish washing machines  | P, Ab, A      | A1,3,4    | E, Ad      | [52,83,136] |
| Re12      | Installation of tankless water heaters (demand-type or instantaneous) | P, Ab, A      | A1,3,4    | E, Ad      | [67] |
| Re13      | Use of greywater for irrigation and toilet flushing | P, Ab, A      | A1,3,4    | F, E       | [52,167] |
| Re14      | Smart consumption of freshwater       | P, Ab, A      | A1,3,4    | E, Ad      | [200] |
| Re15      | Provision of less energy intensive rainwater harvesting systems in buildings | P, Ab, A      | A1,3,4    | E, Ad, Cr  | [167] |
| Re16      | Reclaim and treatment of used water for public drinking water supply | P, Ab, A      | A1,4      | F, E       | [167] |
| Re17     | Use of “municipal wastewater, brackish water and sea water” for water withdrawal and consumption in thermoelectric generation | P, Ab, A      | A1,4      | F, E       | [52, P3] |
| Water–energy nexus |            |               |           |            |
| Re18      | Improvement of water infrastructure to reduce water loss | P, Ab        | A1,4      | E, S       | [125] |
| Re19      | Water and energy resource coupling     | All           | A1,2,4    | E, In, CC  | [67] |
| Re20      | Reducing energy footprint of wastewater collection, treatment and discharge | P, A      | A1,4      | E         | [14] |
| Re21      | Storing water (in aquifers) as insurance against the impact of future droughts | P, Ab, A      | A1,4      | E, FC      | [52] |
| Re22      | Reducing water footprint of energy production and transmission | P, A      | A1,4      | E         | [52,53,125,167,221] |
| Re23      | Improving the efficiency of energy production by enhancing water quality | P, Ab, A      | A1,4      | E         | [67] |
| Re24      | Understanding the water intensity of fuels used for electricity generation | P, Ab, A      | A1,4      | E, FC      | [221] |
| Re25      | Less water-intensive technologies for cooling purposes in thermoelectric plants | P, Ab, A      | A1,4      | E, FC, Ad  | [52,53,167] |
| Re26      | Use of natural gas for steamed plants and combined cycle plants | P, Ab, A      | A1,4      | E, FC      | [52,167] |
| Re27      | Use of wet “cooling towers instead of once-through cooling” | P, Ab, A      | A1,4      | E, FC      | [52, P3] |
| Re28      | Knowing groundwater implications of energy (technologies, extraction, etc.) | P, A      | A1,4      | FC         | [54,67,88] |
| Food–water–energy nexus |            |               |           |            |
| Re29      | Food waste (harvesting, processing, storage, distribution, consumption) | P, Ab, A      | A1,4      | Ad, S, E   | [67,163] |
| Re30      | Energy intensity of agriculture        | P, Ab, A      | A1,4      | Cr, E      | [88] |
| Re31      | Local food production                  | P, Ab, A      | A1,3,4    | Re, CC, C, E| [163] |
| Re32      | Best management practices in irrigation| P, Ab, A      | A1,4      | Re, CC, E, SO | [67,164] |
| Re33      | Efficient irrigation technologies      | P, Ab, A      | A1,4      | CC, E      | [67,164] |

P: Preparation; A: Absorption; R: Recovery; Ad: Adaptation; A1: Availability; A2: Accessibility; A3: Affordability; A4: Acceptability; R: Robustness; S: Stability; F: Flexibility; Re: Resourcefulness; CC: Coordination Capacity; Rd: Redundancy; D: Diversity; FC: Foresight Capacity; I: Independence; In: Interdependence; C: Collaboration; A: Agility; Ad: Adaptability; SO: Self-Organization; Cr: Creativity; E: Efficiency; Eq: Equity.
management, and adopting bottom-up and participatory approaches are the main criteria used for assessing achievement of sustainability goals. For the ease of analysis, we have categorized these different criteria as being related to the four dimensions of energy sustainability that have frequently been mentioned in the literature.

A sustainable urban energy system needs to develop effective strategies to ensure availability, accessibility, affordability, and acceptability of energy over time and under varying conditions of uncertainty [39,42,83,88]. Availability denotes the existence of adequate supplies of energy resources and reserves, and proper infrastructure for transforming them into energy services [83,84]. Accessibility refers to the importance of spatial proximity of energy supply and demand [42]. It also entails equitable distribution of energy services (in terms of both quantity and quality) to all community members [84]. Affordability means that the share of income that households must spend to meet their basic energy needs should not exceed a certain threshold. It is argued that "stability" and "predictability" of energy prices is important for ensuring energy affordability [83,84,87]. The last dimension refers to efficiency of energy generation, transmission, and distribution. It also involves, among other things, minimizing environmental impacts of energy systems, preventing disproportionate exposure of environmental risks associated with energy systems, and addressing social and organizational barriers to technology adoption and innovation [81,82,85,87,89].

In order to ensure continuous fulfillment of the four sustainability-related dimensions mentioned above, urban energy system needs to have "the ability to prepare and plan for, absorb, recover from, and more successfully adapt to" any disruptions that may happen in the future [39,46,56,90,207]. Here, definitions provided by other scholars [17,46,51,91–93] for these four abilities are adjusted to align with the purposes of the study and the adaptive approach to resilience:

- **Preparation**: Predict and prepare for disruption by adopting a wide range of planning and design measures aimed at avoiding and withstand potential disruptions (by determining and improving critical thresholds), and minimizing potential adverse impacts on availability, accessibility, affordability, and acceptability of energy services.

- **Absorption**: No matter how well the system is prepared to withstand shocks, the potential impact may still cross the resistance threshold of the system. Therefore, the system components and their relationships should be configured in a way that initial shocks from the disruptive event can be accommodated without a significant deterioration in the system's performance. Also, there should be mechanisms in place for warding off the disruption(s) and thereby avoiding cascading impacts. Absorption enables the system to minimize the potential overall impacts of the disruption.

- **Recovery**: Establish a risk management approach to respond rapidly and reinstate all the system operations and service availabilities to
### Table 6
Criteria related to urban governance and their relationship with the components of the conceptual framework.

