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Maurizio Sibilla & Massimiliano Manfren

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Envisioning Building-as-Energy-Service in the European context. From a literature review to a conceptual framework

Maurizio Sibilla [a] and Massimiliano Manfren [b]

[a]School of the Built Environment, Oxford Brookes University, Oxford, UK; [b]Faculty of Engineering and Physical Science, Southampton University, Southampton, UK

ABSTRACT

Positive Energy Buildings (PEBs) represent an emerging paradigm for high performance in the building sector. This paradigm focuses on the possibility of exploiting the interaction between individual NZEBs and smart Smart Grids, using energy surplus exchange. Acknowledging this technical potential, building sector should re-think the role of individual buildings as nodes of intelligent energy infrastructures with large penetration of distributed renewable energy resources. This requires a better understanding of the emerging properties related to PEBs and an organisation of new alliances across sectors in order to put PEBs nets into practice. However, there is no evidence of a comprehensive socio-technical framework concerning PEBs nets working at scale. This paper aims to fill this gap. Through a literature review, based on Constructive Grounded Theory Method, it proposes a new conceptual framework focused on *Buildings-as-Energy-Service* as a key enabler for creating PEBs nets. Research findings are organised according to four integrated lines of research, which describe: the trajectory towards PEBs nets; the management of new alliances across sectors; the definition of an ecosystem of applications for PEBs; and, the socio-technical implications in putting PBEs into practice. These research lines may contribute to re-inventing the role of the building sector in delivering tailor-made products and services for a low carbon society. Thus, academic and non-academic stakeholders in the fields of Architecture, Engineering, Construction, and Planning might find this conceptual framework useful, as it summarises significant potential interactions among these sectors, emerging from recent studies.

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Energy transition; socio-technical approach; positive energy building; building sector; Buildings-as-Energy-Service

Highlights

- A conceptual framework is proposed as a key enabler for creating PEBs nets.
- New peculiarities offered by PEBs nets are conceptualised
- The importance of re-thinking buildings as active nodes in infrastructures is motivated.
- Knowledge fragmentation is recomposed to reshape building sector alliances.
- Exploratory research, based on the Constructive Grounded Theory method, is conducted.

CONTACT Maurizio Sibilla msibilla@brookes.ac.uk School of the Built Environment, Oxford Brookes University, Headington Campus, Oxford, OX3 0BP, UK

Introduction

In Europe, the building sector is under a huge renovation pressure determined by the fact that the building stock is, by a large extent, obsolete and underperforming from an energy and environmental perspective. It is estimated that 75% of buildings were built before 1990 (ECSO, 2018). In addition, the current rate of energy renovation (i.e. 0.4–1.2% depending on the country) (EC, 2019), appears to be insufficient to meet the commitments under the Paris Agreement (UN, 2015). Hence, the improvement of the energy performance of existing and new buildings to achieve mandatory NZEB targets (Attia et al., 2017) is needed together with a radical transformation at the infrastructure level in order to decarbonise the European building sector by 2050.

Since 2007, the European Union has focused its energy systems' development strategies on a diversified set of efficient and low carbon technologies to respond to climate change issues by means of a new generation of (smart) buildings and (smart) cities (EC, 2007). Among these strategies, distributed and renewable energy technologies have been recognised as a valid alternative to fossil fuel-based systems (Rahman, Pota, Mahmud, & Hossain, 2016). In addition, they can promote smart citizen-centered energy systems (EC, 2020) and Self-Organised Energy Communities (UE, 2018) at large scale. Furthermore, smart technologies and applications (e.g. based on IoT, remote sensors, smart meters) are now increasingly reliable and integrated within intelligent energy infrastructures (Siddaiah & Saini, 2016). All these technologies are expected to contribute to the enhancement of the spatial, social, and environmental quality of buildings and settlements by means of a co-evolution (Foxon, Reed, & Stringer, 2009) process.

With this regard, an advanced building paradigm is now emerging based on the possibility to exploit the interaction between individual NZEBs and Smart Grids, making them evolve into nets of Positive Energy Buildings (PEBs). Although a standard definition of PBEs does not exist yet, PBEs are considered as NZEBs (Magrini, Lentini, Cuman, Bodrato, & Marenco, 2020), which are so efficient that they produce more energy than they consume, enabling peer-to-peer energy exchange by means of intelligent energy infrastructures. Different studies have emphasised this new paradigm as an opportunity to accelerate the decarbonisation of the building sector, by means of innovative energy services that are intrinsically linked to building features (e.g. Bulut, Odlare, Stigson, Wallin, & Vassileva, 2016; Cole & Fedoruk, 2015; Manfern, Sibilla, & Tronchin, 2021; Sibilla, 2020).

The assumption proposed in this study is that delivering NZEBs and PEBs nets differs profoundly. These two models are both characterised by technological innovations such as efficient heating and cooling technologies, from single buildings up to districts (Buffa, Cozzini, D'Antoni, Baratieri, & Fedrizzi, 2019), adaptive-predictive control strategies (Gholamzadehmir, Del Pero, Buffa, Fedrizzi, & Aste, 2020), and digitalisation of products and processes (Shao, Liu, Li, Chaudhry, & Yue, 2021) among others. However, being based on a completely new institutional organisation (i.e. smart citizen-centered energy systems), PEBs nets will require to establish novel alliances among social and technical sectors to promote a new generation of buildings as energy services. These services will allow buildings to act as intelligent nodes of a smart citizen-centred energy system. However, novel alliances could be inhibited by barriers such as the lack of knowledge (Walker, 2008), which prevents the integration of traditional knowledge silos to solve the deficiencies of technology literacy concerning PEBs and their innovative services potential.

For this purpose, this study proposes a new conceptual framework designed to reconcile different perspectives and reduce the fragmentation of knowledge regarding the topic of *Building-as-Energy-Service* by highlighting the most relevant concepts emerging from interdisciplinary research. This conceptual framework emphasises new connections between social and technical initiatives across the disciplines of Architecture, Engineering, Construction, and Planning. It promotes the *Buildings-as-Energy-Service* concept as a key enabler for PEBs paradigm.

The following sub-section provides the research background and question. Thereafter, Section 2 gives details regarding the methodology adopted. Section 3 reports the results derived from descriptive and content analyses of selected literature. Section 4 discusses the meaning of a conceptual framework routed on *Buildings-as-Energy-Service*. Finally, Section 5 delivers our conclusions, pointing out some implications for future research in this broad area.

Background and research question

This subsection provides the background to point out the current state-of-the-art in respect to the nexus of social and technical energy transition perspectives, which have or could have an impact on the building sector.

The energy transition is expected to impact on society profoundly, although significant resistance persists. Geels and Smit's (2000) review identified three main barriers: the absorptive capacity of industries; the lack of cooperation between actors; and the challenge to organise an innovative supply chain. Likewise, Sibilla and Kurul's (2018) review adopted the concept of *Technology Support Net* (TSN) (Zeleny, 2012) in order to model distributed renewable and interactive energy systems (DRIs) as an example of PEBs nets. On the one hand, TSN is composed of a multitude of local actors, who often have different perspectives and scopes. On the other hand, they are called to collaborate to establish work rules and organisational patterns concerning the new infrastructure. These studies suggested pertinent approaches to deal with the acute fragmentation in the building sector (Chen, Zhang, Xie, & Jin, 2012; Jones, Davies, Mosca, Whyte, & Glass, 2019; Kurul, Tah, & Cheung, 2012; Shen et al., 2010). However, the fragmentation persists, contrasting collaborations across organisational and professional boundaries as a common practice (Chakuu, Godsell, & Glass, 2020; Sibilla, 2017). As a consequence, how to organise an innovative supply chain to put PEBs nets into practice remains an unexplored issue within the building sector.

Others focused on economic perspectives (Gliedt, Hoicka, & Jackson, 2018; Lepoutre & Heene, 2006; Smith, Voß, & Grin, 2010). For example, Gliedt et al.'s (2018) review expressed the relevance of intermediaries to transform the subsystems of society that are locked-in the dominant socio-technical regime. However, in these studies, the building sector is related but not integrated into the energy infrastructure evolution. By contrast, a new perspective comes from the concept of a *Circular Economy*. In this regard, Pomponi and Moncaster (2017) discussed the emerging paradigm of *Circular Buildings* as a part of the Industry 4.0 agenda. This new paradigm goes beyond the topics of energy consumption and carbon emissions. It encompasses better management of resources, involving the life cycle of buildings (De Wolf, Pomponi, & Moncaster, 2017). However, the process of transferring the *Circular Buildings* concept within the realm of a net of PEBs nets is a challenge.

Several studies have elaborated advanced technical and managerial tools in order to deal with the problem of the energy performance gap, to reduce uncertainties and increase transparency in energy and environmental modelling for the construction of NZEB (Bilal et al., 2016; Zhao & Magoulès, 2012). Bilal et al. (2016), for example, pointed out that with the advent of embedded devices and sensors in buildings, the construction industry has also entered the *Big Data* era. This not only can impact on construction but also a new generation of managerial, financial and administrative tools. For instance, Shang, Zhang, Liu, and Chen (2017) reviewed relevant aspects of energy performance contracting, which could allow stakeholders (e.g. energy service companies and energy customers) to establish roles, responsibility and risk about new mechanisms to promote energy services associated with buildings.

