Transdisciplinarity in energy retrofit: A conceptual framework.

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This study explores the role of Energy Retrofit (ER) in Low Carbon Transition (LCT). The literature recognises the need to move towards a transdisciplinary approach in ER, which encompasses multidisciplinarity and interdisciplinarity. However, the fragmentation between different disciplines remains a significant problem, mainly due to challenges associated with knowledge exchange across the allied disciplines that play a role in ER. The authors posit that ER projects has been conceptualised and implemented using a Systems perspective so that an integrated approach that is akin to transdisciplinarity could become commonplace. Against this background, the aim of this paper is to establish to what extent ER has been conceptualised as a System in the literature so that complexities can effectively be managed through a transdisciplinary approach. This work is based on a literature review of 136 peer-reviewed journal papers. The content analysis demonstrates that current research on transdisciplinarity in ER can be conceptualised in five categories and 15 lines of research. They are presented as a Conceptual Framework, which is this paper's main contribution to existing knowledge. It reveals the direction of innovation in ER for LCT, and is illustrated as a cognitive map. This map exposes the current fragmentation implicit in the literature, and proposes critical connections that need to be established for a transdisciplinary approach. It also shows that the discourse on LCT changed by moving beyond the building scale; and recognising the need to embrace disruptive and local technologies, and integrating the social and technical aspects of ER. Innovative technical solutions and robust information modelling approaches emerge as key vehicles towards making decisions that pay regard to the economic, social and technical factors and that empower the prosumers to play an active role in LCT.

Keywords: Low Carbon Transition, Energy Retrofit, Knowledge Exchange, Literature Review,

Conceptual Framework

1. Introduction

Energy Retrofit (ER) is widely recognised as a relevant strategy for delivering Low Carbon Transition (LCT) in European countries (Kerr et al., 2017) for two main reasons. First, buildings contribute 38% to the CO2 emissions in Europe (Basbagill et al., 2013). Second, up to 80% of this stock that will be occupied until 2050 in these countries have already been built (Martínez-Molina et al., 2016; King, 2010). Hence, the European Strategic Energy Technology (SET) Plan seeks to retrofit at least 50% of existing public buildings and 50% of all existing buildings in order to achieve sustainability in the built environment (Kylili et al., 2016; Martínez-Molina et al., 2016).

Traditionally, ER is defined as the modification of existing equipment, systems, or buildings to improve their energy performance (ASHRAE TC 1.6, 2016). Webb, (2017) suggests that the typical retrofit actions are concerned with the interactions between the building components. While these actions are relevant, they mainly focus on the technical aspects, often neglecting the social and environmental ones. Systems Theory describes this approach as a reduction of complexity (Delattre, 1984). At a glance, the system appears easier to manage, but it inherits numerous levels of uncertainty. These uncertainties often result in the selection of inappropriate retrofit technologies, and thus in unsuccessful projects (Ma et al., 2012).

One example of failure is the performance gap, which is defined as the difference between predicted energy performance of buildings and actual measured energy use once buildings are operational (De Wilde et al., 2014). This gap can be 2.5 times the predicted energy use (Menezes et al, 2012) and emanates from the uncertainties within the System (De Wilde, 2014; Menezes et al., 2012; Mohareb et al., 2017). It erodes the credibility of the design and engineering sectors of the building industry (Menezes et al., 2012), and leads to general public scepticism of new High Performance Building concepts (Mohareb et al., 2017).

The fragmentation of the building industry also has a role to play in the performance gap. In addition, the diversity of backgrounds, professions, roles, knowledge, experience, objectives and interests means that those involved often have differing perspectives on the goals that need to be achieved and how to achieve them (De Wilde, 2014). Some studies have investigated how these diversities are key influences on construction innovation (Imam et al., 2016; Pinder et al., 2013; Tuohy and Murphy, 2015). Others have explored the need for a progressive integration among technical and non-technical issues as driving factors in reducing the uncertainties of ER actions (Butera, 2013; Cole and Fedoruk, 2015; Salter and Gann, 2003; Whyte et al., 2003). Recent studies (Lu et al., 2017; Soares et al., 2017; Webb, 2017) have demonstrated that an integrated approach to ER across the different disciplines and professions, is a key project success factor.

It is also necessary to integrate the societal and the technical aspects of sustainability (Robertson, 2016). Such integration should bring about the profound alterations to the current social system that the transition towards a low carbon society calls for Geels, (2011). It should take place at the local level, which provides a context in which innovation comes to the fore (Young and Brans, 2017). Focusing on the local level, firstly, means that designing clean and sustainable energy solutions for cities , including ER, cannot be done without engaging local actors (Suzuki et al., 2010). Secondly, it requires new knowledge concerning advanced technologies that drive the transition (Child et al., 2018).

Knowledge exchange lies at the heart of these processes because it facilitates the tackling of problems from a transdisciplinary perspective as advocated by Kirby, (2019) and Sakao and Brambila-Macias, (2018).This perspective requires operational research methods to be combined in a multi-methodological framework that is adapted to the cognitive skills and habits of the stakeholders and experts involved in mutual and joint learning processes (Sibilla, 2017; Wiek and Walter, 2009). It contrasts with the current common practice, which can at best be described as multidisciplinary. Here, the subject matter is considered from individual disciplinary angles, with each discipline providing their input from their own perspective (Koutsikouri et al., 2008). By contrast, interdisciplinary practice refers to situations where the team as a whole solves the problems. Members are willing, and are encouraged, to contribute in areas beyond their own professions.

A common ER language is critical for knowledge exchange but specific tools to establish it do not exist. As a result, the common practice is to focus on technical and technological solutions for ER, predominantly from a mono-disciplinary perspective. The ambitious goal of reducing building GHG emissions by 80% by 2050 (European Commission, 2011), thus remains challenging. Retrofit projects should be conceptualised and implemented as a System for an integrated approach that is akin to transdisciplinarity to become commonplace (Kaatz et al., 2005; Loftness et al., 2009) so that these challenges can be addressed.

Against this background, this study presents a novel Conceptual Framework to facilitate the management of complexity inherent in Energy Retrofit (ER), which is one of the pillars of action in the 2050 Transition to Sustainable Buildings (International Energy Agency, 2013). The research question is: to what extent has ER been conceptualised as a System in the literature so that complexities can effectively be managed through a transdisciplinary approach, which encompasses multidisciplinarity and interdisciplinarity? In response to this question, we pursue the following objectives:

- Classify the current categories and lines of research on the role of the ER towards delivering a mature low carbon society in order to integrate the dominant themes in the spheres of social and physical sciences
- Explore the levels of fragmentation both in research and in practice to establish and improve the strategic role of ER in LCT.
- Represent the emergent and proposed categories and lines of research as a cognitive map, which is a step towards conceptualising ER as a complex system and developing an innovative learning platform for Knowledge Integration.

The next section establishes the current extent of transdisciplinarity in ER through a state-of-the art literature review. Section 3 describes the methodological approach. The key findings of the literature review are discussed in Section 4. The main categories and lines of research on transdisciplinarity in ER are analysed, and new lines of future research are proposed. They are visualised as a cognitive map, which focuses on the strategic role of ER in LCT, in Section 5. The need to deal with the high levels of fragmentation both in research and in practice in ER is argued. Recommendations on how this framework can be put into practice as a specific tool to improve knowledge exchange in ER, are made.

2. Pertinent literature.

Several authors have focussed on promoting energy conservation and sustainability through ER. Ma *et al.*, (2012) have emphasized that a wide range of retrofit technologies are readily available, but identifying the most cost-effective retrofit measures for particular projects remains a major challenge. Yushchenko and Patel, (2017) have evaluated the different methods to assess the energy and environmental performance of buildings (e.g., life-cycle assessment methodologies, generative design methods and retrofitting tools). Jagarajan *et al.*, (2017) have analysed the new role of facilities management as a tool to sustainably manage space. In the main, the unit of analysis is in these studies is individual buildings.

Lund (2012) advocates moving away from this approach and taking into account a whole urban energy system, given the systemic benefits this alternative approach would bring. The challenge is to manage the vast amount of information and the vast array of specialised language that emerges as a result (Volk, Stengel and Schultmann, 2014; Yushchenko and Patel, 2017; Allegrini et al., 2015. Consequently, it becomes increasingly difficult to recognise and prioritise relevant information. Hosseini et al., (2017) have explored innovative applications, including ICT, for generating insights for better decision-making and optimization of processes. These innovations may be linked to ER strategies. Others are in pursuit of developing an integrated approach to ER, particularly with the support of energy modelling. For example, Volk, Stengel and Schultmann, (2014) have promoted the use of Building Information Modelling (BIM) as a tool to manage the complex energy issues in existing buildings, as well as new buildings. They specifically investigated the uncertainties associated with data, which is one of the most important problems in energy modelling of existing buildings. Lu *et al.*, (2017) and Oti *et al.*, (2016) have examined BIM processes as a solution to facilitate the integration and management of information throughout the building life cycle.

Other researchers have focused on new technologies, which are fundamentally changing the approach to urban transformation. For example, Allegrini *et al.*, (2015) reviewed modelling approaches and tools for the simulation of district-scale energy systems, where the recent advances in information and communications technology gain significance. Lawrence *et al.*, (2016) considered a range of complex issues associated with using emerging technologies to integrate energy systems in buildings with a smart grid. Theodosiou *et al.,* (2019) have recently pointed out unconventional thermal bridging problems related to the implementation of PV façades. Parra *et al.*, (2017) point to a new area of interest in energy storage systems located very close to consumers, which opens up an interdisciplinary avenue of research on the role of community energy storage as a key element within the wider renewable energy system. Several authors focus on social aspects of ER. Sovacool and Watts, (2009) argue that a broad spectrum of social, cultural and institutional barriers need to be overcome to acceleration the transition to a low carbon society. For example, Camprubí *et al.*, (2016) has investigated the relationship between the technical aspects of façade insulation; and the political and social contexts. The scope of this study is to explain the variations across different social groups in implementing façade retrofits for energy performance and in their impact on occupants' health. Martínez-Molina *et al.*, (2016) have conducted a literature review on methods and strategies used in order to maintain heritage values of historic buildings, while achieving significant improvements in their energy efficiency. Webb, (2017) have established how the need to improve energy efficiency in historic buildings informed local policies. Olubunmi, Xia and Skitmore, (2016) have explored the role of the financial and non-financial incentives in developing local ER strategies and how these tools are perceived by different local actors (e.g. owners, tenants, government).