| Urban governance                                      | Ability | Sustainability | Principle | References |
|-------------------------------------------------------|---------|----------------|-----------|------------|
| **Monitoring and assessment**                         |         |                |           |            |
| Go1 Surveillance (manually and/or automated)          | P       | A1            | SO, FC    | [56,74]    |
| Go2 Early discovery of the intervention and stopping its propagation | Ab, R   | A1.2          | A, FC     | [74]       |
| Go3 Performance evaluation and monitoring             | P, A    | A1.4          | Re, S, E  | [41,138,211,238] |
| Go4 Smart metering and visual display technologies to inform occupants of consumption patterns and obtain their feedback | Ab, A   | A1.3,4        | F, C, Re, SO, E | [63,141,200,237] |
| Go5 Fine-scaled, site-specific, and updated database (generation, emissions, consumption, etc.) | P, R    | All           | Re        | [41,54,92,125,142] |
| Go6 Planning and Decision making based on decision support systems and simulation models | P, R    | All           | Re, S, CC, D | [166,227] |
| Go7 Certificates, labeling, and rating tools          | P       | A1.4          | Re, E     | [35,54,86,116,141,142,199,204,212,228] |
| **Planning and management**                          |         |                |           |            |
| Go8 Long-term vision                                  | All     | All           | S, FC, Ad, E, Eq | [117,138,199] |
| Go9 Scenario-based energy planning and risk management | P, R    | All           | Re, E, FC | [46,54,56] |
| Go10 Ability to prioritize tasks at the time of disaster | Ab, R   | All           | Re, A, Ad | [74]       |
| Go11 Leadership qualities to initiate and sustain innovative energy experiments | P, R    | All           | Re, CC, E | [53,138]   |
| Go12 Flexible governance to respond to changes       | P, Ab, R| All           | F, Ad, CC, C | [166,217,239] |
| Go13 Preparation (contingency plans, response & recovery plans) | All | A1 | Re | [56,74] |
| Go14 Forecast and event warning broadcast            | P, Ab   | A1           | FC, A     | [50,56]    |
| Go15 Risk communication and energy response          | All     | A1.4          | SO, C, E  | [74]       |
| Go16 Training and communication for raising awareness | All     | A1.4          | Re, C, E  | [56,66,74,138] |
| Go17 Visual tools and visualization methods to raise awareness | P       | A1.4          | Re, FC, E | [56,199]   |
| Go18 Availability of trained repair personnel        | Ab, R   | A1           | Re        | [83]       |
| Go19 Transparent planning                            | P, Ab, A| A1.4          | SO, C, Eq, E | [36,41,43,56,74,101,116,117] |
| Go20 Harmonization of bottom-up initiatives with top-down engagements | P, R    | A1.2          | CC        | [43]       |
| Go21 Participatory governance                        | All     | A1.3,4        | SO, C, Eq, E | [43,57,83,126,137,143,156,191,199,239] |
| Go22 Self-governance and governance by enabling      | P, R, A | A1.2          | SO, C     |            |
| Go23 Community involvement and/or ownership of renewable energy generation | All | A1.3,4 | SO, In, Eq | [43,56,92,117,204,240] |
| Go24 Knowledge networks based on inter-organizational collaboration for information communication and knowledge sharing | P, Ab, R| A1 | CC, In | [43,56,92,117,204,240] |
| **Regulatory basis and law enforcement**             |         |                |           |            |
| Go25 Cross-scale collaborations and partnerships/ jurisdictional mismatches | P, R    | A1           | CC, In    | [41,125,204] |
| Go26 Institutional coordination on water, food, health and energy nexus | P, Ab, A| A1.4 | CC, In, E | [125] |
| Go27 Reliance on imports                             | P, Ab, R| A1.2,3       | I, In, S  | [44,88,89,98,101,102,133,136,238] |
| Go28 Reliance on nuclear energy                      | P, R, A | A1.3,4        | FC, I, E  | [56,236]   |
| Go29 Travel demand management                        | P, Ab, A| A1.4          | SQ, Ad, E | [214]      |
| Go30 Regular publication of energy planning documents and statistics | P, A    | A1.4          | Re, E     | [83]       |
| Go31 Fuel substitution                               | P, Ab, A| A1.4          | E         | [41]       |
| Go32 Social barriers to adoption of modern and innovative technologies | All | A1.4 | Ad, C, E | [49] |
| Go33 Market competitiveness and investment risk of decentralized renewable energy | All | A1.4 | Re, C, E | [83,138,142,212] |
| Go34 Connections between renewable energy industry and building industry | All | A1.2,4 | CC, E | [49] |
| **Pricing**                                           |         |                |           |            |
| Go43 Carbon pricing                                  | P, Ab, A| A1.4          | Re, CC, Eq | [47,53,125,219] |
| Go44 Road pricing and congestion charging           | P, Ab, A| A1.3,4        | Re, CC, Eq | [40,47,216] |
| Go45 Time-varying rates and prices (electricity)     | P, Ab, A| A1.4          | Re, CC, E | [50,142,155,206] |
| Go46 Pre-payment electricity, rationing, etc.        | P, Ab, A| A1.3,4        | Re, CC, E | [65,241]   |
their pre-event capacity and efficiency. Ideally, planning for recovery process should start before the disruptive event. Restoration to normal states depends on severity of the event and the degree of preparation before the event. Recovery process may be accelerated if planning and absorption activities are well implemented and the system has the ability to effectively mobilize and use all the resources at its disposal in a timely manner.

- **Adaptation**: Learn from the event and seize the opportunity to evaluate the system performance and modify its configurations, training mechanism, and functions to enhance its adaptive capacity and make it more flexible to future disruptions. Adaptation process should result in the overall improvement of the state of the system (as compared with the pre-disaster conditions). Adaptation activities are often "incremental" and in response to small-scale disturbances [94]. However, when a system is highly vulnerable and risks and stresses are relatively severe and intervals between them become shorter, the system may cross thresholds and tip into extremely different pathways. Under such circumstances, incremental and small-scale adaptations may prove inadequate and "transformational adaptation" will be required [51,94,95]. Transformations adaptation enables the system to shift from one "stability domain" (normal state) for development to another [51,94,95].

A diagram illustrating the sequential steps involving these abilities is shown in Fig. 1. This is proposed based on the modification of the diagrams proposed by Shefl and Rice [93] and Linkov et al. [45]. It is important to emphasize that the process involving these four abilities should not be considered as linear and static. Instead, a dynamic and iterative approach is needed to acknowledge that risk profile is subject to constant (sometimes spontaneous) changes caused by uncertainty inherent in socio-ecological and economic systems. Such an approach should also take into account the dynamic interplay between preparation, absorption, recovery, and adaptation. Fig. 2 provides a visual interpretation of our approach to defining urban energy resilience. It shows how different components of an energy resilient urban system are related. Successful development of the four abilities mentioned above hinges on incorporating a set of principles into the urban energy system. These principles are listed in the four boxes at the bottom of Fig. 2 and are briefly described in the next section.

### 3.2. Underlying principles of a resilient urban energy system

Several studies have discussed key underlying principles of resilient urban systems [2,6,7,12,30,70,96,97]. A set of these principles that are required for resiliency of urban energy system are drawn from the literature and described below. It is worth mentioning that most of these principles are not exclusive to energy systems and could be regarded as general principles that any resilient system should possess. Also, it should be noted that they are not mutually exclusive and often overlap. Fig. 2 shows how each principle is related to the four abilities of a resilient urban energy system.

- **Robustness**: described by Wardekker et al. [50] as the system's "homeostasis", robustness refers to a system's strength to withstand short-term (sudden), acute internal and external shocks without suffering from major degradation of the main functions [6,7,77,97,98]. To achieve this and enhance system security, the system needs to have the ability to counteract and/or absorb the disturbance [18,99].

- **Stability**: stability represents the ability of a system to cope with long-term disruptions while maintaining its essential operations and rapidly returning to normal functioning [98,100]. Stability makes the system reliable and durable to operate continuously and satisfactorily ensure the supply continuity [101].
Table 7  
Criteria related to socio-demographic aspects and human behavior, and their relationship with the components of the conceptual framework.

| Socio-demographic aspects and human behavior                                                                 | Ability | Sustainability | Principle | References |
|----------------------------------------------------------------------------------------------------------------|--------|----------------|-----------|------------|
| **Demographics, health and equity**                                                                             |        |                |           |            |
| So1 Household size                                                                                               | P, Ab, A | A1,3,4         | S, E      | [209, 238] |
| So2 Reproductive education and family planning                                                                  | P, Ab, A | A1,3,4         | S, Eq     | [67]       |
| So3 Gender equality                                                                                                | P, Ab, A | A1,3,4         | S, Eq     | [67]       |
| So4 Social-class equality                                                                                         | All     | All            | S, Eq     | [67, 88, 238] |
| So5 “Access to birth control methods and reproductive health services”                                           | P, Ab, A | A1,4           | S, Eq     | [67, 96]   |
| So6 Universal energy access (energy poverty)                                                                    | P, A    | A3,4           | S, Re, Eq | [36, 42, 43, 56, 81, 82, 83, 88, 98, 101, 116, 156, 158, 203, 238] |
| So7 Upgrading slums and informal settlements                                                                    | P, R    | A1,2,3         | Eq        | [64]       |
| So8 "Externalization of impacts"                                                                                 | P       | A4             | FC, Eq    | [125, 16628] |
| So9 Safety of energy production, transmission, and distribution (accidents, etc.)                               | P, Ab   | A4             | Eq        | [88]       |
| **Behavioral aspects**                                                                                           |        |                |           |            |
| So10 Car use frequency                                                                                            | P, Ab, A | A1,4           | Ad, E     | [213]      |
| So11 Driving behavior                                                                                            | P, Ab, A | A1,3,4         | Ad, E     | [218]      |
| So12 Dietary patterns                                                                                            | P, Ab, A | A1,3,4         | Ad, E     | [67, 68]   |
| So13 Respecting, utilizing, and learning from local culture, knowledge and traditions                           | P, Ab, A | A1,3,4         | Ad, SO, E | [43, 236]  |
| So14 Willingness to pay upfront costs of renewable technologies                                                | Ab, A   | A1,3,4         | C, E      | [49]       |
| So15 Communal solutions for social cohesion and energy saving                                                   | P, Ab, A | A1, 3,4        | Ad, SO, E | [40, 56, 81, 141, 159, 191] |
| So16 Energy consciousness of the public and consumption behavior / demand side management                       | Ab, A   | A1,3,4         | E, C, Ad  | [36, 38, 41–43, 46, 48, 56, 59, 83, 86, 117, 118, 123, 128, 138, 140–142, 156, 159, 204, 211, 226] |
| So17 “Smarter selection of the mode of operation of appliances”                                                 | Ab, A   | A1,3,4         | E, Ad     | [142, 156, 159, 204, 211, 226] |
| So18 Load matching to obtain maximum value for on-site energy generation                                       | Ab, A, R All | A1,3,4         | E, Ad     | F          |
| So19 Switching off lighting, air conditioning, etc. in unoccupied rooms                                         | Ab, A   | A1,3,4         | E, Ad     |             |
| So20 Doing activities (e.g. watching TV) in the living room vs separate rooms                                  | Ab, A   | A1,3,4         | E, Ad     |             |
| So21 Acclimatization                                                                                            | Ab, A   | A1,3,4         | E, Ad     |             |