Other studies explored similar topics but from another perspective and scale of observation. Péan, Salom, and Costa-Castelló (2019) investigated the concept of *Energy Flexibility*, collecting advanced applications, amongst which are *Demand-Side Management* and *Model Predictive Control*. These applications also take into account some technical limitations concerning renewable systems (e.g. wind and solar systems) such as the discontinuity of generation related to the local climate and other variables (Baños et al., 2011). Therefore, they can support the decision for establishing renewable energy systems in a given place, and to decide which combination of energy sources is the best option. Thus, optimisation algorithms constitute a suitable tool for solving complex problems in the field of integrated renewable energy systems, taking into account technical and social aspects.

However, how these applications can synchronise the spatial, social, and environmental quality of buildings and settlements requires further empirical applications.

To sum up, previous studies have shown a high level of complexity, which involves the building sector within the energy transition. These studies have reviewed socio-technical components, which can be transferred into the realm of a net of PEBs. Additionally, they have stressed the need for developing new duties and skills based on integrated approaches to making this transfer feasible. Finally, they have drawn attention to the role of the local network to support and consolidate innovative practices in order to organise a reliable infrastructure.

In this complex scenario, envisioning *Buildings-as-Energy-Service* means to establish a clear relationship between a new generation of buildings and the future energy infrastructure. However, Sheffer and Levit (2010) emphasised that innovation in building sector tends to be implemented at the product or process, rather than at a system level because of its fragmented nature. Moreover, the lack of comprehensive socio-technical framework concerning *Buildings-as-Energy-Service* related to the scenario of PEBs reinforces this deficiency. As a consequence, a *Technology Support Net* for PEBs has not yet emerged as a priority, contrasting the acceleration towards a low carbon society. In this sense, the increase of knowledge concerning the concept of *Buildings-as-Energy-Service* can help delivering innovative products, services and practices by creating technological learning at multiple levels.

Therefore, this paper explores the extent to which the fragmented knowledge inherent to *Buildings-as-Energy-Service* can be re-organised into a unitary framework. It contributes to the evolution of the building sector towards the innovative paradigm of PEBs nets, pursuing the following objectives:

- Classify the current categories and lines of research on the role of the building sector towards delivering a new generation of buildings as nodes of a distributed, renewable and intelligent energy infrastructure;
- Re-compose the levels of fragmentation, taking into account a socio-technical perspective, to reshape the patterns of building sector alliances with other realms in order to recognise and respond to the new peculiarities offered by PEBs nets;
- to develop the content of an innovative platform for knowledge exchange and integration, conceived to help operationalising the vision of *Buildings-as-Energy-Service*.

Method

This literature review was based on the Constructive Grounded Theory (CGT) approach (Charmaz, 2008, 2006) to conduct a qualitative analysis of content. CGT is especially appropriate for exploratory research, where categories derive from a subjective understanding of the content of text data through the coding method of systematic classification and patterns recognition. Figure 1 provides a visual representation of the main methodological stages.

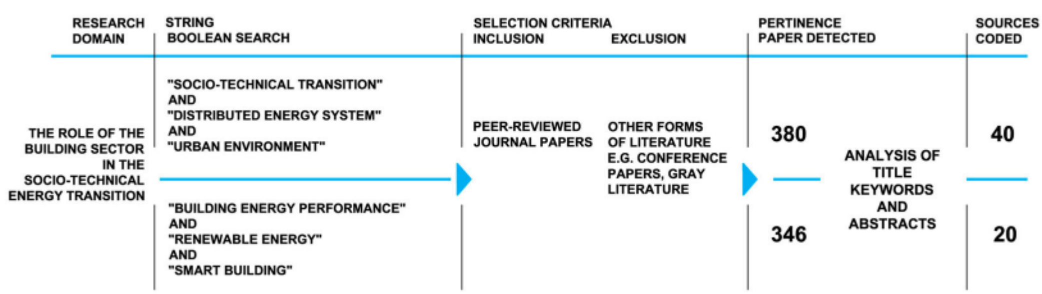


Figure 1. The sequence of the main methodological stages.

Therefore, the first stage was to identify the research domain and to select the pertinent literature. The research domain is the role of the building sector in the socio-technical energy transition. It was specified by a set of filters for the selection of literature. The first filter was based on a stratified sampling approach (e.g. Hess & Sovacool, 2020), which allowed the authors to take into account a multi-perspective screening (i.e. social and technical perspectives) according to the scope of this study. Thus, the authors developed two sets of search. Each set was defined by a Boolean search composed of three keywords, allowing the authors to circumscribe the exploration within the domain proposed. The combination adopted generalises currently debated issues as stressed in the introduction. Additionally, as Hess and Sovacool (2020) stated, using a stratified sampling method with broad search terms (e.g. socio-technical transition, building energy performance), the review limited bias.

The second filter established the inclusion and exclusion criteria. Hence, only papers published in peer-reviewed journals were included; while other formats of literature (e.g. conference proceeding, grey literature) were excluded. As a result, the two sets of searches produced two separate lists of 380 and 346 articles, respectively.

Then, the final filter (i.e. filter 3) established the pertinence of each paper to the research domain. According to prior studies (e.g. Govindan & Bouzon, 2018; Roy & Singh, 2017) each paper's pertinence was assessed by reading the title, keywords and abstract. As a result, several papers were excluded. For example, although focused on energy transition, papers concentrated on mobility were considered not pertinent, as well as, studies exclusively focused on energy performance calculation. Thus, after the pertinence screening, 40 and 20 papers formed the basis of the review; while 9 previous literature reviews were used to build up the background of this research.

Figure 2 displays the strings adopted for the two sets and the candidate sources based on searches in the electronic database. The electronic database used is the (omitted for review) university database, which includes Scopus and Web of Science, among others.

The second stage fixed the unit of analysis. The content analysis was based on a simple unit and context unit (Charmaz, 2006). The former includes concepts (i.e. simple or composed words) and patterns (i.e. sentences or paragraphs); the latter describes the source where concepts and patterns are contextualised. In this analysis, the simple unit was essential for the creation of a dedicated lexicon related to the topic of PEBs; while, the context unit was essential for determining how key concepts were contextualised within the source.

Both units were developed as a part of the third stage (i.e. the coding process and definition of categories). The coding process was carried out with Nvivo software's support, using an inductive approach to the development of the categories (e.g. Jabareen, 2009; Zhang & Wildemuth, 2009). Thus, each paper (i.e. context unit) provided a specific contribution to form the semantic construction of each category.

Figure 3 displays an example concerning the two main steps of the coding process carried out in Nvivo. Firstly, a key concepts (e.g. *supply chain*) was coded from a source. However, the coded concept could be used by other sources within different contexts. Therefore, the distribution of the coded concept among the other sources was assessed. For example, the concept of *supply chain* occurred in 10 sources [Figure 3(a)]. Thus, all patterns concerning the coded concept were visualised and recorded, allowing the authors to select the most appropriate and pertinent to support a

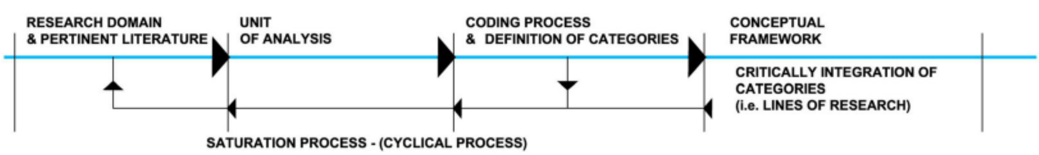
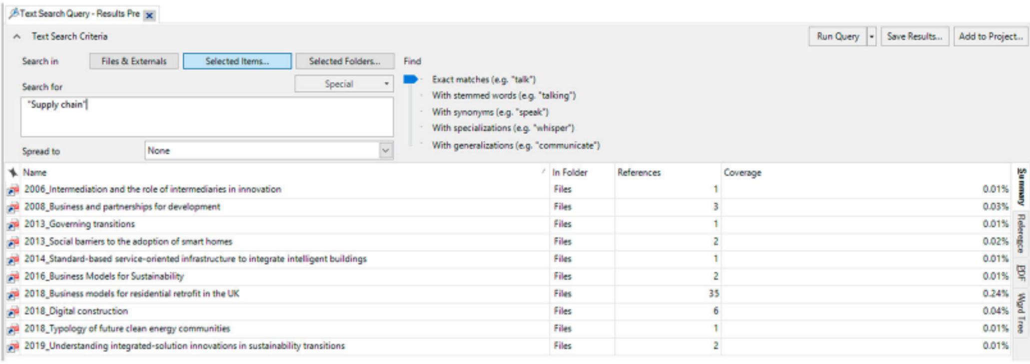
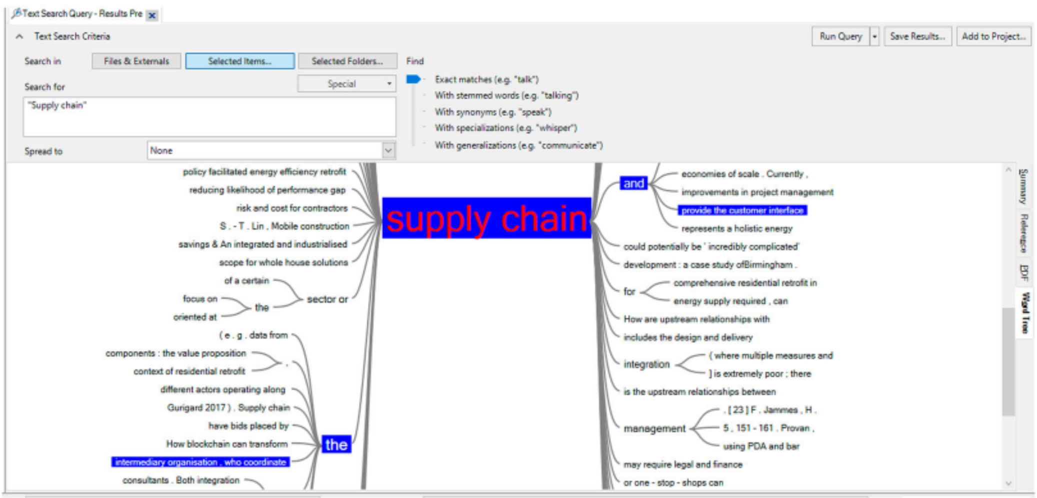