Lastly, other authors have focused on the different phases of LCT. Bhowmik et al., (2017) have investigated the relationships between territories and renewable energy systems.

Wang *et al.*, (2017), have proposed a new framework to guide the possible evolution of the building stock in the next century, based on greenhouse gas emissions as the common thread to investigate the potential implications of new design paradigms, innovative operational strategies, and disruptive technologies. This framework emphasizes integration of multidisciplinary knowledge, and proactive approaches considering constraints and unknowns.

Thus, the state-of-the-art review illustrates that the complex dynamic between the different dimensions of ER has not been fully explored. The literature reviewed relates, at best, to a pair of these dimensions, e.g. innovation technology and social change, or energy modelling and life cycle assessment, or ER solution and cultural heritage. Consequently, a framework to conceptualise ER as a complex system is needed. This framework would pave the way towards: 1) establishing future transdisciplinary lines of research in ER with specific reference to Distributed and Renewable Energy Infrastructures evolution; 2) improving the ability to consistently exploiting external knowledge with particular emphasis on Citizen-centred energy systems; and 3) designing socio-technological solutions for deep ER in order to close the (energy) performance gap.

3. Research methods.

This work is based on a literature review, which is a pertinent approach to identifying the research gap in the existing body of knowledge (Tranfield et al., 2003). The literature review is used as the first step of a broader investigation, which seeks to build an innovative cognitive learning platform to facilitate transdisciplinary collaboration in ER. There are three fundamental steps in this investigation: 1) a state-of-the-art literature review, which visualises and conceptualises ER as a complex system and which is the focus of this paper; 2) development of a cognitive learning platform based on step 1; and 3) testing of this platform through the learning experiences of practitioners, researchers and students.

Mayring's, (2000, 2008) phases for content analysis were adapted for the purposes of this study:

- Phase 1: Determining the research domain and selection of related literature. The research domain is Energy Retrofit (ER). It is explored using a set of filters for the database search, which are illustrated in Figure 1. The first filter is ER, which on its own yielded 17.789 papers. The second filter defines the type of the data source, i.e. prominent scientific collections such as Emerald-insight, Sage, Scopus, Springer, Taylor & Francis. Only journal papers published in English were reviewed in order to allow for a comparative analysis. The next step was a Boolean keyword search, where "multidisciplinary" and "interdisciplinary" were used as additional keywords. 585 papers remained after this filtering. Then, the following criteria were used in order to identify the papers which were directly relevant to the research question: 1) Research papers where the ER concept was applied in the field of building and urban transformation. For example, papers that focus on ER in chemical processing were excluded; and 2) research papers where a Multidisciplinary or Interdisciplinary approach was confirmed through a preliminary assessment of the title, keywords and abstract. Additionally, one exclusion criteria was adopted: research papers discussed in Section 2, which were used to identify the gap this literature review closes. Using the criteria explained above, 136 relevant papers on transdisciplinarity in ER were selected to underpin this review.

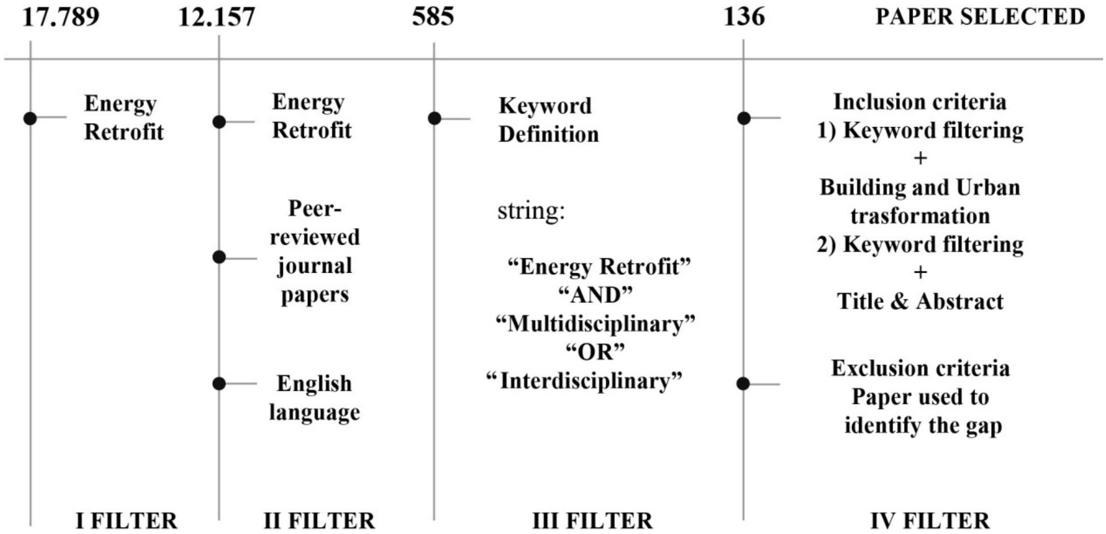

Figure 1. Search process.

- Phase 2: Definition of unit of analysis. Two recording units were used: simple unit and context unit (Table 1). The former includes concepts (i.e words) and patterns (i.e. sentences or paragraphs) used for descriptive analyses; the latter refers to the contextual evaluation of the concepts and patterns. Content analysis was conducted using coding in Nvivo in these units of analysis.

Simple recording unit		Context Unit
Concepts (i.e words)	**Patterns (sentences or paragraphs)**	**Source**
Environment, Planning, Scale, Vision, Innovation, Institutions, Changes, Community, Regeneration, Urban	the complex urban transitions under multiple socio-technical 'regimes', scales and domains within a participatory process.	(Eames et al., 2013)

Table 1. Example of recording units.

- Phase 3: Coding and definition of categories. The categories were established using the inductive method. Here, the inductive method was considered more appropriate than the deductive methods, because the scope of the research was to identify the emerging issues (May et al, 2017) related to ER. As expected, numerous overlaps among the papers were observed during the coding process. In order to reduce the frequency of overlaps, each paper was categorised according to its particular point of view or focus in the field (i.e. Pattern). By doing so, each paper has contributed to the identification and development of a specific theme. After data saturation was achieved on a specific theme, it was defined as a category. There is not a specific rule on how much information is required for the identification and development of a specific topic. Nevertheless, it was deemed reasonable to integrate at least three different points of view on the same theme, in order to define a transdisciplinary category. In this sense, each journal paper was considered to represent a specific point of view in terms of discourse, method or tool. The categories were organized according to the prioritized recording units. The significant relationships within the reviewed body of literature were thus established, while allowing for the introduction of new connections or hierarchical orders. Within a category, the wealth of information on a specific theme has determined the definition of sub-categories. Here, the sub-categories were called lines of research because they point out a current relevant topic about transdisciplinary ER investigation.
- Phase 4: Word-frequency count & identifying the key concepts and their distribution between the different themes as nodes of further interaction levels. In this phase, a set of main concepts were associated with the categories and the lines of research. The main

concepts were identified using word frequency analysis in Nvivo. This analysis was applied on both the categories and the lines of research. The concepts were identified following the procedure, which is illustrated in Figure 2. Firstly, the word frequency criteria were defined. The analysis considers the 10 most frequent words, with a minimum length of 3 letters. All tangential words, date, total, results, however, were discounted from the frequency analysis. Secondly, each concept was associated to a single category (or line of research). The word frequency analysis supports the hierarchical order of each theme within a category. In some cases a concept was the same in two or more different categories. In these cases, a qualitative assessment through content analysis was necessary. The contexts, in which there were references to a theme, were represented as trees through a cluster analysis. So, the most relevant pattern detected for the concepts analysed has determined its category or line of research.

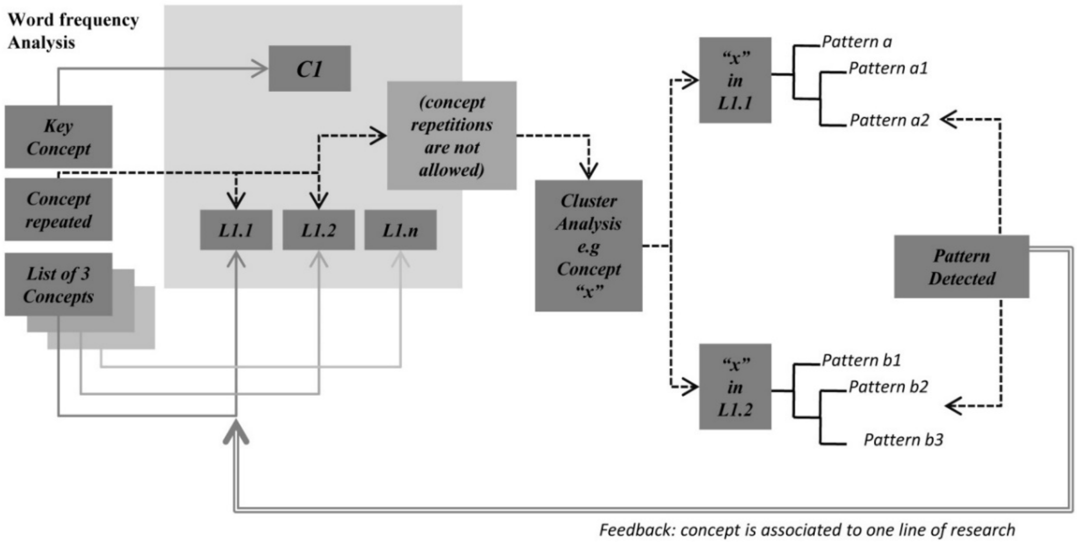

Figure 2. Concepts emerging from categories (C) and lines of research (L).

- Phase 5: Mapping the concepts. Discussion on the themes (and sub-themes), paving the way to a clear future perspective. The emerging themes and patterns and their novel integration with the relevant concepts were presented as a novel cognitive map (Novak and Cañas, 2004) of transdisciplinary in ER. This map reveals the novelty of this investigation, where the role of transdisciplinarity in ER with regard the LCT was highlighted. This map forms the basis for developing a transdisciplinary ER Learning Platform in the next step of this work.

4. Results.

One of the outputs of the literature review is the hierarchical organisation of the categories and lines of research, which are shown in Figure 3. It is composed of 5 categories, e.g. Low Carbon City Transition; 15 lines of research, e.g. Technical & Social Integration; and 50 relevant concepts. It summarises what constitutes current research on transdisciplinarity in ER, as well as relevant, future research themes.