P, Preparation; A, Absorption; R, Recovery; Ad, Adaptation; A1, Availability; A2, Accessibility; A3, Affordability; A4, Acceptability; R, Robustness; S, Stability; F, Flexibility; Re, Resourcefulness; CC, Coordination Capacity; Rd, Redundancy; D, Diversity; FC, Foresight Capacity; I, Independence; In, Interdependence; C, Collaboration; A, Agility; Ad, Adaptability; SO, Self-Organization; Cr, Creativity; E, Efficiency; Eq, Equity.
Fig. 1. The four planning and response abilities affecting the functionality level of a system before and after a disruptive event. Performance level can be divided as follows: before the occurrence of the disruptive event (time $t_d$ indicated by the lightning symbol in the figure) preparations should be made to prevent possible hazards as much as possible and reduce the potential damage in case of a disruption. Performance starts to decline instantly after the disruptive event and initial effects are observed at time $t_e$. First reactions made during the period between $t_e$ and $t_r$ are critical for controlling the conditions and warding off the damage to prevent cascading impacts. While these absorptive responses continue, the system will reach its lowest performance at time $t_f$ (time of full impact). “Absorbed impact” indicated on the figure means that actions done during the absorption stage can significantly reduce the potential overall impacts. The recovery stage (the period between $t_r$ and $t_f$, time of returning to equilibrium level) usually takes more time than the previous stage. Finally, after returning to the equilibrium level the system is expected to plan for enhancing its performance based on the lessons learned from the event (bouncing forward) [17,45,93].

- **Flexibility**: uncertainties innate in future disasters make it difficult to achieve fail-safe design objectives and there may be occasions when system reconfiguration becomes inevitable. Flexibility means that a system should have the ability to “adapt to changing conditions” [102, P21] and undergo a safe failure by changing its configuration. A flexible system is capable of sensing threats, immediately detecting the failure and making prompt changes at smaller scales of its subsystems and thereby maintain overall performance during disaster [77, Roggema] [9] argues that constituent elements (“both functional and physical”) of a flexible urban system should be designed and arranged in a way that it could be possible to disassemble and rearrange them in an opportune manner. This would ensure multi-functionality of the system components, would equip the system with the ability to cope with short-term disturbances, and would facilitate its ability to retain critical functioning, endure short-term deficiencies and return to normal functioning within a relatively short time period [98]. In the context of energy systems, this could (for example) refer to the ability to shift between different energy configurations or adjust regulations or prices according to changing conditions [103].

- **Resourcefulness**: relates to the adequacy of resources at the disposal of urban planners and decision makers to appropriately identify, prepare for, respond, and recover from potential disruptions [7,77,96,97]. This includes having appropriate capacity to understand status-quo, and identify patterns, potential threats, and contingencies [75]. Also, the system should provide a certain degree of “buffering” to ensure that the key thresholds (tipping points) are not easily exceeded and energy requirements of the system are supplied at all times [76].

- **Coordination capacity**: refers to the managerial capacity to effectively coordinate preparatory and recovery actions between various sectors and organizations at different scales. Without this capacity the existing resources would not be effectively utilized to prepare for the disaster, the system will not be able to achieve its full absorptive capacity, and consequently there would be procrastination in the recovery efforts [104].

- **Redundancy**: redundant capacity refers to the availability of (substitutable) components with similar (even overlapping) functions in the urban system to enhance its adaptive capacity and ability to absorb shocks, give it reserve capacity for problem solving [7,56,105], and ensure that uncertain events causing the failure or displacement of one component would not result in the failure of the whole system [6,7,9,18,76,77,97]. In a system featuring redundant capacity, exclusion of an element should not result in significant loss of functioning [106]. As a downside, redundancy can impose considerable costs on the system and have negative impacts on its ability to improve in terms of the other principles of resilience such as efficiency [56,74,107].

- **Diversity**: Wardekker and de Jong [76, P993] chose “omnivory” as a metaphor to explain this principle that refers to the degree to which multiple distinct functions, that can be used simultaneously, are included in the system [76]. The aim of this principle is to hedge against supply disruptions and ensure that a variety of options (resources, instruments, etc.) for dealing with disturbances and ensuring functionality exist in an urban system. An energy resilient city should be diverse in terms of land use patterns, infrastructure, supply providers, knowledge, economy, and demographic structure [7,18,97].

- **Foresight capacity**: any resilient system must be able to face the uncertainty and relativity of the future conditions. The concept of disaster is entangled with uncertainty and nonlinearity of the impacts and behaviors of a portfolio of endogenous and exogenous forces (see Table 1) that can potentially become sources of disturbance in the system. This principle is essential for disaster preparation and also absorption of initial shocks. It implies that only preparation based on shortcomings exposed by past events is not enough and forecasting methods should also be applied in preparation to respond to newer risks that may unfold in the future. Lack of the capacity to foresee, often unavoidable, natural disasters (and their potential impacts) may result in, otherwise controllable, ‘unnatural’ disasters and in ripple effects across and beyond the concerned system [108]. In addition, it can exacerbate risks associated with exposure to unnatural hazards.

- **Independence**: a resilient system should possess a “certain degree of self-reliance that gives the ability to maintain a minimum acceptable level of functioning (without external support) when influenced by disturbance” [2,7, P4, 30]. This also requires the presence of strong leadership that facilitates the ability to set goals and visions, and initiate actions [18,75].

- **Interdependence (interconnectedness)**: refers to having mechanisms in place that enable a system, as part of an interconnected and integrated network, to have functional and physical relationships with other systems in the network and receive support, input, and feedback from them [6,7,109]. In energy systems with high reliance on external sources this could act as a double-edged-sword, with substantial supply disruption in one or more of the components of the broader system potentially leading to serious problems in other parts [74,102]. As examples of interdependence in the energy system, Farrell et al. [74] mention Singapore, Italy, and the Philippines, wherein electricity generation is highly dependent on oil products. Interdependence also implies that functionality of the energy system influences is influenced by operation and performance of other systems such as water supply and distribution, food industry, transportation etc. [109].

- **Collaboration**: “implies that the urban system should facilitate an environment for active participation of a wide range of stakeholders in the decision making process” [6,7, P4, 18]. Collaborative planning, characterized by local involvement and delegation
of power to local institutions, enhances the flexibility of the system to respond to perturbations, increases the capacity for communal practices, helps overcome the hierarchical barriers that impede effective communication and free and smooth of information, and enhances the rapidity of mobilizing resources required for a timely recovery [76,100].