Figure 2. Stratified sampling approach.



a) the search query returns the sources where the coded concept is uded



b) the software displayes the different patterns, focusing on the coded concept. Then, the researcher selects the most appropriate pattern, identifying the source.

Figure 3. Concepts and patterns: an example of coding process.

critical interpretation. For example, in the case of *supply chain*, a specific pattern was selected because it highlighted a relationship with another coded concept (i.e. intermediaries) [Figure 3(b)].

Successively, all the selected patterns belonging to the coded concepts were classified in order to saturate emerging categories. According to Charmaz (2006), the authors have agreed to construct a category after classifying at least three separate sources to explain the same phenomenon; and, aggregate the categories belonging to the same perspective of exploration to form a line of research. Table 1 provides a sample of the inductive process adopted, pointing out the relationships between concepts, patterns, categories, and lines of research.

Finally, these lines of research were used to move from a literature review to a conceptual framework, critically integrating the categories in a unitary cognitive apparatus envisioning *Buildings-as-Energy-Service* as a key enabler for creating a net of PEBs.

Results

This section is divided into two parts: descriptive results and content analysis.

Table 1. From concepts to categories: a sample of the inductive process adopted.

Concept	Pattern	Source	Authors' interpretation (Content Analysis)	Emerging Category	Emerging Line of research
industrial change	[…] industrial change with more macro-level cultural and economic changes […]	(Foxon, 2011)	According to the CGT approach, after coding stimulating concepts and their patterns, authors propose a critical interpretation and a possible connections among these concepts through a content analysis. (e.g. extract for the content analysis) […] The transition needs for a co-evolutionary process (Bolton & Foxon, 2015), involving interactions between […] institutions, […] business strategies […] (Foxon, 2011). So, it is essential to highlight the trajectory of the evolution of new energy networks […]. urban components as active, neutral or passive nodes of the future energy network […] (Sibilla & Kurul, 2020b).	This allowed authors to establish a common perspective, integrating the source analysed. This common perspective is named as 'category' (e.g.) Buildings as component of distributed renewable and interactive energy systems	In this case, a new generation of buildings, which act as components of the energy net involving interactions between technologies, institutions, users, business strategies, represents the trajectory of the evolution. However, through a content analysis the Authors pointed out that the trajectory of the evolution was a topic explored by other sources with different perspectives. These sources generated further categories (e.g. Smart Grid; Energy Services). Thus, together these categories was used to form a Line of research. (i.e. the trajectory toward a PEBs nets). Each line of research defined a specific aspects concerning the new Conceptual Framework on Building-as-Energy-Service. (i.e. Trajectory, Management, Tools and Socio-technical implications).
infrastructure governance	[…] effective and coherent approaches to infrastructure governance […]	(Bolton & Foxon, 2015)			
urban pattern	[…] explore the potential relationships between urban patterns and DRIs features.	(Sibilla & Kurul, 2019)			

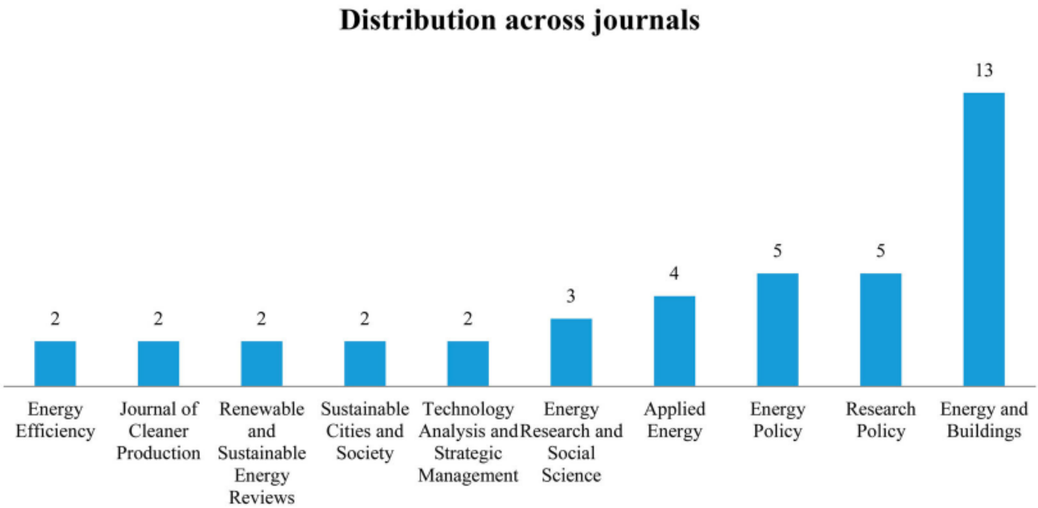


Figure 4. Distribution across Journals.

Descriptive results

The relatively limited number of pertinent papers (60 in total) is due to the fact that the topic of PEBs is hugely new. This confirmed the character of exploratory research of this study.

Figure 4 reports the distribution across leading journals. It shows the broad range of journals consulted. The figure shows only journals with more than one reference. In total, a range of 30 different journals was consulted, covering both social and physical science perspectives. The high number of cases from Energy and Buildings (i.e. 13 papers) can be explained by the fact that this journal covers a wide set of advanced technical applications, which were collected as examples, herein.

Figure 5 displays the publication by year. A substantial number of publications (i.e. 56.6% of the total) are included in the period 2016–2019. Only the first trimester of 2020 was taken into account.

Figure 6 illustrates a co-occurrence network composed of the coded concepts, which were collected in this literature review. It visualises the current relationships explored in the literature selected. The size of every node indicates the number of repetitions of that concept in the literature.

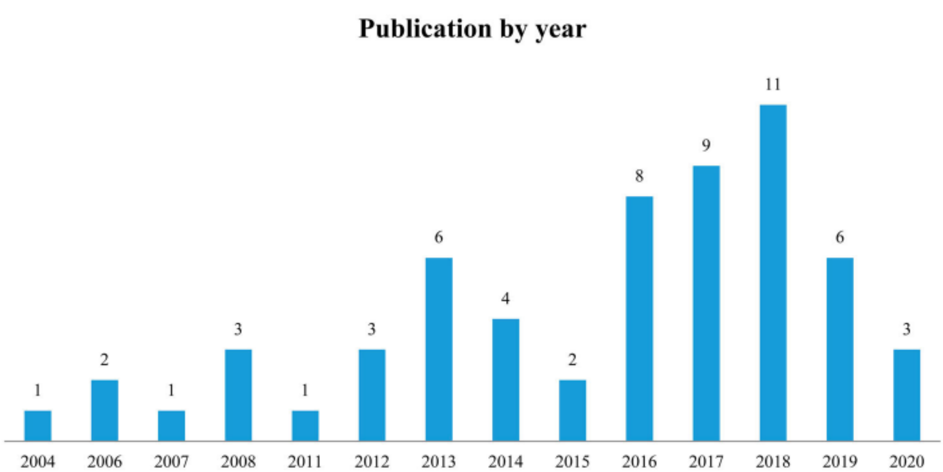


Figure 5. Publication by year.