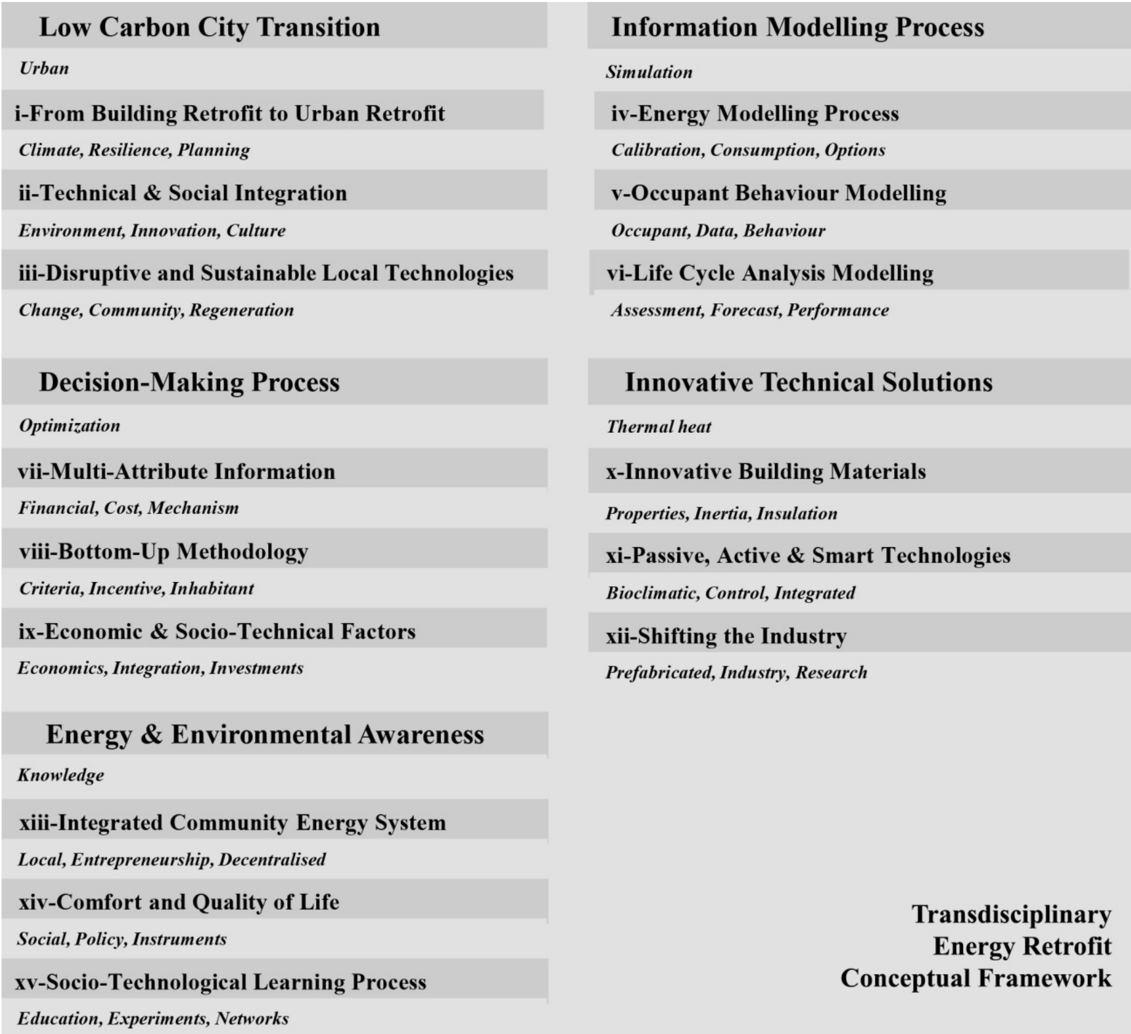

Figure 3. The Conceptual Framework

4.1 Descriptive analysis.

The descriptive analysis illustrated the broad spectrum of the discourse. Table 2 shows the distribution of the papers across different journals, the broad spectrum of specialisms in which ER has been studied, and the hike in interest in transdisciplinary approaches to ER in the five year period from 2013 to September 2017 (Figure 4).

4+ papers		**1 to 4 papers (39 papers in total):**	
Energy and Buildings	39	Automation in Construction,1	Journal of Cultural Heritage,1
Energy policy	11	Advances in Building Energy Research,1	Journal of Industrial Ecology,1
Building Research and Information	10	Applied Thermal Engineering,1	Journal of Urban Technology,1
Renewable and Sustainable Energy Reviews	8	Architectural Science Review,1	Journal of Planning Education and Research,1
Energy	7	Building Research and Information Buildings,2	Land Use Policy,1
Applied Energy	6	Canadian Journal of Civil Engineering,1	Management of Environmental Quality,1
Building and Environment	6	Computers in Industry,1	Philosophical transactions. Series A Mathematical,1
Journal of Cleaner Production	5	Construction and Building Materials,1	Progress in Human Geography,1
Sustainable Cities and Society	5	Construction Innovation,1	Renewable Energy,1
		Energies,2	Research Policy,1
		Energy Conversion and Management,2	Solar Energy,2
		Environment and Planning D: Society and Space,1	Structural Survey,1
		Environmental Science and Policy,1	Technological Forecasting & Social Change,1
		Expert Systems With Applications,1	The Historic Environment: Policy & Practice,1
		Geoforum,1	Urban Design International,1
		Indoor and Built Environment,1	Urban Research and Practice,1
		Journal of Building Physics,3	

Table 2. Distribution across main journals

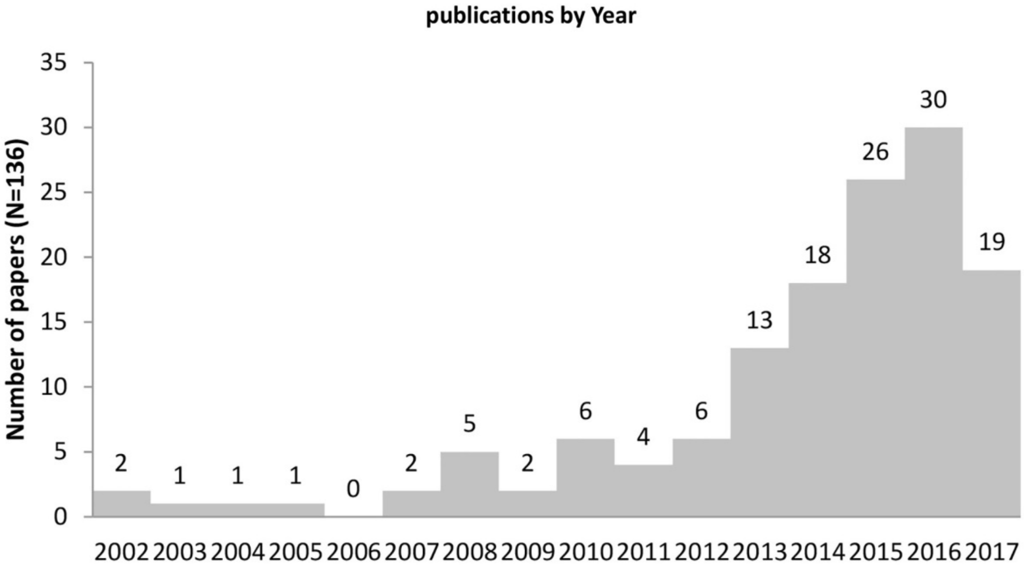

Figure 4. Publication by Year

Table 3 shows the results obtained from the word frequency analysis with regard one specific category (please refer to Annex 1for the complete list). Trivial words were eliminated from the list (e.g. date, number, nouns and others). The words, which were frequently used in all lines of research, were associated to the main categories. The triad of words used to characterise each line of research was determined both using the frequency count and the context in which they were used. Words that were used to elaborate the critical description of the categories and the lines of research proposed were identified to be keywords.

World	Count	Weighted Percentage (%)	Source	Line of Research	Category:
local	470	1.47	(Süsser et al., 2017), (Koirala et al., 2016), (Koirala et al., 2016), (Peck and Parker, 2016), (Rydin et al., 2015), (Gough, 2015), (Van Der Schoor and Scholtens, 2015), (Simpson et al., 2014), (Sauter and Watson, 2007)	Integrated Community Energy System	ER and Energy and Environmental Awareness
community	391	1.22			
integrated	77	0.24			
decentralised	61	0.19			
consumers	56	0.17			
changes	53	0.17			
financial	51	0.16			
municipality	51	0.16			
knowledge	50	0.16			
entrepreneurs	30	0.09			
community	112	1.17	(Santangelo and Tondelli, 2017), (Berry et al., 2014), (Jenkins, 2010), (Walker, 2008)	Comfort and Quality of Life	
consumption	65	0.68			
local	51	0.53			
social	45	0.47			
income	29	0.30			
comfortable	25	0.26			
environment	25	0.26			
policy	25	0.26			
instruments	22	0.23			
knowledge	21	0.22			
planning	59	0.26	(Voytenko et al., 2016), (Kersten et al., 2015), (Petri et al., 2014), (Joss et al., 2013), (KlemeŠ et al., 2013), (Glad, 2012)	Socio-Technological Learning Process	
local	53	0.24			
innovation	51	0.23			
participatory	44	0.20			
integration	43	0.19			
education	29	0.13			
network	28	0.12			
experiments	16	0.07			
universities	14	0.06			
knowledge	12	0.05			

Table 3. Extract of the word frequency analysis

Table 4 provides an overview of the recording unit detected and used to elaborate the Conceptual Framework (please refer to Annex 2 for the complete list).The results were useful to identify the specific contribution each source to the discourse. This analysis provides evidence that the ER concept is mainly characterised by its social and technical aspects in the literature.