- **Agility**: represents the system’s capacity to mobilize the resources necessary for recovery and return to normal functioning within an acceptable time frame [77]. Agility is essential for avoiding cascading failures that can result in the disruption of other functions in the system [76,110]. While human settlements have traditionally been reasonably successful in recovering from disasters [1], they have not always exhibited rapidity in their responses, and the recovery process has often been slow and intermittent. Hence, it should be emphasized that only if achieved in a timely manner, the recovery process will contribute to the resilience of the system.

- **Adaptability**: refers to an urban system’s capacity to learn from the disaster to reduce its pre-disturbance vulnerabilities, and enhance its capacity to adapt to the changing conditions [6,7,18,97,111,112]. Adaptability implies recognition of the inherent vulnerability of the system components, availability of appropriate knowledge and assignment of authority to prioritize tasks at the time of crisis, and ability to respond with rapidity in order to facilitate a “safe-to-fail” (or at least “soft-fail”) urban system [74]. A resilient urban system should entail “adaptive” cycles that “alternate between long periods of aggregation and transformation of resources and shorter periods that create opportunities for innovation”, thereby ensuring survival of the system [9, P462].

- **Self-organization**: refers to the “emergence of macro-scale patterns”, structures or relations from the mutually reinforcing interactions among “smaller-scale rules” and processes [97, P470]. A self-organized system discourses centralization of resources and authorities [77] and should involve community-based management characterized by strengthened local communities capable of independently responding to disaster, cross-scale partnerships, and “horizontal” and “vertical” institutional connections that provide direct feedback to the system and enable better informed decision making [113]. Furthermore, it should entail the ability to build upon and strengthen networks established to respond to an earlier disturbance (“institutional memory”) [113].

- **Creativity**: this principle represents the “urban system’s ability to use the disruption as an opportunity to attain a more advanced state” [7, P4]. This requires utilizing innovation (both technological and non-technological) in management, planning, and design of urban systems [7,70]. Innovation is essential to enhance various resilience abilities and avoid being overwhelmed by the constantly changing nature of risks. It is in particular required for reinforcing the transformational adaptability of the system [95].

- **Efficiency**: means that the proportion of energy and resources provided by an urban energy system to the energy given to it as input, should be positive to improve resource use productivity and avoid waste. In other words, the system should provide a higher energy return on energy and resource investments [6,7,18,87,114]. Reducing energy intensity is essential for improving efficiency of the system. Molynieux et al. [44] argue that efficiency is required for an energy system to absorb variation and maintain its integrity. Enhancing efficiency is also regarded as an essential measure to reduce the system’s demand for inputs (energy) [51]. Improvements in terms of energy saving are required for enhancing the efficiency of urban energy systems.

- **Equity**: equity plays an essential role for achievement of resilience. It is related to urban energy in two respects. First, planning should be based on a fair distribution of energy services in the community. This is to ensure that all urban citizens have the ability to utilize energy services to prepare/plan for, cope with and recover from disruptions [88]. Second, justice is needed in terms of exposure to impacts associated with production, transmission, and distribution of energy. This is to ensure that marginalized and poor people do not bear the brunt of those impacts [115]. Addressing these two issues is also essential for enhancing social cohesiveness required for absorption and recovery from shocks.

4. Planning and design criteria for urban energy resilience

Criteria extracted from the literature are categorized into five themes: infrastructure; resources; land use, urban geometry and
morbidity; governance; and socio-demographic aspects and human behavior. Each theme is then divided into sub-themes, which are further subdivided into several core energy resilience criteria. Note that various complex interlinkages exist among these themes and sub-themes and they are not mutually exclusive. Therefore, some criteria can be classified into more than one theme or sub-theme. Another important issue to note here is that compliance with some criteria may contribute to some aspects of resilience, but have adverse effect on others.

These five categories of energy resilience criteria are briefly described below. Tables in the following sections summarize the relationships between each criterion and the resilience abilities, sustainability dimensions, and resilience principles explained in Section 3. They show if the criterion in question is related to (i.e. contributes to/detracts from) each of the four sustainability dimensions and the four abilities specified for a resilient energy system. Also, they indicate resilience principles that each of these criteria corresponds with (e.g. fortification and physical security of components of the energy system improve its robustness). It is beyond the scope of this paper to provide an in-depth description of all of the criteria specified in this study. Here, we only discuss a selected number of criteria for which more evidence and information is available in the reviewed literature. Readers interested in more information on these criteria and their possible relationships with energy resiliency are referred to the corresponding references given in the tables.

4.1. Infrastructure

As shown in Table 3, the 64 criteria listed under this theme are classified into seven sub-themes namely, supply, transmission, and distribution; backup and storage; green infrastructure; blue infrastructure; buildings and neighborhoods; transportation; and innovative technology. Some of these criteria are briefly explained here.

Fortification is an engineering-based measure of strengthening the production, transmission and distribution infrastructure to protect them against the possible effects of disruptions [92]. One example of these efforts is related to the type of feeder lines. Disruption of overhead lines following severe weather events accounts for the majority of infrastructure and structural vulnerabilities and can result in massive blackouts and brownouts similar to what occurred in summer of 2003 in northern Ohio due to heat-induced sagging [56,92,116]. Burying the power lines can not only increase the physical security, but it can also reduce transmission losses, health impacts, and the need for maintenance [117]. It should, however, be noted that undergrounding distribution lines increases costs and vulnerability to earthquake [109]. Other noteworthy strengthening measures include, but are not limited to, reinforcing pole distribution networks and safeguarding “switching stations and substations” [50, P97]. Energy system and its components should be easy to maintain [112]. Regular maintenance and upgrading is needed to ensure the system’s ability to withstand future shocks that may be more frequent and intense [102]. This process could also contribute to energy resiliency by enhancing efficiency through reducing transmission and distribution leakages and identifying the inefficient infrastructure that needs to be phased out and replaced by a newer, less energy intensive one [44].

Stability, reliability, flexibility, and efficiency of the energy system can improve substantially by deployment of smart grid systems. These systems utilize sensors and control and communication algorithms to further enhance the internal interactions between the system components and rapidly detect any abnormalities in the system [86]. Smart grid can also improve demand side management by enabling consumers to monitor their consumption levels and make more informed choices based on various parameters such as market conditions. One major difference between smart grid and traditional grid is that the former is often integrated with various types of distributed energy generation [86].

Diversification of energy supply and infrastructure is one of the most important measures to enhance energy resilience. This is to ensure continuity of supply in case supply of one energy source is disrupted. For instance climate change may induce changes in the precipitation patterns and reduce the amount of water necessary for hydroelectric generation (e.g. drought-induced disruptions that occurred in Brazil in 2000) [44]. Given the uncertainty involved with predicting the occurrence and impacts of extreme events, diversification is a good “hedge option” for dispersing the risk [42,101]. Diversification will also improve the market competitiveness and could help avoid “technological lock-in” [44,83,118].

A flexible energy system featuring a combination of both centralized and distributed generation facilities can enhance system diversity and ensure continued flow of energy. Distributed generation is essential because centralized systems have a high level of consolidation, making them vulnerable to supply chain disruptions. Decentralized systems are less sensitive to “availability of remote generation and of transmission networks” [119, P4504]. There is evidence demonstrating how distributed generation can enable critical infrastructure to sustain fundamental functioning during extreme events by “islanding” from the grid [50, P114]. Distributed generation also facilitates coupling of energy production and consumption. This reduces transportation footprint and conversion deficiencies and enhances acceptability of the energy system. Other benefits can also be achieved due to the fact that distributed generation is usually based on renewable energy that reduces emissions and in case of systems such as combined heat and power installations, waste heat can also be recovered and utilized for other purposes [119]. There is also evidence showing how decentralized energy systems can promote affordable energy options and serve as means of activating and mobilizing ("bridging") social capital [120]. Overall, distributed generation is an economically competitive option (as compared to centralized generation) that can improve flexibility, efficiency, diversity, and redundancy and enhance security in case of climate-induced disruptions, geo-political conflicts, and terrorist attacks [50,119].