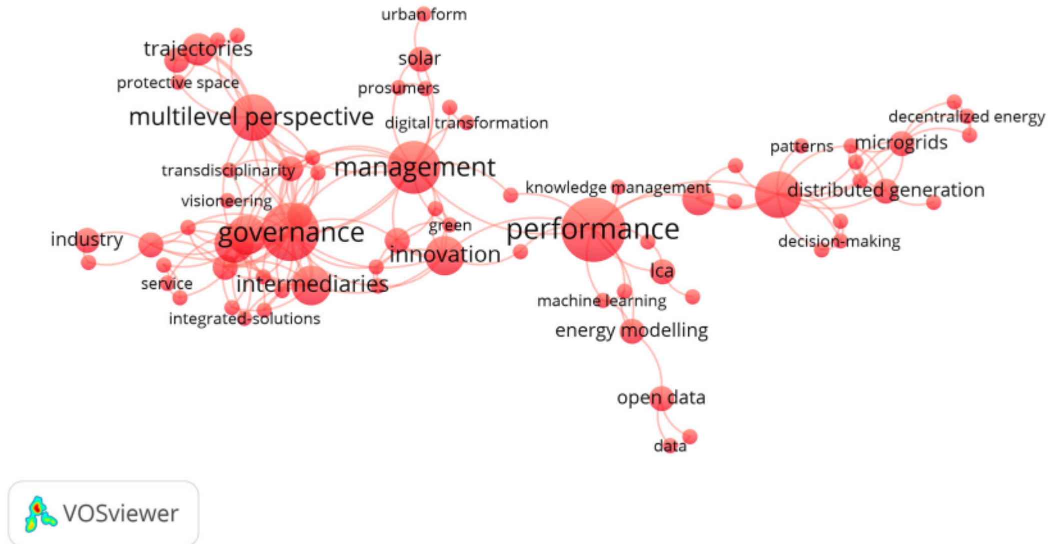


Figure 6. Co-occurrence network map of the coded concepts as reported in the literature.

On the one hand, Figure 6 makes evident that relevant concepts were coded and a structural relationship exists among some of them (e.g. governance, management, and performance). On the other hand, it emerges that other relationships can be established, focusing on the emerging paradigm of PEBs nets (e.g. decentralised energy, urban form, and service). These new relationships are explored in the following section (i.e. content analysis).

Content analysis

Four lines of research were identified as a result of the categories aggregation. A description of each line of research is provided in the following sections.

First line of research. Trajectory: towards PEBs nets

Table 2 shows the literature collected into the first line of research.

Academic literature supports that the low carbon transition cannot be purely considered in technical terms. The transition needs for a co-evolutionary process (Bolton & Foxon, 2015), involving interactions between technologies, institutions, users, business strategies and wider ecosystem change (Foxon, 2011). So, it is essential to highlight the trajectory of the evolution of new energy networks, according to their main characteristics. This is particularly true for distributed and renewable energy systems. Indeed, one of the most important characteristics is that distributed and renewable energy systems can be adapted and implemented according to the local geographical conditions. As a consequence, they can contrast the indifference toward the local geographical conditions, which is one of the features of both fossil and nuclear-based systems. Therefore, these forms of energy networks promote new concepts in terms of dimensions, localisation and construction. The dimension depends on two main factors: the local demand for energy and the technical capacity to organise the system. The dimension of the system is highly dependent on the physical and environmental local conditions. Localisation is related to the availability of local energy sources, which impacts on the efficiency of the system. Finally, the construction is related to the identification and hierarchical classification of urban components as active, neutral or passive nodes of the future energy network, where energy flow exchanges can be balanced with the support of appropriate computerised protocols. Thus, the energy system becomes interactive, allowing the node's association with different energy demand profiles (Sibilla & Kurul, 2020b).

Table 2. The first line of research. Trajectory: towards PEBs nets.

	Simple unit		
Context unit	Concept	Pattern	Categories
(Foxon, 2011)	Industrial change	[…] industrial change with more macro-level cultural and economic changes […]	Buildings as component of distributed renewable and interactive energy systems
(Bolton & Foxon, 2015)	Infrastructure governance	[…] effective and coherent approaches to infrastructure governance […]	
(Sibilla & Kurul, 2020b)	Urban patterns	[…] explore the potential relationships between urban patterns and DRIs features.	
(Oliveira-Lima et al., 2014)	Intelligent buildings	[…] service-oriented infrastructure to integrate intelligent buildings in distributed generation […]	Smart grid for buildings and districts
(Kolokotsa, 2016)	Micro-grids	[…] energy management system for polygeneration micro-grids […]	
(Paoletti et al., 2017)	Construction features	[…] construction features of a set of nZEB […]	
(Torcellini et al., 2015)	Zeb technologies	[…] demonstrating how to combine zeb technologies […] into an overall efficiency package	
(Darby & McKenna, 2012)	Demand-response	[…] exploring the relationship between demand response and energy efficiency.	Set of energy services for buildings as active, netutral and passive nodes of the net
(Balta-Ozkan et al., 2013)	Social barriers	[…] understanding the social barriers to adoption of smart homes […]	

Distributed, renewable and interactive energy systems mark an evolutionary trajectory, which started to minimise the building energy demand. After which it evolved into the NZEB concept aimed at obtaining an energy balance (consumption-production) through on-site generation from renewable energy sources (RES) (Paoletti, Pascuas, Pernetti, & Lollini, 2017). Furthermore, such a trajectory has built up alternative strategies for both on-site generation and off-site generation from RES. Off-site generation is relevant because it allows buildings with limited solar access for PVs due to urban morphologies (e.g. high density) or building typology (e.g. high-rise) (Torcellini, Pless, & Leach, 2015) to take part as components of the energy network. In other words, the integration of on-site and off-site generation from RES can be an exceptional opportunity for creating smart grids to assemble active, neutral or passive nodes of the network. In addition, smart grids can include advanced techniques such as cluster analysis, optimising the organisation of the future energy infrastructure (Oliveira-Lima, Delgado-Gomes, Martins, & Lima, 2014). Data from cluster analyses can be used by machine learning algorithms to infer the complex relationships between the energy consumption and other variables (e.g. temperature, solar radiation and occupancy). Therefore, the trajectory of the evolution of new energy networks can affect the energy sector, shifting investments from the expansion of large-scale generation systems to the energy efficiency in the building sector, i.e. improving building fabric and increasing decentralised and renewable infrastructure in the community (Kolokotsa, 2016).

The concept of *Buildings-as-Energy-Service* provides a new way of looking at the role of buildings as components of an energy grid. It requires new insight from disparate disciplines or expertise to understand how technologies and services may interact with values, behaviour and society (Balta-Ozkan, Davidson, Bicket, & Whitmarsh, 2013). Indeed, *Buildings-as-Energy-Service* should be understandable to the user who interacts with them. In this scenario, three issues emerge with administration; interoperability; and reliability. Administration relates to the challenges faced by actors, who will manage such services, which permeate into the building. Interoperability concerns the adoption of universal standards for communications protocols for the services offered. Reliability involves the interconnection of technologies with different tolerances for technical errors. At present, the ability of smart devices to predict human behaviour correctly is limited. For this reason, the industry promotes smart services at mass-scale, only focusing on daily routines (Balta-Ozkan et al., 2013). Such smart services are managed by smart meters, which may be categorised according to specific target and user's, needs, e.g. comfort and energy efficiency. In the future, other services can also be delivered as standard services, e.g. communication between user's needs and on-site/off-site generation grid. By doing so, end-users can obtain benefits from further demand response programmes (Darby & McKenna, 2012). Furthermore, to enhance the communication between users and the grid such programmes can be associated with social policy goals, which can provide a better understanding of individual environmental impacts. Thus, it is possible to fill the socio-technical gap concerning meaningful interactions between technology and society.

Second line of research. Management: new alliances across sectors

Table 3 illustrates the literature collected into the second line of research.

Low-carbon energy transition involves a new network of actors, such as energy authorities, governments, utilities, consumers/producers, and technology providers. On the one hand, socio-technological innovations depend on opportunities for these actors to access new information, knowledge, and resources, which are critical for developing new ideas and products. On the other hand, these innovations are also affected by the network structure. Traditionally, energy infrastructures have been established around distinct groups of actors (e.g. policymakers, regulatory authorities, transmission and distribution authorities, amongst others), organising strong politico-economic coalitions. The *Multi-Level Perspective* (MLP) outlines pathways for destabilising such coalitions which belong to the fossil-fuel regime (Loorbach, Frantzeskaki, & Avelino, 2017). MLP is based on three analytical levels: Niches, where typologies of socio-technical organisations are created and tested; Regime, where technologies, institutions and practices are aligned and conformed; Finally, Landscape, which provides the context for regime stability or change (Kivimaa & Kern, 2016). The scope of MLP is to enhance niche experiments to scale-up and change the regime, exploiting some external pressures (i.e. opportunities) which can emerge at the local level (Wittmayer, Avelino, van Steenbergen, & Loorbach, 2017).