Line of Research	References	Recording Unit – Pattern: scope detected
Integrated Community energy system	(Süsser et al., 2017)	the multifaceted interplay between place, local entrepreneurship and 'community renewable energy'.
	(Koirala et al., 2016)	a model-based framework to assess the distributed energy resources-consumer adoption model.
	(Peck and Parker, 2016)	how organisations may implement renewable energies and improve energy efficiency.
	(Rydin et al., 2015)	local energy initiatives identifying barriers, drivers and incentives to explain their emergence (or not).
	(Gough, 2015)	the complementarity of liveability and sustainability at a theoretical level but recognizes that linkage in practice is complex
	(Van Der Schoor and Scholtens, 2015)	the transition towards renewable and sustainable energy focusing on what is happening at the local community level.
	(Simpson et al., 2014)	the variation in operational performance due to the intervention sequence.
	(Sauter and Watson, 2007)	social acceptance of renewable energy innovation
Comfort and Quality of life	(Santangelo and Tondelli, 2017)	the existing energy policy instruments and the current analysis methods in relation to occupant behaviour.
	(Berry et al., 2014) (Jenkins, 2010)	the level of householders' knowledge on smart technologies. the problem of installing non-cost effective measure.
	(Walker, 2008)	the meaning of "community-owned production and use"
Socio-technological learning process	(Voytenko et al., 2016)	how the Urban Living Lab concept is being operationalised in contemporary urban governance for sustainability and low carbon cities.
	(Kersten et al., 2015)	methods to transfer technological knowledge among residents
	(Petri et al., 2014)	a web-based platform solution that provides integrated access to sustainability resources in the form of interactive, user-oriented services
	(Joss et al., 2013)	the 'ubiquitous eco-city' paradigm with strong local contextualisation and social sustainability measures
	(KlemeŠ et al., 2013)	the development of methods and tools, multimedia internet-based teaching and learning programs for future practitioners.
	Glad, 2012)	a socio-technical approach, based on social learning theory in order to examine the energy system transition.

Table 4. Extract of recording units detected.

4.2 Content analysis.

The content analysis and the resultant Conceptual Framework are discussed in this section. It is structured around the categories and the lines of research.

4.2.1 ER and low carbon city transition.

The references in this category are listed in Table 5. The key consideration is the relationships between ER actions and low carbon transition. The frequency analysis yields 'urban' as the key concept. Therefore, the content analysis provides three relevant lines of research, where the deep renovations discussed in this context are concerned with both technical and non-technical strategies, which relate to the large-scale retrofit of buildings to improve their energy efficiency.

References	Concepts detected	Key Concept	Line of Research	Category:
(Cajot et al., 2017), (Gregório and Seixas, 2017), (Becchio et al., 2016) , (Wu et al., 2016), (Magrini and Franco, 2016), (Gupta et al., 2015), (Mazzarella, 2015), (Jennings et al., 2014), (Dixon and Eames, 2013), (Mehaffy, 2013), (Bai, 2007)	Climate Resilience Planning	Urban	From Building Retrofit to Urban Retrofit	ER and Low Carbon City Transition
(Gianfrate et al., 2017), (van Krugten et al., 2016), (Broto, 2015), (Cosmi et al., 2015), (Dall'O' et al., 2013), (Head, 2010), (Kelly, 2010), (Smith et al., 2010), (Moffatt and	Environment Innovation Culture		Technical and Social Integration.	

Kohler, 2008)				
(Fonseca et al., 2016), (Glackin and Dionisio, 2016), (Dixon et al., 2014), (Eames et al., 2013),(Mills, 2003)	Change Community Regeneration		Disruptive and Sustainable Local Technologies	

Table 5. Low carbon city transition category and lines of research

4.2.1.1 From Building Retrofit to Urban Retrofit.

The documents categorized in this line of research support a fundamental step in ER, from improving building performance towards Urban Retrofit, as a set of strategies to improve the resilience of the local settlements to address global concerns associated with Climate Change. This approach seeks to reduce the risks, which are often considered at individual building level, that fragmentation yields. The need for a much more coordinated and strategic approach to improving energy performance at-scale, and at city and neighbourhood levels is acknowledged. Urban planning is called to provide strategic approaches which will facilitate economies of scale for energy saving and funding.

4.2.1.2 Technical and Social Integration.

This line of research classifies several papers in which the interactions between technical and social innovations in the ER sector emerge. The discussion focuses on disseminating environmental awareness among all the actors (i.e. public, private, communities, industries). It is argued that each actor could play a specific role in low carbon transition but the difficulty of achieving integration between these actors is acknowledged. Consequently, economic considerations take precedence. But, in the last decade, increased uptake of information and communication technologies seems to have supported a better alignment between the actors, promoting an innovative culture. This innovation is becoming the main tool to improve both environmental qualities and the quality of life.

4.2.1.3 Disruptive and Sustainable local technologies.

The title of this line of research is borrowed from Dixon, Eames, Britnell, Watson, & Hunt (2014). It expresses the need to work across the disciplinary boundaries of ER rather than strengthening disciplinary silos. The reviewed papers demonstrate that the diffusion of smart technological solutions is facilitating information diffusion. However, the effective use and integration of this vast array of information represents a clear challenge. Consequently, the need to identify relevant information and appropriate sustainable local technologies remains. Glackin and Dionisio, (2016) suggest deep engagement of local communities in order to bring about the change towards the low carbon society through processes of regeneration.

4.2.2 Information modelling process.

This category comprises the studies which have developed methods and tools in order to optimize processes and products related to ER actions. Simulation, which centres around reducing the level of uncertainties, is the key concept. It is widely accepted that these uncertainties undermine not only the environmental qualities, but also the investment opportunities and urban energy policies. So, in order to reduce the level of uncertainties three transdisciplinary lines of research have been underlined. The references are organized in Table 6.

References	Concepts detected	Key Concept	Line of Research	Category:
(Cao et al., 2017), (Heidarinejad et al., 2017), (Wu et al., 2017), (Alwan, 2016), (García Kerdan et al., 2016), (Marasco and Kontokosta, 2016), (Munarim and Ghisi, 2016), (Bomberg et al., 2015), (De Lieto Vollaro et al., 2015), (Dineen et al., 2015), (Hsu, 2015), (Fawcett and Killip, 2014), (Wang et al., 2014), (de Wilde and Tian, 2012), (Heo et al., 2012), (Lawrence et al., 2012)	Calibration Consumption Options	Simulation	Energy Modelling Process	ER and Information Modelling Process
(Mohareb et al., 2017), (Roberti et al.,	Occupant		Occupant	

2017), (Parker et al., 2017), (Gupta and Gregg, 2016), (Hong et al., 2016), (Terés-Zubiaga et al., 2016), (Yan et al., 2015), (Rhodes et al., 2015), (Tianzhen Hong et al., 2014), (Chuah et al., 2013), (Neto and Fiorelli, 2008), (Yalcintas, 2008), (Bazjanac, 2004)	Data Behaviour		Behaviour Modelling	
(Fedoruk et al., 2015), (Beccali et al., 2013), (Peuportier et al., 2013), (Ardente et al., 2011), (Dong et al., 2005)	Assessment Forecast Performance		Life Cycle Analysis Modelling	

Table 6. Building information modelling process category and lines of research

4.2.2.1 Energy modelling process.

This line of research includes papers which have investigated the methods and tools for energy modelling processes. There is a specific reference to calibrating the modelling to reflect actual consumption as closely as possible. Hence, developing a framework for simulating energy consumption is one of the key concerns. Traditionally, the energy modelling has been focused on the building scale, analysing mainly the building envelope and its interactions with the M&E systems. In contrast, the most advanced experiences in ER seek to assess the available options, taking into account the influence of the internal and external factors of the building, the environmental impact of technological solutions in the long term and the potentialities for large scale investments in energy retrofit of buildings. Nevertheless, these variables are often interpreted differently among disciplines, datasets and contexts. The improvement of these tools is ongoing.

4.2.2.2 Occupant behaviour modelling

This line of research focuses on the role of occupant behaviour within the modelling process and so, the use of representative data. Traditionally, in ER, energy efficiency issues are overemphasized, while other key issues, e.g. health and comfort of occupants associated with indoor air quality and noise levels, received less attention. Moreover, traditional energy models rely on predictive indicators and assumptions that are usually made at the design stage, without acknowledging behavioural patterns of actual users. Recently, occupant behaviour has been recognised as an important element of a transdisciplinary approach. Here the aim is to provide a detailed understanding of user behaviour in a specific local context.

4.2.2.3 Life cycle analysis.

This line of research highlights the interaction between the life cycle approach and the ER actions. The key concept is the assessment of performance over the life cycle of buildings. The importance of appropriate building energy monitoring capabilities, of the understanding of energy system boundaries in design and analysis, of closing the gaps between different the stages of a building's life cycle, and of feedback loops throughout design and operation, have been acknowledged. The research reveals the complexity of assessing the impact of embodied energy in retrofit actions. This assessment involves: construction materials and components used during ER, the main components of conventional and renewable energy systems, the impact of the building technology used in the different elements of a building, and as a whole.

4.2.3 Decision-making process

Under this category there are papers which are focused on systematic methodologies and corresponding tools to support innovative decision-making in ER. The integration of various improvement options, including new technologies, urban infrastructure, as well as, energy and market policies are discussed. Multi-Optimization is the main concept, which refers to integrated process analysis in ER. The content analysis yields three relevant lines of research. The references are organized in Table 7.

References	Concepts detected	Key Concept	Line of Research	Category:
(Ascione et al., 2017a), (Ascione et al.,	Financial	Optimization	Multi-Attribute	ER and

2017b), (Broderick et al., 2017), (Tadeu et al., 2016), (Tariku et al., 2015), (Shao et al., 2014), (Taehoon Hong et al., 2014), (Xu et al., 2014), (Kumbaroğlu and Madlener, 2012), (Kanapeckiene et al., 2011), (Diakaki et al., 2010), (Diakaki et al., 2008)	Cost Mechanism		Information	Decision-Making Process
(Yushchenko and Patel, 2017), (Vilches et al., 2017), (Delmastro et al., 2016), (Kontokosta, 2016), (Shen et al., 2016), (Trencher et al., 2016), (Senel Solmaz et al., 2016), (Mauro et al., 2015), (Yang et al., 2015), (Vlasova and Gram-Hanssen, 2014), (Asadi et al., 2011), (Kolokotsa et al., 2009)	Criteria Incentive Inhabitant		Bottom-up Methodology	
(Ahmed et al., 2015), (Shakouri et al., 2015), (Asadi et al., 2014), (Ballarini, Corgnati and Corrado, 2014), (Eriksson et al., 2014)	Economics Integration Investments		Economic and Socio-Technical Factors	

Table 7. Decision-making process category and lines of research

4.2.3.1 Multi-attribute information.

This line of research includes the optimization of methods and tools for gathering multi-attribute information. Traditionally, the multi-attribute information in the ER field was applied in order to determine the optimal solution in terms of the cost of investment. Recently, new multi-attribute decision-making methods have been developed in order to prioritize the alternatives of comparative projects quite accurately. Currently the multi-attribute information in ER seeks to define the local mechanisms, which help to optimize the solution.