Various criteria related to on-site, micro- and small- energy production mentioned in this paper are beneficial for sustainability, flexibility, and rapidity of the energy system. Unlike large scale production systems, these options are less complex and can be more easily installed at the time of disaster [48,121]. In addition, participation in micro-generation programs can be a social practice to increase collaboration capacities in communities and thereby contribute to social capital and adaptive capacity [122]. It can also encourage innovation, help alleviate energy poverty [122,123], strengthen local economy [124], and make energy more accessible. Related to accessibility, with efficiency co-benefits, is also the criterion of collocating high energy supply and demand infrastructure. This way one industry can use “waste or by-product” of a neighboring industry as an energy source [114, P246]. As a co-benefit, collocation will reduce the impacts associated with energy generation away from the point of consumption [125]. Realizing the aims of collocation requires inter-industry collaborations and interconnectivities [109]. Interconnectivity may also refer to structural arrangements for making connections between energy grids possible. For instance after the Great East Japan Earthquake, eastern parts of the country suffered power shortages, but the western grid could not compensate for this shortage due to the fact that these two grids have different configurations [126].

Gaining maximum benefit from micro-scale, renewable energy technologies would not be achievable without investment and improvement on storage capacity. Storage infrastructure is needed to tackle the issues associated with ephemerality and intermittency of renewable energy sources and temporal mismatch between supply and demand [86,117,167]. The need for storage is
particularly important for locations that have invested in solar and wind renewable energy sources. Battery storage is necessary, but not sufficient to utilize the full capacity of solar and wind energy [48]. As a case in point, Esteban et al. [48] argue that batteries would not be capable of responding to the peak demand in summer in Japan and suggest that in addition to Electric Vehicle batteries, the installed wind and solar capacity should be increased and other options such as hydrogen should be considered for long-term storage purposes. One important point is that storage capacity should be coupled with connectivity (infrastructure) to facilitate transmission of the stored energy from high potential areas, with less demand, to areas featuring more demand [60]. Furthermore, a resilient energy system needs redundant, spare capacity to buffer against sudden power cuts and/or peak load rises in demand and design margin to accommodate the needs for potential future expansion [44,61,112]. Existence of reserve capacity also helps avoiding price volatility that can have negative implications for energy affordability [172].

Criteria mentioned for green and blue infrastructure yield various benefits for energy saving, health, and environment. Infrastructure such as green space, green roofs, and roof ponds provide efficient passive methods for attenuating indoor and outdoor temperatures, reducing daily indoor temperature fluctuations, mitigating heat island effect, improving the thermal performance of the building environment, and thereby facilitating long term economic gains [185,187,197,201,220]. For instance, urban greenery as one of the simplest and most affordable form of green infrastructure, provides benefits such as: solar control using shading, reducing ambient temperature through evaporation and evaporatranspiration, and carbon capture and storage for climate stabilization [178,179,185–187]. Enough space between vegetation and overhead transmission lines should be maintained to avoid potential negative effects due to vegetation encroachment on transmission lines [109,166]. Urban waterscape has also evaporative cooling effects and can act as a natural heat sink that absorbs the excess heat and therefore indirectly reduces energy consumption [180].

Measures to be taken in buildings and neighborhoods involve, inter alia, refurbishment, insulation, developing net-zero and net-positive buildings and neighborhoods, deploying district energy systems (“using low-temperature heat from renewable sources” and “industrial waste heat” [161, P2]); waste heat from energy production for heating water, homes and for air-conditioning, etc.), and design issues such as pooling of the built environment. As an example from this sub-theme, considerable CO₂ emission cuts can be achieved through redesign and refurbishment of buildings. Retrofitting the built environment will have significant implications for energy demand [207] and can be considered as a method for addressing fuel poverty and enhancing energy affordability [58]. Given the long-term life cycle of buildings, and in order to prevent infrastructure lock-in, refurbishment should be considered as an opportunity to incorporate elements such as green infrastructure, improve insulation, etc. [178].

The sub-theme on transportation encourages paying attention to issues such as active transportation (e.g. walking, cycling, public transportation), modal split, fuel flexibility and efficiency of cars, supporting promotion of hybrid vehicles, and promoting smart grid networks that allow “two-way flow of electricity and information” [86, P254], installing electric vehicle plug-ins in locations where multiple use can be achieved (e.g. multi-occupant buildings), utilizing information and communications technology infrastructure for transportation planning, and technological innovations. These all improve the energy availability and provide co-benefits for health and environment.

Frequency and percentage distribution of relevance of the selected criteria to the specified abilities, sustainability dimensions and resilience principles is shown in Tables 2 and 3 of Appendix A. As can be seen from Table 2 of Appendix A, criteria related to urban infrastructure enhance the ability of urban energy system to plan and prepare for, absorb, recover from, and adapt to potential disruptive events. In particular, they have major implications in terms of preparation for and absorption of shocks. It is also evident that these criteria have strong linkages to the availability and acceptability of energy services. Table 3 of Appendix A shows that, among other things, these criteria contribute to efficiency, diversity, adaptability, foresight capacity, independence, stability, redundancy and flexibility of the urban energy system. This extensive relevance of the infrastructure-related criteria to the underlying components of an urban energy resilience system is an indication of their significance for enhancing energy resilience. Given the long lifetime of urban infrastructure and the high cost of post-construction alterations, decisions made today will “lock-in” emission commitments as well as vulnerability or resilience to climate change for decades to come” [47, P774]. Therefore special attention is required to prevent irreversibility and lock-in effects.

4.2. Resources

Table 4 shows the 33 resources-related criteria that are subdivided into energy, water-energy nexus, and food–energy nexus as three major sub-themes. The energy sub-theme is focused on reducing carbon intensity, wise consumption of resources, enhancing self-sufficiency, and minimizing generation-related impacts on various resources such as forests, biodiversity, water, and air.

Reducing carbon intensity of generation is essential for enhancing resilience. The CO₂ emissions are one of the drivers of climate change and emissions from fossil fuel combustion account for the majority of annual carbon emitted to the atmosphere. The CO₂ emissions have been increasing constantly over the past decade and are projected to further increase in the coming years. This constant increase means that climate stabilization at a level lower than a global mean of 2 °C over pre-industrial levels would be a great challenge requiring deep emission cuts across various sectors [222]. Failure to stay within the 2 °C limit may have catastrophic impacts that will exacerbate medium-and long-term adaptation opportunities and make it even harder to achieve the goals of energy resilience. This is due to the projected growth in the frequency and intensity of extreme climatic events and the significant implications that they may have for availability, accessibility, and affordability of generation. The latter could be substantially affected in case “carbon pricing or environmental regulation” is introduced [44, P191]. Efforts such as energy conservation, “shift from coal- to gas-fired electricity generation” [53, P13], waste incineration (for use as an energy source for other industries), and other types of energy cycling (e.g. “capturing, converting, and earmarking waste streams for use in powering the water and wastewater systems”), could help reduce the carbon intensity of generation and improve the “buffer capacity” of the energy system under critical situations [38, P663, 53]. Waste management should also include minimizing hazardous waste as it can pose significant risks to the environment and intensify possible adverse impacts in case of disasters [135].

The nexus-related criteria refer to the importance of gaining synergistic efficiencies in resource and infrastructure management. Integrated and cyclical processes should be adopted in order to minimize negative impacts on resources and make it possible for different infrastructure sectors to utilize the waste and by-products of the other facilities [86]. Achievement of this aim requires due attention to proximity and placement of facilities.

The water–energy nexus sub-theme deals with the implications of energy generation and consumption for water resources and vice versa. It is important to use new approaches and technological innovations that can help reduce water requirements of energy systems.
For instance use of “natural gas combustion turbines” (instead of coal) for steam turbines will significantly reduce the amount of water needed in the process. Furthermore, CO₂ emissions from natural gas are approximately half of the CO₂ of coal and this replacement can provide further CO₂ emission reduction co-benefits [52]. In a similar way, the sub-theme on food–water–energy nexus includes criteria that are added to acknowledge the considerable energy requirements throughout the life-cycle of food products, including fertilization, irrigation, storage, cooking, waste generation, etc [67]. The traditional engineering paradigm deals with each of these resources separately, thereby failing to capture the interplay between their diverse components. Complying with the nexus-related criteria can provide significant cost-saving, and reduce food, water, and energy demand [86]. It is also necessary to minimize knock-on effects that may arise when limitations of one resource trigger limitations in the others [167].