Policymakers and incumbent firms often represent a core alliance at the regime level. They are oriented towards maintaining the status quo (Geels, 2014). On the contrary, radical innovations can be applied within *Protective Spaces*, which are contexts for experimentation, where uncertainty and poor returns are accepted (Schot & Geels, 2008). The development of *Protective spaces* requires intermediary organisations and actors to manage concrete projects at the local level (i.e. experiments) (Geels & Raven, 2006), adopting the so-called *Strategic Niche Management* (SNM) method. SNM is a practical approach to governing socio-technical niches, promoting the organisation of new socio-technical networks. These new networks can act within towns, villages, and cities, providing a sustainable alternative to resolve persistent unsustainable problems. Therefore, SNM is based on three key processes: (i) managing expectations; (ii) building social networks; and (iii) learning. Expectation management concerns how niches present themselves to external audiences. Expectations should be widely shared, realistic and achievable. Networking activities have to embrace many different stakeholders, who can support the niche's growth. Learning processes are useful to point out how people deal with regime systems. Successful niches are those which are able to attract more participants; and translate niche ideas into ordinary settings (Seyfang & Haxeltine, 2012). These three key processes involve several types of organisations such as building owner organisations; outreach organisations; educational organisations or professional societies. These actors are engaged to identify best practices to control the cost of innovative solutions (e.g. NZEB).

Nevertheless, while distributed and renewable energy systems, as technical systems, are well-known, the heterogeneity of actors and related questions of governance are not sufficiently explored. Understanding how actors can influence and support energy transition is a crucial question, which involves the new figure of intermediaries (Smith & Raven, 2012). These intermediaries are actors that facilitate relationships between key actors and enable sharing and pooling of knowledge (Bush et al., 2017). The role of intermediaries in SMEs is relevant in order to seek network contacts to reduce time and knowledge constraints and increase the absorptive capacity of SMEs. Intermediaries are commonly understood as third-party organisations, which can be clustered

Table 3. Second line of research. Management: new alliances across sectors.

	Simple unit		
Context unit	Concepts	Patterns	Categories
(Kivimaa & Kern, 2016)	POLICY mix	[…] including the two policy mix dimensions – creation and destruction.	Multi level perspective to promote innovation, improving the absorptive capacity of the local firms
(Loorbach et al., 2017)	Transdisciplinarity	[…] implications of transdisciplinarity for sustainability research.	
(Wittmayer et al., 2017)	Actor roles	[…] roles and relations between actor roles as indicative of changes.	
(Geels & Raven, 2006)	Niche development trajectories	[…] perspective on niche development trajectories, conceptualising interactions between learning processes, expectations and social networks.	Strategic niche management to respond to the peculiarities offered by PEBs nets
(Schot & Geels, 2008)	Strategic niche management	[…] strategic niche management suggests that researchers can act as […] mappers of change dynamics.	
(Seyfang & Haxeltine, 2012)	Grassroots innovations	[…] a model of grassroots innovations to describe innovative networks of […] organisations that lead bottom-up solutions for sustainable development.	
(Geels, 2014)	Resistance	[…] shifts attention to the resistance by incumbent regime actors to fundamental change.	
(Howells, 2006)	Intermediaries	[…] identify the role that intermediaries could play in […] identifying partners.	Innovation intermediaries for re-shaping patterns of the building sector collaborations
(Kolk et al., 2008)	Cross-sector partnerships	[…] cross-sector partnerships have become important instruments for addressing problems of global development […]	
(Smith & Raven, 2012)	Protective space	[…] within this protective space, niche actors can nurture the path-breaking innovation […]	
(Bowen et al., 2013)	Job creation	[…] making green business and job creation more likely […]	
(Abdelkafi & Täuscher, 2016)	Values–beliefs–norms	[…] values, beliefs, and norms constitute important drivers of sustainable behaviour of firms.	
(Inglesi-Lotz, 2016)	Economic welfare	[…] to estimate the impact of the renewable energy consumption to economic welfare by employing panel data techniques.	
(Bush et al., 2017)	Empowering processes	[…] understanding how actors can influence and support empowering processes is a key question […]	
(Brown, 2018)	Supply chain	[…] intermediary organisation, who coordinate the supply chain and provide the customer interface through marketing activities and project management […]	
(Lazarevic et al., 2019)	Integrated-solutions	[…] offering integrated-solutions at the intersection of building and energy regimes.	

into three distinct groups: public, non-profit, and private (Kolk, van Tulder, & Kostwinder, 2008). More specifically, in the context of innovation, an intermediary that assists in the innovation process is an organisation that acts as an agent to manage the innovation process between two or more parties (Howells, 2006). Intermediaries can contribute directly to green entrepreneurship, and indirectly to other green job strategies focusing on attracting (Bowen, Park, & Elvery, 2013), retaining (Abdelkafi & Täuscher, 2016) and expanding (Inglesi-Lotz, 2016) of niche experiments as part of sustainability transitions. Therefore, intermediaries play a significant role in delivering *Buildings-as-Energy-Service*, enhancing the cooperation between different types of actors (Brown, 2018). They can promote flexibility (i.e. response to systemic challenges and opportunities), efficiency (i.e. reducing transaction costs) and benefits from innovation (i.e. increased innovation and improved technology transfer opportunities) (Lazarevic, Kivimaa, Lukkarinen, & Kangas, 2019).

Third line of research. Tools: an ecosystem of applications

Table 4 displays the literature collected into the third line of research.

The sustainability transition of the construction industry is a grand socio-technical challenge, which is focused on three generic domains, namely project, product and service. Each one is characterised by different markets, companies, business models and regulation. The assessment of the sustainability of these domains often refers to the advanced application of *Life Cycle Assessment* (LCA) methods. LCA applications are fundamental for the development of innovative economic paradigms such as the *Circular Economy* in the built environment. However, there are significant variations in how this method is currently used in practice, making it difficult to use for transparent comparability and benchmarking (Pomponi & Moncaster, 2018). Indeed, the measurement of embodied carbon equivalent of buildings represents a critical element, which makes it challenging to transparently document the results for consistency and credibility of practices and policies. As a consequence, a particular effort has to be devoted to the identification of influential factors in LCA, in order to assess the robustness of results (Pannier, Schalbart, & Peuportier, 2018) concerning uncertainty and variability in model inputs.

The sustainability transition of the construction industry is also represented by the evolution of *Energy Performance Contracting* (EPC). Whilst EPC is not a new concept for the market, the potential of energy efficiency measures (in terms of energy, emission and cost savings, as well as other related co-benefits) is still largely untapped. First of all, it is necessary to critically rethink the structure of EPC, through better understanding of the role of relevant actors and stakeholders and by engaging them successfully, considering barriers such lack of interest, awareness, knowledge and human and financial capacity (Winther & Gurigard, 2017). Further, from a technical stand-point, a link between energy performance simulation in the design phase (project domain) and measurement and verification (M&V) in the operation phase (service domain) should be established. This can be achieved, for example, by creating integrated data analysis workflows from design to operation. These workflows can be performed in a semi-automated or automated manner, utilising state-of-the-art technology (Gallagher, Leahy, O'Donovan, Bruton, & O'Sullivan, 2018). They can be considered as an evolution of current M&V 2.0 approaches. Finally, the idea of creating energy labelling of buildings has definitely had an impact on market dynamics, generally leading to higher property values in relation to higher energy efficiency results. Clearly, in order to draw more far-reaching conclusions in this sense, large-scale investigations are necessary to document the actual energy, cost and emission savings together with the potential co-benefits of energy efficiency measures.

This issue stresses the relevance of open data and software in energy research (Pfenninger, DeCarolis, Hirth, Quoilin, & Staffell, 2017) and the fundamental necessity of creating more transparent modelling processes (Pfenninger et al., 2018) that can be trusted in decision-making. Further, the availability of data and models (Bollinger, Davis, Evins, Chappin, & Nikolic, 2018) can be a key driver for the development of ecosystems of applications for energy transitions in the built environment. Indeed, by employing measurement and verification (M&V) principles together with large-scale data analysis techniques, it could be possible to characterise energy performance transparently

Table 4. Third line of research. Tools: an ecosystem of applications.