4.2.3.2 Bottom-up methodology.

This line of research underlines the importance of the bottom-up methodology to aid decision-makers in the energy planning process. New bottom-up methodologies seek to improve voluntary and regulatory approaches and develop new planning processes for urban resilience. In such a scenario, the policies are called: to identify the local criteria for successful renovation packages; to consider the local incentives for policy implementation; and, to identify local renovation packages that need to be prioritized from the point of view of the locals.

4.2.3.3 Economic and socio-technical factors

This line of research seeks to place emphasis on the economic and socio-technical factors which are associated with ER actions. An example is represented by the integration of renewable energy systems, e.g. PVs, at scale. In this context, the economic and socio-technical factors are strongly related to each other. Consequently, neglecting this relationship can influence the investment capacity and consequently reduce the success of retrofit actions.

4.2.4 ER and innovative technical solutions

The papers in this category describe several technical innovations concerning the building envelope, the M&E systems, users and their interactions. Insulation is the main concept and this category explains how technical solutions for insultation involve transdisciplinary goals. Such transdisciplinarity is here presented by the following lines of research. The references are organized in Table 8.

References	Concepts detected	Key Concept	Line of Research	Category:
(Tovarović and Ivanović-Šekularac, Jelena Šekularac, 2017), (Berardi, 2016), (Pérez-Urrestarazu, Luis Fernández-Cañero, Rafael Franco-Salas and Egea, 2016), (Aste et al., 2015), (Saber et al., 2015), (Ascione et al., 2014)	Properties Inertia Thermal heat	Insulation	Innovative Building Materials	ER and Innovative Technical Solutions
(Carlos, 2017), (Eliopoulou and Mantziou, 2017), (Biyanto et al., 2016), (Cuce, 2016), (Evola and Margani, 2016), (Hengstberger et al., 2016), (Si et al., 2016), (Giovanardi et al., 2015), (Monetti et al., 2015), (Smith	Bioclimatic Control Integrated		Passive, Active and Smart Technologies	

and Svendsen, 2015), (Capeluto and Ochoa, 2014), (Moran *et al.*, 2014), (Häkkinen, 2012), (Halawa, 2009), (Hestnes and Kofoed, 2002), (Santamouris and Dascalaki, 2002)				
(Carbonaro et al., 2016), (Thomsen et al., 2016), (Li et al., 2013), (Ochoa and Capeluto, 2015), (Rovers, 2014), (Silva et al., 2013), (Xing et al., 2011), (Aouad et al., 2010)	Prefabricated Façade Research		Shifting the Industry	

Table 8. Innovative technical solutions category and lines of research

4.2.4.1 Innovative building materials.

Traditionally, the energy performance of building materials is discussed with regards to their thermal properties, e.g. transmittance, inertia and specific heat. These properties are used to analyse the steady-state or dynamic state in order to reveal the building energy behaviour under determined conditions. This line of research extends the interaction to a transdisciplinary investigation, which include environmental and ecological issues. These interactions concern the embodied energy inherent in retrofit choices, e.g. natural insulation, as well as, construction systems, e.g. green roofs and vertical greening systems. In particular, these systems are recognised as optimal retrofit solutions in order to mitigate the urban heat island affect. Consequently, this line of research reinforces, again, the importance of economies of scale, starting from a confined technical solution.

4.2.4.2 Passive, active and smart technologies.

This line of research focuses on the integrated strategies among passive, active and smart energy technologies in order to improve buildings' energy efficiency and the quality of life. Traditionally, the indoor air comfort and energy performance are considered to be strongly related, but only recently the user's understanding of available technologies has started to play a central role. Smart devices have allowed the customization of both the passive and active energy systems, as well as remote controlling of the engineering devices which can govern bioclimatic parameters, i.e. solar and ventilation, for optimisation.

4.2.4.3 Shifting the Industry.

It is commonly accepted that the building industry could play an important role in reducing buildings' environmental impact. The importance of social, economic and environmental measures in reducing this impact is highlighted. The experiences reveal that the competitiveness of the industry relies on the development of: Systems to, for example, capture CO_2 from the polluting industrial processes, e.g. cement manufacture; Low cost technical solutions for interventions on existing buildings e.g. prefabricated modules for energy retrofit; A more consistent dialogue between the industry and research centres, adopting an integrated multi-objective design process.

4.2.5 Energy and environmental awareness.

This category collects works which have focused their investigation on methods and tools to improve energy and environmental awareness among the actors who are involved in the urban regeneration process. The main concept in this category is Knowledge. A distinction between the knowledge of communities and of users is made. In addition the roles of practitioners, researchers and the industry have been examined. Three lines of research have emerged as representative of transdisciplinarity in ER. The references are organized in Table 9.

References	Concepts detected	Key Concept	Line of Research	Category:
(Süsser et al., 2017), (Koirala et al., 2016), (Peck and Parker, 2016), (Rydin et al., 2015), (Gough, 2015), (Van Der Schoor and Scholtens, 2015), (Simpson et al., 2014), (Sauter and Watson, 2007)	Local Entrepreneurship Decentralised	Knowledge	Integrated Community Energy System	ER and Energy and Environmental Awareness
(Santangelo and Tondelli, 2017), (Berry et al., 2014), (Jenkins, 2010), (Walker, 2008)	Social Policy		Comfort and Quality of Life	

	Instruments		
(Voytenko et al., 2016), (Kersten et al., 2015), (Petri et al., 2014), (Joss et al., 2013), (KlemeŠ et al., 2013), (Glad, 2012)	Education, Experiments Networks	Socio-Technological Learning Process	

Table 9. Energy and environmental awareness category and lines of research

4.2.5.1 Integrated Community energy system

Recently, the importance of socio-geographic places of energy transition is emerging as a key factor in developing efficient retrofit actions. In particular, one of the emerging topics is the multifaceted interplay between place, local entrepreneurship and community. Integrated community energy systems, are emerging as a modern economic and social development to re-organize local, renewable and decentralized energy systems. The new energy scenario allows the simultaneous integration of distributed energy resources through the engagement and acceptance of local communities.

4.2.5.2 Comfort and Quality of life.

Strategies to promote behaviour change are investigated. The results point out that the relation between comfort and quality of life can be interpreted in several ways. On the one hand, some smart technologies have been successfully applied and integrated in ER actions in order to improve the energy performance of buildings. On the other hand, fuel poverty exists and renders reduced consumption a secondary issue. In the first case, the behaviour of end-users is particularly important in terms of the reliability and user-friendliness of the energy technologies. The level of satisfaction of the end-users and their confidence in using smart devices are the main topics investigated. In the second case, the need to move from behaviour change to systemic change in order to develop energy policies to eradicate fuel poverty is highlighted. Therefore, the environmental considerations go hand in hand with the social need to reduce inequalities.

4.2.5.3 Socio-technological learning process

A new set of complex urban issues, e.g. urban energy transition, have emerged, resulting in the need for knowledge transfer. Citizen-centred energy systems are likely to attract more interest in the near future. Citizens will need to be better educated on technological aspects of reducing energy consumption. Both experts and non-experts are called to expand their ability to transfer and acquire information. At the same time, the future practitioners will be called to manage material and immaterial processes in an inter-disciplinary manner. New forms of technology education are emerging through experiments which are focused on improving the technological knowledge of local communities, e.g. Urban Living Labs. Nevertheless, there is a need to clarify what makes these new approaches attractive and novel for this socio-technological transition. Their role in this transition also needs to be defined.

5. Discussion.

Transdisciplinarity has been a concern for academics in the field of Cleaner Production and Sustainability (see for example Sakao and Brambila-Macias, (2018) and Kirby, (2019). The purpose of this paper is to explore transdisciplinarity inherent in ER. Here, ER is envisaged as an approach to 'cleaner production' which could play a significant role in LCT. Our framework:

a) facilitates going beyond the obsolete technical concept of ER, and promoting it as a socio-technical system to achieve a low carbon society;

b) becomes a starting point, to build up an innovative learning platform for knowledge integration in ER in order to deal with fragmentation that affects ER actions.

This discussion evaluates the main features introduced by the Conceptual Framework, and how these features may be relevant in the design-for-sustainability context.

5.1 Novelties of our Conceptual Framework.

This is one of the first studies to explore the transdisciplinarity inherent in ER. Our study underscores the importance of facilitating knowledge exchange in ER, to further elucidate the interconnections between the new dimensions of ER, e.g. Distributed and Renewable Energy Infrastructures and Citizen-centred energy systems. Our findings seek to conceptualize ER such that the level of uncertainties associated with it can be reduced. How this can be achieved is discussed under the different categories of the Conceptual Framework.

The first category, i.e. Low carbon city transition, clarifies *what is changing*. ER at scale is offered as a way of addressing global climate concerns, which brings global issues to the local level. In particular, the lines of research show that an innovative dimension of ER actions should consider the built environment as a socio-ecological system, in which ER is a strategy to develop the adaptation capacity of the local community, promoting social, cultural and technical innovation. In this context, the disruptive and sustainable local technologies encourage regeneration of the settlements, emphasizing the need for more proactively seeking external knowledge and coordination among diverse actors and industry groups. Therefore, the most significant change, underlined by the transdisciplinary perspective, lies in the connections between the ability to involve consistent parts of cities, which need to improve their energy and carbon emissions profiles with creative strategies to stimulate the participation of local actors (Mat et al., 2016; Suzuki et al., 2010; Young and Brans, 2017).

The second category, i.e. Information modelling process, suggests *what we need* to deal with the vast amounts of data that accumulate as a result of tackling the issues from a whole urban energy system perspective. Recognising and prioritising relevant information requires innovative ICT applications (Lund, 2012). While tools for gathering vast amounts of information have been developed (e.g. Volk, Stengel and Schultmann, 2014; Yushchenko and Patel, 2017; Allegrini *et al.*, 2015), the managerial skills to exploit this data in ER are often neglected.