Percentages and frequencies shown in Table 2 of Appendix A indicate that criteria listed under this theme have major implications for preparation and adaptation abilities as well as availability of energy services and acceptability of the means to make them available. Table 3 of Appendix A shows that, among other principles, efficiency and coordination capacity are two major resilience principles that can be improved by compliance with these criteria.

4.3. Land use, urban geometry and morphology

Criteria related to this theme are summarized in Table 5. The four main sub-themes, including 28 criteria, are land use, urban morphology, urban geometry, and passive design. Traditionally these have been regarded as the central focus of urban planning and design efforts. The land use criteria encourage facilitating functional mix and proximity in the city. Inter alia, this can have implications for travel patterns and energy consumption, enhance accessibility, and reduce resources needed for energy distribution. The urban morphology criteria are related to settlement types, density patterns and the configuration of urban street networks. Sprawl and suburbanization can undermine the energy resilience by contributing to frequency and intensity of “extreme heat events” [177], increasing car dependency and frequency of single family dwelling, thereby affecting the direct components of energy consumption and CO₂ emissions [157], and delaying restoration following a power outage due to the time necessary for the repair staff to access the outage site [55].

The reviewed literature yields mixed evidence regarding the relationship between density and energy resilience. However, it is important to have a minimum threshold of urban density to promote transit-oriented development, operationalize communal solutions, and provide infrastructure for local systems such as district energy systems that enhance efficiency, independence, reliability, and flexibility of urban energy systems [161]. Furthermore, an average density of between 80 and 200 persons/ha is believed to be optimal in terms of energy implications [190].

Street patterns and connectivity can improve the accessibility of energy services and have influence on driving and walking patterns of urban dwellers [35]. The urban geometry sub-theme includes criteria that are related to size and physical arrangement of buildings and urban blocks in a way that patterns of airflow, daylight penetration, sunlight exposure, and shade are optimized. Like many other criteria mentioned in this paper these are context-specific and different combinations of “optimum geometries” can exist in different climatic locations [223]. Compliance with these criteria is considered as a less energy intensive way of addressing the heat island effect and maintaining the outdoor and indoor temperature within a tolerable range for human comfort [224]. Closely related to these criteria, the criteria clustered under the passive design sub-theme can induce reductions in the energy demand for heating and cooling and also provide co-benefits by minimizing the environmental impacts. For instance, enhancing the albedo of pavements and rooftops (that account for more than 50% of the urban surface) not only reduces the cooling load by decreasing the mean ambient temperature [182,183,198,225], but also can be regarded as an effort towards achieving the 2 °C target in the long term. This is because increasing albedo can decrease ambient temperature and since higher albedo materials have longer life span, it can also reduce the lifecycle costs and atmospheric concentrations of CO₂ [211,225].

Overall, although short-term responsiveness of energy consumption and climate impacts to urban form is proved to be smaller in comparison with other parameters such as energy efficiency of the system achieved through technological innovation and occupant behavior, the long-term, cumulative amount of energy saved through modification of urban form can have significant impacts on the energy budget at the city scale [216,227].

As can be observed from the results (Tables 2 and 3 of Appendix A), meeting criteria listed under this theme improves urban energy system’s preparation, absorption, and adaptation abilities. In terms of the sustainability-related principles, these criteria contribute to availability, acceptability, and affordability of energy services. They also enhance resilience to energy shocks through improving efficiency, diversity, and independence of the system.

4.4. Governance

As the second most populous category, the governance theme consists of five sub-themes and 50 criteria (Table 6). In addition to technological and design qualifications, energy resilient urban systems should also feature powerful institutional mechanisms. Among other things, urban governance plays the essential role of coordinating the activities of various components of the system; monitoring conditions and performance achievement; developing pricing strategies, managing market forces; enforcing regulatory actions and policies; and developing planning strategies for knowledge transfer, community outreach, and open and broad-based stakeholder participation.

The first sub-theme, monitoring and assessment lists criteria related to monitoring the reliability and proper functioning of the system and developing decision support systems to facilitate more informed decisions. Human and/or mechanical surveillance facilitates early detection of threats and prevents their diffusion, thereby avoiding potential cascading effects [74]. In order to achieve desired outcomes and avoid being overwhelmed by the emergence of severe or abrupt changes, early detection should also be coupled with early warning [94].

Smart metering can be used to ensure stability of energy system and availability of energy services by countering energy theft and helping establish “dynamic tariffs” [237]. When coupled with information feedback systems such as in-home displays, smart metering is also proved to reduce residential energy consumption [155]. As a preparation measure, decision makers need to have access to, and frequently update a database that includes data related to a variety of contents including supply, transmission, and distribution networks; consumption patterns and emissions; microclimatic conditions; digital elevation models, etc. This database should be used as a decision support system facilitating more informed decision making. For instance digital elevation models can inform decision makers of the energy implications of urban form [227].

The planning and management sub-theme includes a mixture of top-down and bottom-up approaches that can provide holistic and synergistic solutions for improving energy resilience. To be appropriately prepared, urban authorities and utilities need to prepare contingency, response and recovery plans, establish a forecast and risk communication system, and provide resources and funding necessary for training personnel and raising
awareness of citizens. These actions are required for controlling and monitoring performance and sustaining communication abilities between different system components [166].

Political commitment and strong leadership qualities are needed to, inter alia, set a long-term vision for urban energy transition, initiate and sustain innovative energy experiments, prioritize tasks at the time of disaster, and establish and continue transformational adaptation [94,120,138]. This needs to be integrated with efforts at the local scale that encourage bottom-up support and engagement [57]. Bottom-up approaches such as community involvement in agenda making, community ownership of energy technologies and infrastructure, and "social judgment" on suitability and acceptability of options can help overcome social barriers, seek common grounds for resolving potential conflicts, improve local attitudes, and take crucial steps towards implementing strategies designed towards transition to energy resiliency [86,242].

Transparent and participatory governance would also facilitate learning from past events and "learning by doing" that are essential for boosting the adaptive capacity of the system. Furthermore, bottom-up feedback from users is useful for rapid detection of potential failures. It can also provide evidence on the suitability of particular energy systems for specific local contexts and help determine if any adjustments or adaptations are required [124].

Criteria related to collaboration cover issues related to inter- and intra-organizational relationships and public-private partnerships that need to be established within and across scales. Among other things, these criteria emphasize the need for making agreements to share information, knowledge, and technology; establishing mutual aid agreements; interlinking water-food-energy management; "reconciling spatial scales of resource coupling" [125, P6629]; addressing the issue of jurisdictional mismatches; and providing institutional support to inadequately resourced local authorities [125,204]. At the same time, urban management should be aware of the need for having a certain degree of self-sufficiency required for maintaining the stability of the system in the face of various natural and man-made disasters.

Transition towards urban energy resilience cannot take place in the absence of a legal and regulatory system that can play the role of pushing forward criteria and measures that have been discussed under the other themes. Building codes are critically important and need to be updated with stipulations that promote green buildings equipped with green and cool roofs and other renewable technologies. Equally important, land use and zoning bylaws should be modified to allow for and encourage in-fill, brownfield, and mixed use development and optimize utilization of renewable energy sources beyond the scale of individual buildings. However, green development industry is highly influenced by market forces and long payback period on the investment of these technologies may inhibit their uptake and diffusion [35]. To address this issue, minimum mandatory requirements should be incorporated into building codes and zoning regulations [34,197]. Also, organizational transformation and strategies on "market liberalization" are needed to break the monopoly of fossil fuel-based generation, improve market openness and competitiveness, reduce investment risk, and overcome market barriers of decentralized energy systems such as photovoltaics, combined heat and power, combined cooling, heat and power (trigeneration), etc. [120,126].