	Simple unit		
Context unit	Concepts	Patterns	Categories
(Pomponi & Moncaster, 2018)	Embodied carbon (life cycle assessment)	[…] significant discrepancies are already being seen between embodied carbon assessments at the design stage and 'as-built'[…]	Innovative business models for PEBs based on principles of Circular Economy (i.e. Circular Buildings)
(Pannier et al., 2018)	Sensitivity analysis	[…] sensitivity analysis helps at investigating the sources of uncertainty and variability in a model and assessing the results' robustness.	
(Winther & Gurigard, 2017)	Energy performance contracting	[…] energy performance contracting (epc) is a particular form of service contract in that the contractor pledges, through a binding commitment[…]	
(Gallagher et al., 2018)	Measurement & verification (machine learning)	[…] artificial intelligence based approaches (i.e. machine learning) are advantageous in capturing the behaviour of complex energy (measurement & verification)	
(Pfenninger et al., 2017)	Transparency (input data)	[…] the most important aspect is the quality or transparency of input data, rather than the novelty of the modelling methodology.	Ecosystem of applications for flexibility of energy services
(Pfenninger et al., 2018)	Open energy modelling initiative	[…] the open energy modelling initiative helps individual researchers to adopt open-source alternatives[…]	
(Bollinger et al., 2018)	Multi-mode ecologies	[…] multi-model ecologies are essential for exploring the interactions amongst energy consumption, production, distribution and transmission […]	
(Meng et al., 2020)	Solar radiation	[…] pursue retrofit measures that use solar radiation to reduce energy use […] rather than adding thermal insulation.	
(Oh et al., 2020)	Smart meter data	[…] smart meter data from distribution feeders […] can also improve the prediction of high voltage loads.	
(Yoshino et al., 2017)	Actual energy use	[…] actual energy use is the real building energy performance.	Physical-statistical models to implement the Reference Building concept at scale
(Corgnati et al., 2013)	Reference buildings	[…] to define a set of reference buildings as typical national or regional buildings.	
(Kneifel & Webb, 2016)	Statistical modelling	[…] statistical modelling to estimate the energy performance of a building using predictive models and regional weather conditions.	
(Meng & Mourshed, 2017)	Building type	[…] studies on how degree-days base temperatures vary depending on building type are scarce.	
(Lundström et al., 2019)	Meteorological analysis data	[…] a procedure to obtain and utilise meteorological analysis data (air temperature, ground temperature, wind, and thermal radiation and surroundings).	
(Michalak, 2019)	Heating and cooling power	[…] calculation method to obtain heating and cooling power[…]	
(Oliveira Panão et al., 2016)	Internal air temperature	[…] prediction of the internal air temperature[…]	
(Andriamamonjy et al., 2019)	Multi-objective optimisation	[…] the use of a multi-objective optimisation ensures the combination of two seasonally different (winter and summer) datasets.	
(Lehmann et al., 2013)	Model predictive control	[…] model predictive control can be flexibly configured to represent typical building types and variants of technical systems.	
(Stadler et al., 2018)	Distributed energy systems	[…] indicator describes the degree of penetration of distributed energy systems […]	
(Junker et al., 2018)	Flexibility function	[…] flexibility function brings new possibilities for enabling the grid operators […] to control the demand through the use of penalty signals	
(Clauß & Georges, 2019)	Demand response	[…] increased utilisation of advanced control systems to enable flexible demand through demand response technologies […]	

and effectively (Meng et al., 2020), from single buildings up to building stocks. Large-scale data acquisition can potentially take place inexpensively, employing state-of-the-art metering technologies (i.e. smart meters) (Oh, Haberl, & Baltazar, 2020), even though applications should be conceived considering the principles and regulations of data protection.

In order to move from single buildings to building stocks energy analysis, integration of a new set of data and models is needed. This integration requires understanding both the human and technical influencing factors (Yoshino, Hong, & Nord, 2017). These factors can create a discrepancy between design (i.e. project domain) and measured performance (i.e. service domain), i.e. a performance gap. In order to enable large-scale performance benchmarking for buildings, it is necessary to introduce the concept of statistical *Reference Buildings*, i.e. building models that represent the conventional typologies, technologies and end-uses in the building stock, identified by means of statistical analysis. Their use is common today for the techno-economic optimisation of buildings, using methods such as cost-optimal analysis (Corgnati, Fabrizio, Filippi, & Monetti, 2013), and for large-scale energy planning. A statistical approach to building energy performance analysis and prediction is crucial to find new insights from the data (Kneifel & Webb, 2016). It is possible to identify examples of successful application of *Reference Buildings* approach for utility-scale analysis of design phase and operation phase (Meng & Mourshed, 2017) performance. These insights can enable the development of the next generation of energy services and technologies.

The *Reference Buildings* approach is also related to models for predicting the energy performance of buildings, which can be roughly classified as white-box (i.e. detailed) models, grey-box (i.e. physical-statistical reduced-order) models, and black-box (i.e. statistical and machine learning reduced-order) models. White-box models are generally detailed models based on physical laws, which are used for simulations in the design phase. In contrast, black-box models are used in data analysis workflows, for example, in M&V in operation. Grey-box models can represent a good compromise between the two. Indeed, physical-statistical models can be used both for simulation (i.e. in forward mode) and system identification (i.e. inverse mode). More specifically, for building applications, they can be validated according to building energy simulation test standards (Lundström, Akander, & Zambrano, 2019; Michalak, 2019). Additionally, they can be used to characterise the behaviour of technologies in experimental test-facilities (Oliveira Panão, Santos, Mateus, & Carrilho da Graça, 2016). Furthermore, they can be integrated into the design process using *Building Information Modelling* software (Andriamamonjy, Klein, & Saelens, 2019). Therefore, they can create a certain degree of continuity among different phases of performance analysis during the building life- cycle, from design to operation (Lehmann, Gyalistras, Gwerder, Wirth, & Carl, 2013). Grey-box models can be crucial for the effective penetration of renewable energy resources in the built environment (Stadler, Girardin, Ashouri, & Maréchal, 2018). With this regard, it is also necessary to recognise the importance of *Flexibility of Energy* Services (Junker et al., 2018), which can be defined as the ability to manage demand and generation according to climate, user needs and grid conditions. Flexibility in buildings can be created by exploiting storage resources and by acting on appliances (turning on–off or modulating), following a trigger (e.g. time, power, and energy price). Appropriate control strategies are necessary also for unlocking building flexibility potential, as shown in recent research. Finally, the definition of an appropriate level of modelling complexity is crucial to realistically simulate the impact of existing control strategies (Clauß & Georges, 2019) in the design phase.

Fourth line of research. Socio-technical implications: Smart-Citizen Energy Systems

Table 5 shows the literature collected into the fourth line of research.

The increasing integration of renewable energies into current energy systems brings new players into electricity industry decision making. Consequently, the energy supply chain requires an in-depth re-configuration of its structure. Indeed, the general public and communities are no longer simply passive consumers of electricity services, but they are involved as *Prosumers*. Prosumer refers to an energy user, who generates renewable energy in their domestic environment, and stores the

Table 5. Fourth line of research. Socio-technical Implications: Smart-Citizen Energy Systems.

Context unit	Simple unit		Categories
	Concepts	Patterns	
(Arapostathis et al., 2013)	Decision-making processes	[…] addressing the significance of power, trust and networking in the decision making processes involved in the governance of energy transitions […]	Prosumers-prosumerships to re-write traditional energy policies, integrating dimension, localitation and construction components of the energy infrastructure
(Gui & MacGill, 2018)	Decentralised management	A decentralised energy vision will involve the deployment of new infrastructure and/or the reconfiguration of existing infrastructure[…] long-term strategy and collective actions […]	
(Lowitzsch et al., 2020)	Energy communities	[…] with the rise of decentralised RE-production and various forms of consumer (co-)ownership in renewables, energy communities have the potential to become a standard model on the energy markets […]	
(Jensen et al., 2007)	Knowledge management	[…] the need to reconcile knowledge management strategies prescribing the use of ICT as tools for codifying and sharing knowledge with strategies […]	Self-organised energy communities. Taylor-made products and services from the construction industry
(Schweizer-Ries, 2008)	Public acceptance	[…] public acceptance can be seen as the positive description of the social dimension of energy sustainable communities concerning RES.	
(Turnheim & Geels, 2013)	Regime destabilisation	[…] destabilisation distinguishes three core dimensions: (1) flow of financial resources from an external economic environment, (2) legitimacy and support from wider public and policymakers in an external socio-political environment, (3) endogenous commitment of firms-in-industries to the existing regime (trust, confidence).	
(Van Der Schoor et al., 2016)	Local energy Cooperatives	[…] cooperatives need to be knowledgeable about subjects such as energy technology, political strategies and financial housekeeping […]	
(Engels et al., 2017)	Visioneering	[…] conceptualise visioneering as a process of collective practice that enables the integration of new actors with diverse interests and forms of knowledge over time […]	
(Tam et al., 2004)	Green construction assessment	Green construction assessment serves as an assessment tool for construction activities in measuring the environmental performance[…] as well as providing a consistent basis for comparisons […]among companies and construction sites.	Shifting the construction industry adopting digitalisation to implement innovations at system level
(Marique & Reiter, 2014)	urban form	Each urban form presents its own specificities and characteristics, especially as far as the built density and the types of buildings are concerned […] and requires personalised solutions regarding […] on-site production of renewable energy.	
(Orehounig et al., 2014)	Energy hub	The energy hub concept is used to evaluate and optimise the management of energy flows.	
(Ma et al., 2016)	Smart building cluster	[…] the Smart Building Cluster Operator can act as an agent for sharing of RES power among adjacent Smart Buildings.	
(Vigna et al., 2018)	Smart Readiness Indicator	[…] the development process of the Smart Readiness Indicator […] by supporting the assessment of smart technologies and strategies for building readiness improvement in demand response.	
(Woodhead et al., 2018)	Digital Transformation	[…] the drive for Digital Transformation starts enabling new players to dislodge established players in the industry […]	

surplus energy for future use or sells it on to energy buyers (Gui & MacGill, 2018). As a consequence, new concepts of management also emerge. For instance, *Active Network Management* (ANM) is a concept which involves both the management of supply-side and demand-side options (Arapostathis et al., 2013). Therefore, exploring the network managerial components of *Buildings-as-Energy-Service* means focusing on how societies can move from the traditional energy distribution governance to a participatory energy governance model (e.g. *Prosumerships*). This new model seeks to understand the co-evolutionary interactions between a broad range of social and institutional actors, such as utility companies, sector regulators, policymakers, and end-users. *Prosumerships* are expected to be increasingly embedded in energy communities, promoting the configuration of renewable energy clusters (Lowitzsch, Hoicka, & van Tulder, 2020).