The third category, i.e., Decision-making process, explains *how we manage*. The Conceptual Framework pointed out how the multi-attribute information approach seeks a network synergy effect, to take financial, human, local and technical resources into account. The results showed that the new approaches aim to improve the skills of the local community to understand the value of the local resources, the investment opportunities and the benefit of ER actions. Thus, the Conceptual Framework contributes to promoting the integration of smart products and e-services in order to satisfy the needs of individual consumers, reduce the environmental impact of the construction industry, and closing the (energy) performance gap.

The fourth category, i.e., Innovative Technical Solutions, expresses *what we implement*. The emergent lines of research point to the convergence of efforts to improve energy performance and to retain ecological and historic qualities of the buildings and settlements through the integration of smart devices and systems (i.e. micro-grids, smart buildings, see for example Theodosiou et al. (2019), Lawrence *et al.*, (2016) and Parra et al., (2017).

The fifth category, i.e. Energy and environmental awareness, emphasizes *the outputs* and closes the loop. In other words, this category deals with the level of fragmentation between the different domains of knowledge, which involves technicians, lay people and institutions (e.g. Sovacool and Watts, (2009). This type of fragmentation emanates from the barriers to transferring the outputs of experimental actions into common practice. This transfer can be impracticable due to community resistance, the inappropriateness of policies and the lack of dialogue between disciplines and sectors. As a consequence, the development of tools to stimulate this dialogue becomes a priority.

In the near future, these lines of research are expected to be integrated. Accordingly, a new frontier of ER actions, which involves a new set of organizational rules and new knowledge for the actors engage in LTC, will emerge. This innovative collaboration will require a Technology Support Network (Zeleny, 2012, 1986). This network consists of work rules, task rules, requisite skills, work content, standards and measures, styles, culture and organizational patterns (Zeleny, 2012). It will have to be developed in situ, and Knowledge will have to be produced within the specific local context (Zeleny, 2009). Thus, this contribution provides a new insight into improving the ability to consistently exploit external knowledge, promoting socio-technological solutions for deep ER in order to close the (energy) performance gap. This Conceptual Framework illustrates that ER research mainly requires a new -dimension of

Knowledge Exchange, which in this study refers to a new dimension of the relationships associated with ER actions that are illustrated in Figure 5. Our Conceptual Framework offers an organized and systemic view of the relationships between ER actions, exploring the components involved and clarifying the key elements of the process for further implementation.

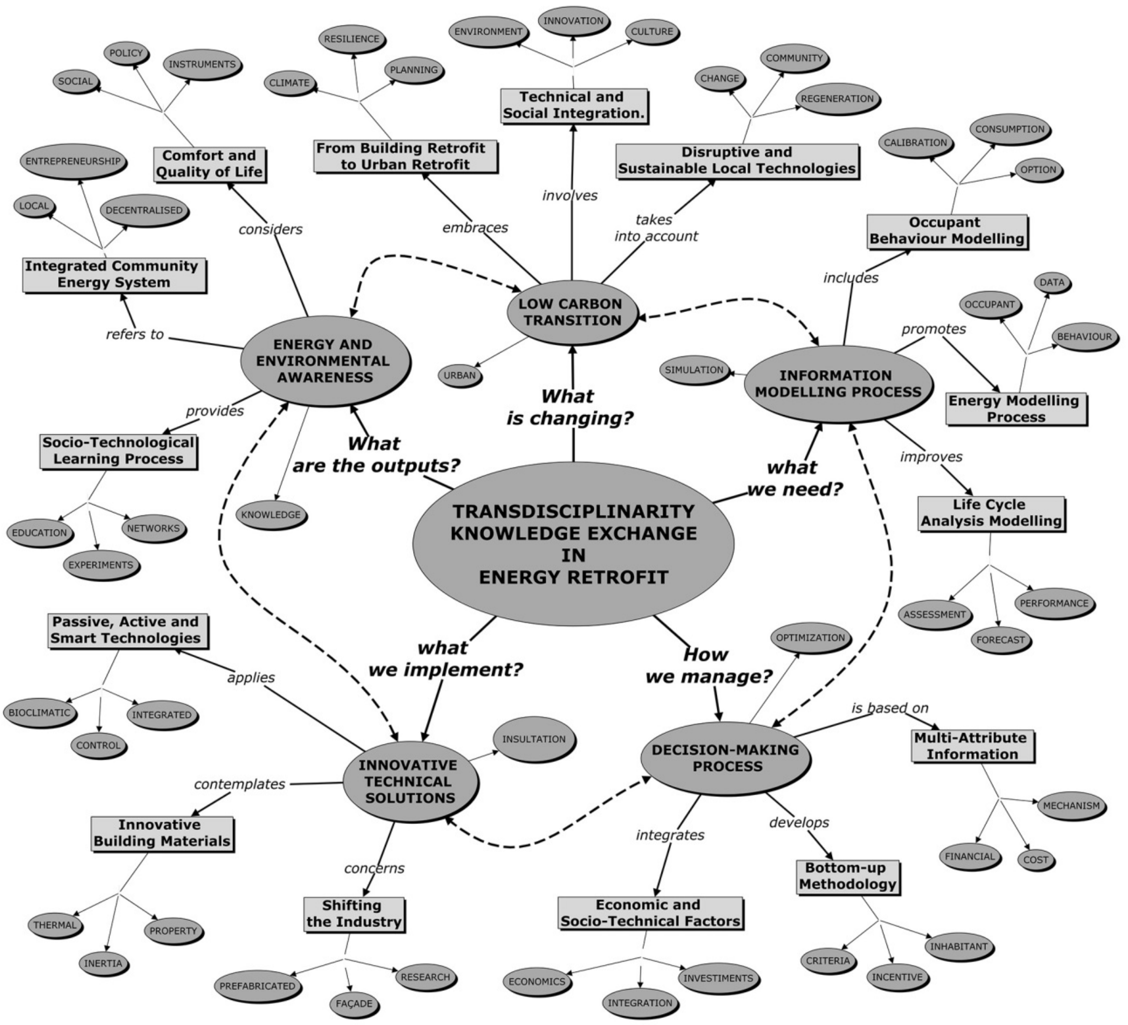

Figure 5. The Transdisciplinary Energy Retrofit Conceptual Framework as a cognitive map

As pointed out in the introduction, the transition towards a low carbon society requires profound alterations to the current social system as a whole (Child et al., 2018; Geels, 2011; Robertson, 2016). Therefore, a new trend which takes into account ER as a socio-technical system, may have an important influence on the decentralized and renewable energy system. Under this circumstance, the role of Built Environment Professionals, as main intermediaries, who act at the local level to involve technicians, lay people and institutions in the implementation of Technology Support Networks may be identified as a new trend. Kivimaa et al., (2019) define 'transition intermediaries' as those that mediate a sector towards a systemically new and more sustainable socio-technical configuration. Hence, importance of providing a Transdisciplinary ER Conceptual Framework, which can support a better understanding of the context-specific factors affecting the ER as a tool for low carbon transition, comes to light again. The next phase of our study will move from a Transdisciplinary ER Conceptual Framework to a Cognitive Learning Platform. This platform is designed to develop new skills for the future Built Environment Professionals for achieving sustainable development.

5.2 Future research

Knowledge Exchange in ER is undoubtedly related to a new energy infrastructure paradigm, as a more resilient and ecologic system to support the LCT. This point of view inherits the opportunity to apply the Conceptual Framework in practice. We move from a desk-based exploration and evaluation, towards a process which seeks to support knowledge transfer within networks through which ER is undertaken. Thus, the Conceptual Framework has the potential to stimulate an inclusive debate. It can be used to enable the network of actors in ER access interdisciplinary knowledge. Although this access is necessary, it does not, on its own, result in knowledge transfer. New cognitive abilities should be developed to facilitate knowledge transfer within ER networks.

Cohen and Levinthal, (1990) define these abilities as absorptive capacity. Absorptive capacity implies the ability to recognize the value of new, external information, assimilate it, and apply it in a particular context. The ability to exploit external knowledge is thus a critical component of innovative capabilities (Cohen and Levinthal, 1990). The papers analysed in this study strongly stress the role of absorptive capacity in facilitating cross-disciplinary interactions. Nevertheless, studies that examine an organization's ability to acquire new, external knowledge and to transfer it through its network of actors are limited. Hence, the new conceptualisation should facilitate the move from a hierarchical organization of complex topics towards a knowledge transfer network (Figure 6).

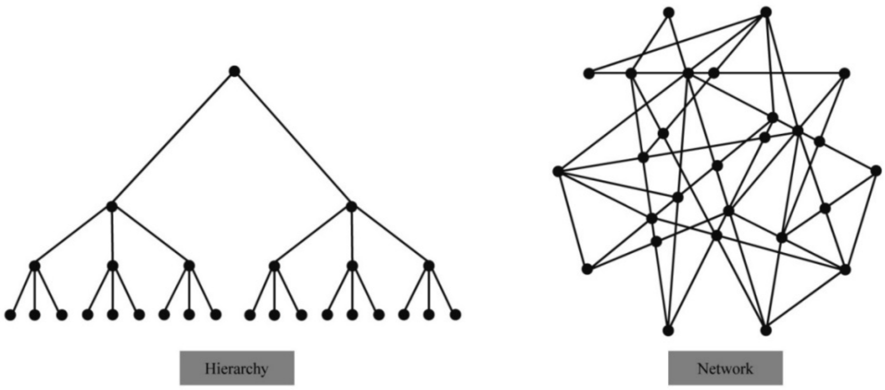

Figure 6. From a hierarchy model of the knowledge towards a network of knowledge transfer.

So, what is the challenge in the near future? Ismail, Keumala and Dabdoob, (2017) argue that future professionals need to be better equipped with advanced technical skills in order to deliver sustainability. Moreover, a better understanding of the integration issues with regards to sustainability need to be developed in higher education (Adams et al., 2018). Higher education is called to develop a new generation of practitioners, who will become the actors in the knowledge transfer networks. These future actors should be able to manage the complex layers of technical and social issues that relate to sustainability. In addition, future researchers and practitioners interested in LCT could play an important role in organizing a technology support network for sustainability (Sibilla and Kurul, 2018).