Urban governance needs to experiment with a wide array of other carrot and stick measures to reduce energy consumption and encourage technology development. These measures are needed to deal with the issues related to the higher initial investment costs of resilient energy technologies and investors’ preference for rapid return on initially invested capital [88]. Strategies related to carbon pricing can play a critical role in improving market competitiveness of technologies based on clean and renewable resources and reduce the carbon intensity of generation and consumption [219]. Numerous success stories exist including the 20% reduction in CO₂ emissions achieved by charging congestion fee in the “Congestion Charge Zone” of London [216], and the success of “time-based pricing” in reducing 5–10% and 10–15% of residential peak energy consumption (during a typical winter evening) in the Pacific Northwest area of the U.S. and New Zealand, respectively [155]. On the other hand, support and incentives should include providing funding for research and technology development, attracting private sector’s investment in low-carbon development, and offering financial and non-financial incentives for green products and renewable energy development. This is to compensate partly for the high upfront cost of green and renewable technologies [120]. Some examples of financial measures include feed-in-tariff systems, subsidies, social loan benefits, tax deduction, and “lower interest rates coupled with longer repayment periods” [48,206,P2591], "Height and density bonuses", and expediting permission process are major non-financial incentives mentioned in the literature [35]. These are vital for covering the initial investment costs, improving competitiveness, and diversifying energy mix.

Table 2 of Appendix A shows that these criteria have major implication for preparation, absorption, and recovery abilities and are highly relevant to availability, acceptability, and affordability of energy services. Also, as can be expected from discussions above, Table 3 of Appendix A highlights that compliance with these criteria can enhance efficiency, resourcefulness, coordination capacity, and equity as some core principles of any resilient urban energy system.

4.5. Socio-demographic aspects and human behavior

Last, but not the least, is the theme on socio-demographic aspects and human behavior. Twenty one related criteria are listed under two sub-themes, namely, demographics, health and equity; and behavioral aspects (Table 7).

The vast majority of global population increase will happen in cities of the developing world where, in many cases, a considerable proportion of the population is not connected to the grid and is still dependent on traditional fuels such as firewood, agricultural residues, animal waste, and charcoal for fulfilling energy needs. In addition to causing health problems, this can create immense pressure on environment and resources. Therefore, while demand rise is a worldwide issue to be addressed, energy transformation in the global south needs to include tackling problems that are considerably different [36,151,158].

Family planning, improving gender and socio-economic equality, providing access to reproductive health services, and raising awareness are some important measures that need to be taken to avoid unbridled population growth that might have significant implications for energy availability, accessibility, affordability and acceptability. There is evidence to suggest that the total energy consumption correlates more with the household size than with the “total floor area” [209, P1623]. While uncertainties about the availability of energy in the future are increasing, population control would be indispensable for providing universal energy access.

In addition to the impacts discussed above, lack of access to energy can cause a significant loss in the potential annual economic development [43]. Energy resilience also entails ensuring that impacts associated with production and transmission of energy are not unevenly distributed and also safety issues throughout the process are appropriately taken into account.

The second sub-theme deals with criteria focused on human behavior and importance of attitudinal and life style transformation for transition to low-carbon and resilient communities. Technological improvements are necessary for urban energy transition but, they
Table 8
Associations between the main components of the urban energy resilience system (numbers refer to percentage of criteria that are relevant to both elements of each pair in the matrix. E.g. 79 in the first cell means that 79% of criteria are relevant to both preparation and absorption).

|   | A  | R  | Ad | A1 | A2 | A3 | A4 | P  | R  | Ad | A1 | A2 | A3 | A4 | R  | S  | F  | Re | CC | Rd | D  | FC | I  | In | C  | A  | Ad | SO | Cr | E  | Eq |
|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| P | 79 | 30 | 69 | 92 | 32 | 46 | 80 | 2  | 12 | 7  | 16 | 12 | 5  | 22 | 15 | 17 | 6  | 4  | 5  | 20 | 9  | 4  | 71 | 14 |
| A | 26 | 68 | 85 | 29 | 47 | 74 | 2  | 9  | 7  | 12 | 10 | 4  | 22 | 11 | 16 | 5  | 5  | 6  | 24 | 8  | 4  | 68 | 12 |
| R | 17 | 31 | 23 | 14 | 20 | 0  | 5  | 5  | 10 | 8  | 3  | 6  | 4  | 5  | 4  | 3  | 4  | 4  | 4  | 4  | 17 | 5  |
| Ad| 73 | 23 | 44 | 70 | 0  | 8  | 4  | 10 | 8  | 1  | 19 | 8  | 15 | 3  | 5  | 3  | 22 | 8  | 4  | 65 | 11 |
| A1| 83 | 50 | 33 | 11 | 8  | 17 | 12 | 5  | 22 | 14 | 17 | 6  | 6  | 6  | 24 | 9  | 4  | 76 | 12 |
| A2| 21 | 26 | 0  | 5  | 5  | 8  | 7  | 2  | 11 | 5  | 10 | 3  | 1  | 4  | 5  | 2  | 1  | 23 | 4  |
| A3| 49 | 0  | 8  | 4  | 15 | 10 | 5  | 1  | 15 | 4  | 13 | 1  | 3  | 3  | 18 | 5  | 2  | 45 | 11 |
| A4| 1  | 8  | 4  | 15 | 10 | 1  | 21 | 12 | 15 | 4  | 5  | 4  | 24 | 8  | 4  | 75 | 14 |
| R | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
| S | 1  | 2  | 1  | 0  | 2  | 1  | 2  | 1  | 0  | 2  | 1  | 0  | 2  | 1  | 0  | 5  | 3  |
| F | 1  | 1  | 2  | 1  | 1  | 0  | 1  | 1  | 2  | 1  | 1  | 0  | 3  | 0  |
| Re| 0  | 1  | 1  | 2  | 1  | 0  | 2  | 1  | 3  | 1  | 1  | 0  | 8  | 3  |
| CC| 7  | 1  | 1  | 2  | 1  | 0  | 2  | 1  | 3  | 1  | 1  | 0  | 12 | 4  |
| Rd| 0  | 1  | 0  | 0  | 3  | 1  | 1  | 1  | 1  | 0  | 0  | 0  | 12 | 4  |
| D | 5  | 13 | 1  | 0  | 1  | 2  | 2  | 1  | 20 | 2  |
| FC| 0  | 1  | 0  | 3  | 1  | 1  | 0  | 10 | 2  |
| I | 2  | 0  | 0  | 1  | 3  | 1  | 30 | 0  |
| In| 0  | 1  | 0  | 1  | 1  | 3  | 1  |
| C | 0  | 0  | 2  | 3  | 0  | 5  | 1  |
| A | 1  | 0  | 3  | 1  | 2  | 2  | 23 | 3  |
| Ad| 0  | 8  | 2  | 4  | 0  | 9  |
alone are not sufficient. As anthropogenic activities and demand are among the main forces causing vulnerabilities in the energy system, addressing these vulnerabilities and improving energy resilience could not be achieved unless citizens agree to participate and change their behavior. Therefore, it is necessary to understand the importance of and promote “co-evolution” of social/behavioral and technological elements [112].

Behavioral changes are required to reinforce technological advances and prevent rebound effects [43,212]. These include a range efforts such as reducing automobile use frequency; improving driving behavior; changing dietary patterns to consume less processed food and products such as beef that are energy intensive; initiating cultural change through for example encouraging the use of local food and reducing polymer use for packaging; respecting, utilizing, and learning from local culture, knowledge and traditions; smarter selection of the mode of operation of appliances (e.g. adjusting air-conditioning set point to (≥ 25 °C) and (≤ 20 °C) in summer and winter, respectively and; use of “eco” or “quick” modes instead of “intensive modes” in appliances such as dishwashers, washing machines, and tumble dryers); and “load matching to obtain the maximum value for on-site electrical generation” [123, P2126]. In addition, behavioral change should entail communal solutions that go beyond individual and household level. Examples include, but are not limited to, car sharing, shared heating or air conditioning system, shared combined heat and power system or groundwater source heat pump, and co-housing. These communal solutions contribute to the iterative process of adaptive social learning and increase the social capital of communities that would be vital for absorption and recovery from shocks (see references mentioned in Table 7 for further information on these behavioral measures).