Although both the governance model of energy communities and the engineering model of energy clusters are acknowledged in practice, comprehensive regulation is still in development. This is because policymakers and incumbent business actors, concerning fossil-fuel regimes, tend to form close alliances because of mutual dependencies (Turnheim & Geels, 2013). Thus, in order to destabilise these dependencies, a plausible scenario is to shift from the dominant *STI-mode* (Science, Technology and Innovation) of innovation, to a *DUI-mode* (Doing, Using and Interacting of innovation) (Jensen, Johnson, Lorenz, & Lundvall, 2007). The former emphasises research and development investment in green technologies. The latter focuses on social interactions in configuration of *Self-organised Energy Communities* through the approaches of learning by doing and learning by using. Therefore, energy communities have emerged as a concept which defines the relationship of communities with their intended energy management (Schweizer-Ries, 2008). In detail, *Self-organised Energy Communities* consist of a small number of households (up to hundreds of thousands of households) in close proximity, covering a wide geographic area. These households will, however, share specific common goals as members of the community. These goals may include promoting cleaner production, energy autonomy and self-sufficiency, participating in the electricity market as a group, and revitalising the local economy (Gui & MacGill, 2018). Thus, an energy community can form a new type of energy provider, interacting with local, regional, and national networks, to provide social innovations in a decentralised energy system (Van Der Schoor, Van Lente, Scholtens, & Peine, 2016). Yet, energy communities are social and organisational structures formed to achieve specific goals of their members, primarily in the production of cleaner energy, consumption, supply, and distribution. *Living Labs* are an example of activity applied at the local level, which goes beyond technological developments. They promote inter-sectoral and interdisciplinary cooperation in research and development to manage the current socio-technical challenges on a smaller, feasible scale, as well as disseminating new business models (Engels, Münch, & Simon, 2017). Members within the community can formally organise these *Self-organised Energy Communities*, or external actors outside the community, for example, technology companies, utilities, governments, or NGOs. So, members in *Self-organised Energy Communities* may play different roles, such as producers, consumers, investors, asset owners, or a combination of these (Gui & MacGill, 2018).

Taking into account the opportunities mentioned above, the transformation of the industry has now become a necessity for local economic competitiveness (Tam, Tam, & Tsui, 2004). Distributed and renewable energy systems can play a significant role in the transformation of the industry, putting *Buildings-as-Energy Service* at the centre of such competitiveness. The physical connection to the same grid of building clusters allows the exchange of energy between buildings. The possible presence of market aggregation enables the management of building clusters by a common agent or company who can potentially exploit the *Energy Flexibility* of each cluster (Vigna, Pernetti, Pasut, & Lollini, 2018). The concept of *Energy Flexibility* can be linked to the definition of a *Smart Building Cluster*, indicating a group of neighbouring smart buildings electrically interconnected to the same micro-grid (Ma et al., 2016).

At present, the *Smart Building* concept still considers individual buildings as autonomous entities and neglects the importance of reaching energy efficiency at a larger scale. In the future, the organisation of distributed and renewable energy systems can take into account the numerous interactions between urban forms, building energy needs, and on-site/off-site generation from RES (Marique & Reiter, 2014). The construction industry can provide its contribution. On the one hand, it can adopt innovative technologies such as *Internet of Things* (IoT), *Big Data* and *Cyber-physical Systems* (Woodhead, Stephenson, & Morrey, 2018) to drive towards the concept of *Industry 4.0*. On the other hand, it can also embrace the new energy infrastructure model, where buildings act as components of the energy network. In this respect, the key concept is the possibility to jointly manage the energy flows from multiple energy sources in order to improve the sharing of renewable energy between different interconnected buildings (Orehounig, Mavromatidis, Evins, Dorer, & Carmeliet, 2014). By doing so, the construction industry is called to be a part of the energy network organisational system, promoting new partnerships, products and services in order to increase its resilience.

Discussion

While NZEB has become a part of the regulatory system in European countries, PEB is emerging as a new topic. However, the literature has shown a multitude of overlapping concepts such as *DRIs*, *Renewable Energy Clusters*, *Smart Building Cluster,* amongst others. The resulting fragmented framework is a barrier to deal with the energy transition. Yet, the present study was designed to determine how to critically re-compose it. As a result, the four lines of research that arose from this literature review have been critically interpreted in order to produce a new conceptual framework (Figure 7). In doing so, this study offers a new insight bridging fragmented pieces of socio-technical domains of knowledge with the aim of envisioning *Buildings-as-Energy-Service* as a possible solution to put PEBs nets into practice. More widely, in line with Geels and Smit's (2000) results, our findings provide a further contribution to identifying barriers which impact on how technology transforms society.

The first line of research represents the *Trajectory* towards PEBs nets. This study emphasises the direction of innovation to which all actions should converge in order to embrace a co-evolutionary approach. Specifically, the direction of innovation refers to distributed, renewable and interactive energy systems, stressing the infrastructural role of PEBs rather than their isolated applications. This contrasts with previous studies (e.g. Magrini et al., 2020), which consider PEBs to be a more efficient model of NZEB in terms of engineering performance rather than an entirely new socio-technical apparatus. For this reason, the conceptual framework suggests moving from a smart grid for buildings to a smart grid for districts. This means that while the balance between building energy consumption and demand remains a pre-requisite to organise a local grid, as suggested by the concept of *smart building cluster* (Ma et al., 2016); a new set of energy services should be developed. These services concern: Firstly, the implications in terms of urban planning procedures; Secondly, the impact on the assessment of the energy performance of each single components of the grid; Finally, the inferences about how the exchange of energy works within a specific socio-economic context.

Hence, envisioning *Buildings-as-Energy-Service* means placing buildings at the core both of the energy infrastructure and urban asset development. In other words, the building sector will no longer be a passive recipient of the infrastructural innovation. On the contrary, according to Jones et al. (2019), it may be the agent to reform infrastructural investments, enabling new alliances to design suitable business models for PEBs. In addition, it may be the fly-wheel to operationalise the new energy infrastructure, going beyond the traditional distinction between building and urban scale. This role emerges from the process of a hierarchical classification of buildings as active, neutral and passive nodes of the energy grid (e.g. Sibilla & Kurul, 2020). Indeed, this process cannot be reduced in a mere energy balance problem, where the role of the building sector is limited to deliver innovative products in terms of energy performance. Indeed, within an interactive network, the concept of energy performance is not static; it varies dynamically with the technical and social components involved. Therefore, in order to play a crucial role in the energy transition, the building sector is expected to establish collaborations across a new supply