The next step for the authors is to identify and test an approach to transform this Conceptual Framework to a tool to facilitate effective knowledge exchange through such networks. While the methodological approach adopted herein may be considered in continuous evolution through a sequence of saturation process (Strauss and Corbin, 1990), a new key question emerges: how can the absorptive capacity of future researchers and practitioners be improved? The combined use of the cognitive approach and meaningful learning activities to transform the Conceptual Framework to a cognitive interdisciplinary learning platform is a possible solution. This aspect will be explored in the next phase of this research.

6. Conclusions

Although the literature recognises the need to move towards a more collaborative approach in

ER, the fragmentation between different disciplines remains a significant problem. A critical analysis of 136 journal papers was used as the basis of a Conceptual Framework on the extent of multidisciplinary and interdisciplinary approaches currently adopted in ER at both the urban and building levels. Thus, 5 categories, 15 lines of research and 50 main concepts have been identified and discussed in order to better understand the role of the ER towards delivering a mature low carbon society. The Conceptual Framework clearly identified the components that are relevant to the transition towards a decentralized sustainable energy system.

Here, *knowledge exchange* in ER research has been underlined as an emerging topic, which can facilitate transdisciplinarity in ER. Following this view, the actors involved in the ER actions will be called to improve their ability to transfer knowledge across disciplinary domains. Hence, bridging the *Knowledge gap* among the actors emerged as a key issue in establishing and sustaining a Technology Support Network to improve the retrofit actions at scale in pursuit of LCT.

Specifically, the results of the literature review have emphasized the interactions among ER actions and the emerging technologies, such as the decentralized sustainable energy systems. They clearly show that this new energy paradigm can successfully be disseminated at local level if, and only if, a new organized system, which involves researchers, practitioners, industries, governance and citizens as parts of a Technology Support Network, is developed. This approach is in contrast with the current approach to viewing the issues as sectorial engineering problems. The focus on improving the energy performance of individual buildings in order to reduce the carbon emissions from the building sectors across the Globe, is outdated. The new vision should encompass a complex set of strategies to achieve a mature low carbon society.

This study into transdisciplinarity in ER has pointed out that several typologies of the *performance gap* exist as obstacles for a mature low carbon society. A new perspective which conceptualises the *performance gap* as a *knowledge gap* is proposed to deal with fragmentation at different levels. While the *performance gap* illustrates the inconsistencies between building performance at different stages of its life, the *knowledge gap* refers to the local actors' ability to manage ER within a wider and complex LCT agenda. In other words, the *knowledge gap* relates to the local capacity to organize a technology support network.

Finally, the paper has proposed a new direction of investigation, which moves from the Conceptual Framework towards an innovative learning platform in order to provide a new tool to train the next generation of researchers and practitioners, who will become members of the Technology Support Network. The focus of this learning is to develop a better understanding of collaboration in a complex built environment.

References

Adams, R., Martin, S., Boom, K., 2018. University culture and sustainability: Designing and implementing an enabling framework. J. Clean. Prod. 171, 434–445.

Ahmed, S., Elsholkami, M., Elkamel, A., Du, J., Ydstie, E.B., Douglas, P.L., 2015. New technology integration approach for energy planning with carbon emission considerations. Energy Convers. Manag. 95, 170–180.

Allegrini, J., Orehounig, K., Mavromatidis, G., Ruesch, F., Dorer, V., Evins, R., 2015. A review of modelling approaches and tools for the simulation of district-scale energy systems. Renew. Sustain. Energy Rev. 52, 1391–1404.

Alwan, Z., 2016. BIM performance framework for the maintenance and refurbishment of housing stock. Struct. Surv. 34, 242–255.

Aouad, G., Ozorhon, B., Abbott, C., 2010. Facilitating innovation in construction. Constr. Innov. 10, 374–394.

Ardente, F., Beccali, M., Cellura, M., Mistretta, M., 2011. Energy and environmental benefits in public buildings as a result of retrofit actions. Renew. Sustain. Energy Rev. 15, 460–470.

Asadi, E., Da Silva, M.G., Antunes, C.H., Dias, L., 2011. Multi-objective optimization for building retrofit strategies: A model and an application. Energy Build.

Asadi, E., Silva, M.G. Da, Antunes, C.H., Dias, L., Glicksman, L., 2014. Multi-objective

optimization for building retrofit: A model using genetic algorithm and artificial neural network and an application. Energy Build. 81, 444–456.
Ascione, F., Bianco, N., De Masi, R.F., De Rossi, F., Vanoli, G.P., 2014. Energy refurbishment of existing buildings through the use of phase change materials: Energy savings and indoor comfort in the cooling season. Appl. Energy 113, 990–1007.
Ascione, F., Bianco, N., De Masi, R.F., Mauro, G.M., Vanoli, G.P., 2017a. Resilience of robust cost-optimal energy retrofit of buildings to global warming: A multi-stage, multi-objective approach. Energy Build. 153, 150–167.
Ascione, F., Bianco, N., De Stasio, C., Mauro, G.M., Vanoli, G.P., 2017b. Artificial neural networks to predict energy performance and retrofit scenarios for any member of a building category: A novel approach. Energy 118, 999–1017.
ASHRAE TC 1.6, 2016. ASHRAE Terminology: A Comprehensive Glossary of Terms for the Built Environment. [WWW Document]. URL https://www.ashrae.org/resources--publications/free-resources/ashrae-terminology (accessed 11.9.17).
Aste, N., Leonforte, F., Manfren, M., Mazzon, M., 2015. Thermal inertia and energy efficiency – Parametric simulation assessment on a calibrated case study. Appl. Energy 145, 111–123.
Bai, X., 2007. Integrating Global Environmental Concerns into Urban Management. J. Ind. Ecol. 11, 15–29. doi:Article
Basbagill, J., Flager, F., Lepech, M., Fischer, M., 2013. Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts. Build. Environ. doi:10.1016/j.buildenv.2012.11.009
Bazjanac, V., 2004. Building energy performance simulation as part of interoperable software environments, in: Building and Environment. pp. 879–883. doi:10.1016/j.buildenv.2004.01.012
Beccali, M., Cellura, M., Fontana, M., Longo, S., Mistretta, M., 2013. Energy retrofit of a single-family house: Life cycle net energy saving and environmental benefits. Renew. Sustain. Energy Rev. 27, 283–293.
Becchio, C., Corgnati, S.P., Delmastro, C., Fabi, V., Lombardi, P., 2016. The role of nearly-zero energy buildings in the transition towards Post-Carbon Cities. Sustain. Cities Soc. 27, 324–337.
Berardi, U., 2016. The outdoor microclimate benefits and energy saving resulting from green roofs retrofits. Energy Build. 121, 217–229.
Berry, S., Whaley, D., Davidson, K., Saman, W., 2014. Near zero energy homes – What do users think? Energy Policy 73, 127–137.
Bhowmik, C., Bhowmik, S., Ray, A., Pandey, K.M., 2017. Optimal green energy planning for sustainable development: A review. Renew. Sustain. Energy Rev. 71, 796–813.
Biyanto, T.R., Gonawan, E.K., Nugroho, G., Hantoro, R., Cordova, H., Indrawati, K., 2016. Heat exchanger network retrofit throughout overall heat transfer coefficient by using genetic algorithm. Appl. Therm. Eng. 94, 274–281.
Bomberg, M., Gibson, M., Zhang, J., 2015. A concept of integrated environmental approach for building upgrades and new construction: Part 1—setting the stage. J. Build. Phys. 38, 360–385.
Broderick, Á., Byrne, M., Armstrong, S., Sheahan, J., Coggins, A.M., 2017. A pre and post evaluation of indoor air quality, ventilation, and thermal comfort in retrofitted co-operative social housing. Build. Environ. 122, 126–133.
Broto, V.C., 2015. Contradiction, intervention, and urban low carbon transitions. Environ. Plan. D Soc. Sp. 33, 460–476.
Butera, F.M., 2013. Zero-energy buildings: the challenges. Adv. Build. Energy Res. doi:10.1080/17512549.2012.756430
Cajot, S., Peter, M., Bahu, J.M., Guignet, F., Koch, A., Mar?chal, F., 2017. Obstacles in energy planning at the urban scale. Sustain. Cities Soc. 30, 223–236.
Camprubí, L., Malmusi, D., Mehdipanah, Roshanak Palència, L., Molnar, A.M., 2016. Façade insulation retrofitting policy implementation process and its effects on health equity determinants: A realist review. Energy Policy 91, 304–314.