Overall, these criteria are highly important for improving preparation, recovery and absorption abilities of the system and enhance availability, acceptability and affordability of energy services (Table 2 of Appendix A). In terms of the resilience principles, the main contributions would be to the efficiency, adaptability, equity, and stability of the energy system (Table 3 of Appendix A).

5. Association between the components, and relevance to mitigation and adaptation

Earlier in this paper it was mentioned that the constituent elements of urban energy resilience (Fig. 2) are inextricably linked and changes in one may affect the others. Determination of such correlations requires access to quantitative data collected from real-world case studies. Unfortunately no such data was available for this study. As an alternative, it was decided to explore the existence of associations between the elements by using data available in Tables 3–7. The detailed procedure is explained in Section 2.

Although this analysis cannot provide an exactly accurate account of the associations, it can be considered as a reasonable approximation. Results acquired this way do not show the direction of the relationship. The direction should be determined by reader’s interpretation. For instance, as Table 6 highlights, “efficiency” and “availability” are significantly associated. One interpretation of this correlation would be that improving efficiency can increase energy saving capacity and thereby contribute to the availability of energy. Note also that some dependencies may not be unidirectional. Matrix cells highlighted in blue indicate that a considerable percentage of the criteria are relevant to both elements, but the relationship is not statistically significant.

One aim of this study was to determine the criteria’s relevance to adaptation and mitigation. Definitions suggested by Intergovernmental Panel on Climate Change (IPCC) were adopted for this purpose:

- Mitigation: “An anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gases” [243, P379].
- Adaptation: “Adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities” [243, P365].

It was found that most of the criteria identified in this study (74.49%) are related to both mitigation and adaptation. Percentage of criteria related to adaptation only and mitigation only are respectively 24.49 and 102. This is in contrast with the dominant thinking in the literature, which defines resilience as a concept mainly related to adaptation [33,244,245]. This important finding indicates that compliance with resilience criteria can provide co-benefits and offer opportunities for addressing both mitigation and adaptation issues associated with climate change. Details on the relationship of the criteria to mitigation and adaptation can be found in Tables 4 and 5 of Appendix A.

6. Discussion and conclusions

As climate change and other risks combine to increase the frequency and intensity of shocks that urban areas may experience in future years, energy resilience is becoming increasingly important. Concerted efforts across various scales are needed to progress towards urban energy resilience which is an emerging field within the broader context of urban resilience. A vast body of work has been published on different issues related to urban energy resilience, indicating the availability of a substantial amount of (fragmented) knowledge on this subject. This preliminary study attempted to synthesize existing knowledge on urban energy resilience and address the following objectives: (1) develop a conceptual framework for assessing urban energy resilience; (2) introduce several categories of planning and design criteria that can be used for assessing urban energy resilience; (3) explore possible associations between the selected criteria and the components of the energy resilience framework; and (4) identify the selected criteria’s relevance to mitigation and adaptation to climate change.

The conceptual framework proposed in this paper is composed of three intertwined components, namely, sustainability-related dimensions, resilience abilities, and resilience principles. To sustain availability, accessibility, affordability, and acceptability as the four sustainability-related dimensions, the system should be able “to prepare and plan for, absorb, recover from, and more successfully adapt to any risks or adversities over time. A number of principles, ranging from robustness to equity were also introduced. Compliance with these principles is essential for enhancing resiliency of urban energy systems.

After developing the conceptual framework for urban energy resilience, 196 planning and design criteria were extracted from the literature and categorized into five themes: infrastructure; resources; land use, urban geometry and morphology; governance; and socio-demographic aspects and human behavior. These criteria are chosen from both supply and demand perspectives and have implications for energy resilience in different sectors including, but not limited to, infrastructure, building, industry, agriculture, housing, transport, and services. Identified criteria are related to various scales, implying that energy systems function from micro- through to meso- and macroscales and these scales cannot be disentangled. Therefore, coordinated efforts across all of them are necessary.

The results of examining the relevance of the identified criteria to the underlying abilities, sustainability dimensions, and principles of the conceptual framework indicate that availability is the most prevalent element related to energy resilience, followed by acceptability and affordability. The significance of “availability” was also mentioned by Kruyt and his colleagues [42]. Regarding their relationship with the
four abilities of the system, preparation was the most dominant element, indicating that these measures should be taken into account early in the planning process. Among the resilience principles, “efficiency”, “diversity”, “adaptability”, and “redundancy” were the most relevant.

Investigation of the associations between the components of the resilience framework revealed that decisions related to one component are likely to affect other components too. This highlights the complex, interconnected, and multi-faceted nature of energy resilience as a synergistic concept and underlines the importance of adopting a systemic approach towards its improvement. Put another way, efforts related to improving the state of these components should not be taken in isolation from each other. As exemplified by the water-food-energy nexus, the same applies to the issue of compliance with the resilience criteria and they should not be pursued independently.

One of the most important findings of this study is that most of the identified criteria can provide both mitigation and adaptation benefits. Emissions of CO2 drive climate change and failure to meet the 2 degree target may have significant consequences that will make adaptation an even more costly and challenging task. Therefore, both adaptation and mitigation should be pursued. The finding that most criteria provide win-win arrangements means that they improve the medium- and long-term mitigation opportunities and enhance the prospects of adaptation to climate change.

The conceptual framework and criteria introduced in this study can be used as an important preliminary step for development of tools for assessing urban energy resilience. Assessment tools are useful for informing decision making by local authorities. Such tools can be used for three main purposes: to capture the complexity and effectively simplify the route to resiliency; to benchmark and measure resilience and track achievement of goals; and to provide guidelines for future developments that can be communicated to citizens, planners, and policy makers. There are a number of issues regarding the use of the selected criteria that need to be mentioned here. Inclusion of a large number of criteria in the assessment framework raises many concerns about data availability for conducting assessment. Access to the required data would be an important challenge for many local governments, as they may not have adequate financial, technical, and human resources for acquiring them. Another challenge would be to standardize the required data (related to various criteria mentioned here) which are often collected by different agencies, using different methods and data collection protocols [102].

Implementing most of the criteria mentioned in this paper would be also very challenging and costly and could not be realized in the absence of huge political commitments. It is the responsibility of the scientific community to communicate with the citizens and local authorities and show them how investments today could save the city money and resources in the future. It should, however, be noted that the importance of “co-design, co-production, and co-implementation of knowledge” should not be forgotten. Effective communication should include mechanisms to actively engage various stakeholders throughout the process and acknowledge the vitality of collaborative and transparent decision making for transition towards sustainable and resilient communities. As implementation of any resilience enhancement framework would inevitably involve a certain degree of trade-off, the public communication process should also include information on potential trade-offs. Exploration of trade-offs is beyond the scope of this paper and will be investigated in detail in future work. It should also be kept in mind that some of these criteria are not appropriate for use in all contexts. Although we have made some recommendations on what types of measures will be contributing to resilience, the selection of appropriate criteria will always depend on the specific local conditions and should be done in coordination with the public. Furthermore, indicators chosen to evaluate progress against these criteria should be context-sensitive. Also, baselines and benchmark values used for assessment are not static, but are rather dynamic, subject to changing socio-economic and environmental conditions, and influenced by the state of a city’s adaptive capacity and the type of disruptive event that should be dealt with.

Much work remains to be done, especially in determining indicators to make specific measurements (For each criterion, one or several relevant indicator can be designated), and adopting a methodology for aggregating the scores on different criteria to obtain a composite index. Following this, several pilot case studies should also be carried out to test the feasibility of the framework and acquire feedback for possible future revisions. Case study analysis could also be regarded as a learning process showing how cities and communities can learn from each other regardless of their socio-economic standing. This study has only scratched the surface in terms of investigating co-benefits and trade-offs between the resilience criteria. Some degree of trade-off between the criteria is inevitable and this should be adequately informed. It is hoped that the results of this preliminary work provide useful guidance to extend the scope of the study on assessment of urban energy resilience. Future research will have a special focus on providing a rather complete understanding of co-benefits and trade-offs between the criteria introduced in this study.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.rser.2016.03.028.

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2 Terms frequently used by the Future Earth community. http://www.futureearth.org/.