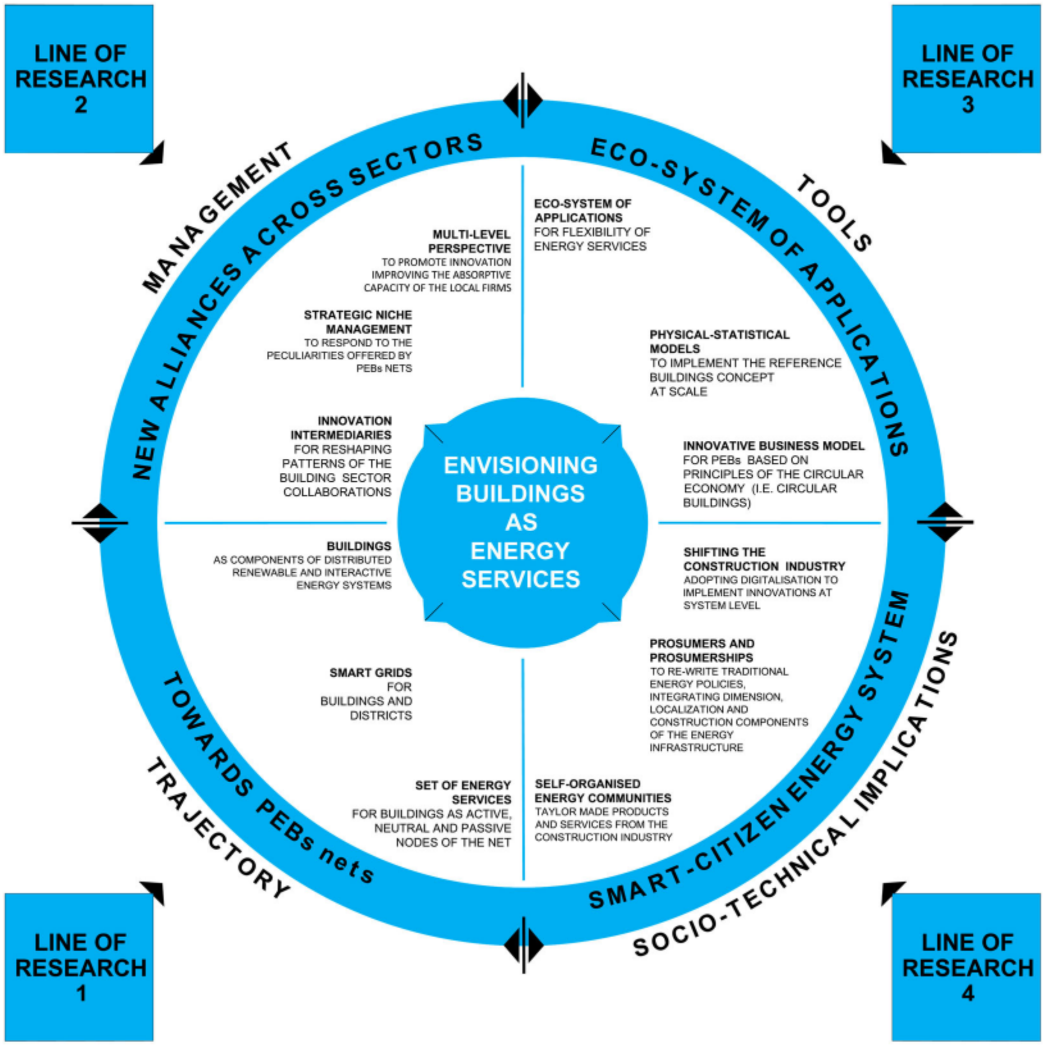


Figure 7. Conceptual framework concerning *Buildings-as-Energy-Service.*

chain, where products (i.e. buildings) and service (i.e. energy supply and exchange) are inextricably interconnected.

This is because the second line of research points out *Management* components, with a special emphasis on the role of innovation intermediaries. Intermediaries can help the building sector to reshape its patterns of collaboration with other domains in order to interpret and respond to the new peculiarities offered by PEBs nets. Then, on these peculiarities, intermediaries may make it easier for the building sector to encourage developments at a system level, taking into account the absorptive capacity of the local firms. According to Sheffer and Levit (2010), this is an ambitious process, and therein lies the relevance of developing strategic niche management for PEBs. Successful examples of new alliances between the construction industry and energy providers (e.g. Azcárate-Aguerre, Den Heijer, & Klein, 2018) have demonstrated that conventional building components (e.g. façades) can be re-thinking in terms of product-service systems. So, strategic niche management will therefore allow the building sector to test and enforce new rules, requisites and alliances *in situ*.

For this reason, the conceptual framework emphasises the role of intermediaries to support local SMEs to be a part of a new supply chain. In line with Kurul et al.'s result, (2012), which stressed the need to improve the absorptive capacity of the SMEs to innovate their products and services, the building sector should better understand the opportunities provided by envisioning *Buildings-as-Energy-Service* in order to be a more competitive and resilient industry. This is possible focusing on technology literacy dissemination, adopting *learning by doing* and *learning by using* approaches (Jensen et al., 2007). This process involves the public (as individuals and community), institutions and industries. As a result of this new form of alliance, new concepts such as *prosumerships* may acquire a broader sense. For example, in contrast with the current literature (e.g. Lowitzsch et al., 2020), *prosumerships* can be adopted to re-write traditional energy policies, integrating dimension, localisation and construction components of the energy infrastructure, which have been separate considerations until now. By doing so, *prosumerships* can act not as a simple business model, but as a process to destabilise fossil-fuel-based coalitions, which is a necessary action towards a low carbon society (Gast, Gundolf, & Cesinger, 2017; Gliedt et al., 2018; Lepoutre & Heene, 2006; Smith et al., 2010).

New alliances involve interactions of a multitude of socio-technical information. This characterises the third line of research, named *Tools*. On the one hand, this line of research establishes the need for transparent procedures to identify the energy quality of every single component of the grid, which are connected to each other. However, within the framework of a distributed energy infrastructure, physical and statistical models would have to provide support in defining the hierarchical classification of these components (i.e. active, neutral, and passive nodes of the grid). This is possible through adopting the concept of ecosystems of applications, which analyses how each component of the system interacts with others. This means to establish new algorithms, which can drive the elaboration of appropriate business models built on human and financial local resources. Therefore, envisioning *Buildings-as-Energy-Service* emerges as a strategy to address environmental and technological innovations in line with the principles of a *Circular Buildings* (Pomponi & Moncaster, 2017). In addition, it comes up as a guide for the building sector to explore, as stressed by Chakuu et al. (2020), what type of supply chain flexibility and economy of repetition can be pursuit, taking part in the process of change.

Therefore, our findings encourage the integration of advanced technical tools. In contrast to prior works, focused on specific aspects such as business models (De Wolf et al., 2017), energy modelling (Bilal et al., 2016; Shang et al., 2017; Zhao & Magoulès, 2012), and prediction methods (Baños et al., 2011; Péan et al., 2019); this study promotes large-scale investigations in order to develop an ecosystem of applications in the built environment for identifying *Reference Building*. Herein, *Reference Building* is considered not only in terms of energy performance but in terms of active, neutral and passive nodes of the energy network. This means to re-think the criteria adopted until now concerning the definition of *Reference Building*. For example, the concept of *grey box* (e.g. Andriamamonjy et al., 2019) can be expanded, taking into account a *Buildings-as-Energy-Service* vision, which can be crucial to the generation of new energy services, urban policies and building codes.

The last line of research focuses on *Socio-technical Implications* as an output of the trajectory of innovation. It highlights the role of the construction industry and energy communities in developing a low carbon society, based on smart citizen-centered energy systems. *Buildings-as-Energy-Service* is pursuing a new generation of buildings; thus, the entire building sector can operate within a new paradigm of building performance, serving as an intermediary of low carbon transition. This means to shift from an industrial sector, which uses to deliver buildings to one that organises local infrastructures. This allows us to envisage a new social role for the construction industry, where the success of its business is closely related to its capacity to promote tailor-made products and services. In doing so, the construction industry would be able to contrast homogenised socio-technical solutions, which are typical of a globalised society and fossil-fuel-based economy. This role is of interest to those European countries that have recently ratified the RED directive (EU, 2018/2001), enabling local communities not only to generate energy but also to exchange it locally (e.g. Self-Organised Energy Communities). This is another step towards affirming *PEBs nets* as a feasible and reliable infrastructure.

Conclusion

This study proposes a new conceptual framework focused on *Buildings-as-Energy-Service* as a key enabler for creating PEBs nets. This conceptual framework aims to re-compose the fragmented scenario of research efforts in low carbon transitions, with a particular focus on the building sector. The unitary framework is organised in four lines of research, respectively focused on: the trajectory of innovation based on a distributed, renewable and intelligent energy infrastructure; the management of new alliances among sectors to put PEBs nets into practice; the need of an ecosystem of applications to model the high level of information, which comes from both social and technical domains; and, the output of this trajectory, which refers to smart citizen-centered energy systems as potential forms of aggregation of prosumers in a low carbon energy system.

Findings highlight the technology literacy as one of the most relevant socio-technical barriers in developing a reliable and competitive low carbon energy system. In particular, they can contribute to re-inventing the role of the building sector as one of the essential components of energy systems and infrastructures. Therefore, the conceptual framework proposed may be considered as a research contribution that could help identifying the emerging properties of evolving socio-technical systems in the built environment, which can revolutionise the approach of designing and managing infrastructures, and delivering innovative products and services in the construction sector. Further, the framework is aimed at promoting the role of intermediaries to establish new alliances among disciplines (e.g. Architecture, Engineering, Construction and Planning) and industrial sectors (e.g. construction and energy industries). This study emphasises the fact that these new alliances should be addressed in order to enhance the spatial, social, and environmental quality of buildings and settlements coherently. By doing so, it will be possible to increase the resilience of the building sector and support the development of a low carbon society.

Further research is needed to clarify the state-of-the-art of multi-perspective integration in envisioning *Buildings-as-Energy-Service*. The conceptual framework elaborated is a part of a broader investigation, which seeks to develop the content of an innovative platform for knowledge exchange and integration. A platform conceived to help operationalising the vision of Buildings-as-Energy-Service. The lines of research elaborated herein were used to define the main structure of the platform, which has been designed to support intermediaries in the ambitious scope to increase the level of technological literacy and awareness among academic and non-academic stakeholders concerning the inter and trans-disciplinary implications related to the proposed concept of *Buildings-as-Energy-Service*. Groups of academic and non-academic stakeholders will test the platform as a final step of this study.

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ORCID

Maurizio Sibilla http://orcid.org/0000-0002-8125-2108

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