Cao, J., Metzmacher, H., O'Donnell, J., Frisch, J., Bazjanac, V., Kobbelt, L., van Treeck, C., 2017. Facade geometry generation from low-resolution aerial photographs for building energy modeling. Build. Environ. 123, 601–624.
Capeluto, I.G., Ochoa, C.E., 2014. Simulation-based method to determine climatic energy strategies of an adaptable building retrofit façade system. Energy 76, 375–384.
Carbonaro, C., Tedesco, S., Thiebat, F., Fantucci, S., Serra, V., Dutto, M., 2016. An integrated design approach to the development of a vegetal-based thermal plaster for the energy retrofit of buildings. Energy Build. 124, 46–59.
Carlos, J.S., 2017. Optimizing the ventilated double window for solar collection. Sol. Energy 150, 454–462.
Child, M., Koskinen, O., Linnanen, L., Breyer, C., 2018. Sustainability guardrails for energy scenarios of the global energy transition. Renew. Sustain. Energy Rev. doi:10.1016/j.rser.2018.03.079
Chuah, J.W., Raghunathan, A., Jha, N.K., 2013. ROBESim: A retrofit-oriented building energy simulator based on EnergyPlus. Energy Build. 66, 88–103.
Cohen, W.M., Levinthal, D.A., 1990. Absorptive Capacity: A New Perspective on Learning and Innovation. Adm. Sci. Q. 35, 128. doi:10.2307/2393553
Cole, R.J., Fedoruk, L., 2015. Shifting from net-zero to net-positive energy buildings. Build. Res. Inf. 43, 111–120. doi:10.1080/09613218.2014.950452
Cosmi, C., Dvarionenė, J., Marques, I., Di Leo, S., Gecevičius, G., Gurauskienė, I., Mendes, G., Selada, C., 2015. A holistic approach to sustainable energy development at regional level: The RENERGY self-assessment methodology. Renew. Sustain. Energy Rev. 49, 693–707. doi:10.1016/j.rser.2015.04.094
Cuce, E., 2016. Toward multi-functional PV glazing technologies in low/zero carbon buildings: Heat insulation solar glass – Latest developments and future prospects prospects. Renew. Sustain. Energy Rev. 60, 1286–1301.
Dall'O', G., Norese, M., Galante, A., Novello, C., 2013. A Multi-Criteria Methodology to Support Public Administration Decision Making Concerning Sustainable Energy Action Plans. Energies 6, 4308–4330.
De Lieto Vollaro, R., Guattari, C., Evangelisti, L., Battista, G., Carnielo, E., Gori, P., 2015. Building energy performance analysis: A case study. Energy Build. 87, 87–94.
De Wilde, P., 2014. The gap between predicted and measured energy performance of buildings: A framework for investigation. Autom. Constr. 41, 40–49. doi:10.1016/j.autcon.2014.02.009
de Wilde, P., Tian, W., 2012. Management of thermal performance risks in buildings subject to climate change. Build. Environ. 55, 167–177. doi:10.1016/j.buildenv.2012.01.018
Delattre, P., 1984. Teoria dei sistemi ed epistemologia, Italian. ed. Editore, Giulio Enaudi, Torino.
Delmastro, C., Mutani, G., Corgnati, S., 2016. A supporting method for selecting cost-optimal energy retrofit policies for residential buildings at the urban scale. Energy Policy 99, 42.
Diakaki, C., Grigoroudis, E., Kabelis, N., Kolokotsa, D., Kalaitzakis, K., Stavrakakis, G., 2010. A multi-objective decision model for the improvement of energy efficiency in buildings. Energy 35, 5483–5496. doi:10.1016/j.energy.2010.05.012
Diakaki, C., Grigoroudis, E., Kolokotsa, D., 2008. Towards a multi-objective optimization approach for improving energy efficiency in buildings. Energy Build. 40, 1747–1754. doi:10.1016/j.enbuild.2008.03.002
Dineen, D., Rogan, F., Ó Gallachóir, B.P., 2015. Improved modelling of thermal energy savings potential in the existing residential stock using a newly available data source. Energy 90, 759–767.
Dixon, T., Eames, M., 2013. Scaling up: the challenges of urban retrofit. Build. Res. Inf. 41, 499–503.
Dixon, T., Eames, M., Britnell, J., Watson, G.B., Hunt, M., 2014. Urban retrofitting: Identifying disruptive and sustaining technologies using performative and foresight techniques. Technol. Forecast. Soc. Chang. 89, 131–144.
Dong, B., Kennedy, C., Pressnail, K., 2005. Comparing life cycle implications of building

retrofit and replacement options. Can. J. Civ. Eng. 32, 1051–1063. doi:10.1139/l05-061
Eames, M., Dixon, T., May, T., Hunt, M., 2013. City futures: exploring urban retrofit and sustainable transitions. Build. Res. Inf. 41, 504–516.
Eliopoulou, E., Mantziou, E., 2017. Architectural Energy Retrofit (AER): An alternative building's deep energy retrofit strategy. Energy Build. 150, 239–252.
Eriksson, P., Hermann, C., Hrabovszky-Horvth, S., Rodwell, D., 2014. EFFESUS Methodology for Assessing the Impacts of Energy-Related Retrofit Measures on Heritage Significance. Hist. Environ. Policy Pract. 5, 132–149.
European Commission, 2011. A Roadmap for moving to a competitive low carbon economy in 2050.
Evola, G., Margani, G., 2016. Renovation of apartment blocks with BIPV: Energy and economic evaluation in temperate climate. Energy Build. 130, 794–810.
Fawcett, T., Killip, G., 2014. Anatomy of low carbon retrofits: evidence from owner-occupied Superhomes. Build. Res. Inf. 1–12.
Fedoruk, L.E., Cole, R.J., Robinson, J.B., Cayuela, A., 2015. Learning from failure: understanding the anticipated–achieved building energy performance gap. Build. Res. Inf. 1–15.
Fonseca, J.A., Nguyen, T.-A., Schlueter, A., Marechal, F., 2016. City Energy Analyst (CEA): Integrated framework for analysis and optimization of building energy systems in neighborhoods and city districts. Energy Build. 113, 202–226.
García Kerdan, I., Raslan, R., Ruyssevelt, P., Gálvez, M.D., 2016. An exergoeconomic-based parametric study to examine the effects of active and passive energy retrofit strategies for buildings. Energy Build. 133, 155–171.
Geels, F.W., 2011. The multi-level perspective on sustainability transitions: Responses to seven criticisms. Environ. Innov. Soc. Transitions. doi:10.1016/j.eist.2011.02.002
Gianfrate, V., Piccardo, C., Longo, D., Giachetta, A., 2017. Rethinking social housing: Behavioural patterns and technological innovations. Sustain. Cities Soc. 33, 102–112.
Giovanardi, A., Passera, A., Zottele, F., Lollini, R., 2015. Integrated solar thermal façade system for building retrofit. Sol. Energy 122, 1100–1116. doi:10.1016/j.solener.2015.10.034
Glackin, S., Dionisio, M.R., 2016. 'Deep engagement' and urban regeneration: tea, trust, and the quest for co-design at precinct scale. Land use policy 52, 363–373.
Gough, M.Z., 2015. Reconciling Livability and Sustainability. J. Plan. Educ. Res. 35, 145–160.
Gregório, V., Seixas, J., 2017. Energy savings potential in urban rehabilitation: A spatial-based methodology applied to historic centres. Energy Build. 152, 11–23.
Gupta, R., Gregg, M., 2016. Do deep low carbon domestic retrofits actually work? Energy Build. 129, 330–343.
Gupta, R., Gregg, M., Passmore, S., Stevens, G., 2015. Intent and outcomes from the Retrofit for the Future programme: key lessons. Build. Res. Inf. 1–18.
Häkkinen, T., 2012. Systematic method for the sustainability analysis of refurbishment concepts of exterior walls. Constr. Build. Mater. 37, 783–790.
Halawa, E., 2009. Exploring Synergies with Innovative Green Technologies for Advanced Renovation using a Bioclimatic Approach. Archit. Sci. Rev. 52, 229–236.
Head, L., 2010. Cultural ecology: adaptation - retrofitting a concept? Prog. Hum. Geogr. 34, 234–242.
Heidarinejad, M., Mattise, N., Dahlhausen, M., Sharma, K., Benne, K., Macumber, D., Brackney, L., Srebric, J., 2017. Demonstration of Reduced-Order Urban Scale Building Energy Models. Energy Build.
Hengstberger, F., Zauner, C., Resch, K., Holper, S., Grobbauer, M., 2016. High temperature phase change materials for the overheating protection of facade integrated solar thermal collectors. Energy Build. 124, 1–6.
Heo, Y., Choudhary, R., Augenbroe, G.A., 2012. Calibration of building energy models for retrofit analysis under uncertainty. Energy Build. 47, 550–560.
Hestnes, A.G., Kofoed, N.U., 2002. Effective retrofitting scenarios for energy efficiency and comfort: Results of the design and evaluation activities within the OFFICE project. Build.

Environ. 37, 569–574. doi:10.1016/S0360-1323(02)00003-3
Hong, Taehoon, Koo, C., Kim, H., Seon Park, H., 2014. Decision support model for establishing the optimal energy retrofit strategy for existing multi-family housing complexes. Energy Policy 66, 157–169.
Hong, T., Taylor-Lange, S.C., D'oca, S., Yan, D., Corgnati, S.P., 2016. Advances in research and applications of energy-related occupant behavior in buildings. Energy Build. 116, 694–702.
Hong, Tianzhen, Yang, L., Hill, D., Feng, W., 2014. Data and analytics to inform energy retrofit of high performance buildings. Appl. Energy 126, 90–106.
Hosseini, M.R., Banihashemi, S., Rameezdeen, R., Golizadeh, H., Arashpour, M., Ma, L., 2017. Sustainability by Information and Communication Technology: A paradigm shift for construction projects in Iran. J. Clean. Prod. doi:10.1016/j.jclepro.2017.08.200
Hsu, D., 2015. Identifying key variables and interactions in statistical models of building energy consumption using regularization. Energy 83, 144–155.
Imam, S., Coley, D.A., Walker, I., 2016. Are building modellers literate? - studying the relation between modelling literacy and the performance gap. CLIMA 2016 - Proc. 12th REHVA World Congr.
International Energy Agency, 2013. Transition to Sustainable Buildings. Iea.Org 290. doi:10.1787/9789264202955-en
Ismail, M.A., Keumala, N., Dabdoob, R.M., 2017. Review on integrating sustainability knowledge into architectural education: Practice in the UK and the USA. J. Clean. Prod. doi:10.1016/j.jclepro.2016.09.219
Jagarajan, R., Abdullah Mohd Asmoni, M.N., Mohammed, A.H., Jaafar, M.N., Lee Yim Mei, J., Baba, M., 2017. Green retrofitting – A review of current status, implementations and challenges. Renew. Sustain. Energy Rev. doi:10.1016/j.rser.2016.09.091
Jenkins, D.P., 2010. The value of retrofitting carbon-saving measures into fuel poor social housing. Energy Policy 38, 832–839. doi:10.1016/j.enpol.2009.10.030
Jennings, M., Fisk, D., Shah, N., 2014. Modelling and optimization of retrofitting residential energy systems at the urban scale. Energy 64, 220–233. doi:10.1016/j.energy.2013.10.076
Joss, S., Cowley, R., Tomozeiu, D., 2013. Towards the 'ubiquitous eco-city': An analysis of the internationalisation of eco-city policy and practice. Urban Res. Pract. 6, 54–74. doi:10.1080/17535069.2012.762216
Kaatz, E., Root, D., Bowen, P., 2005. Broadening project participation through a modified building sustainability assessment, in: Building Research and Information. pp. 441–454. doi:10.1080/09613210500219113
Kanapeckiene, L., Kaklauskas, A., Zavadskas, E.K., Raslanas, S., 2011. Method and system for Multi-Attribute Market Value Assessment in analysis of construction and retrofit projects. Expert Syst. Appl. 38, 14196–14207.
Kerr, N., Gouldson, A., Barrett, J., 2017. The rationale for energy efficiency policy: Assessing the recognition of the multiple benefits of energy efficiency retrofit policy. Energy Policy 106, 212–221. doi:10.1016/j.enpol.2017.03.053
Kersten, W.C., Crul, M.R.M., Geelen, D. V, Meijer, S.A., Franken, V., 2015. Engaging beneficiaries of sustainable renovation – exploration of design-led participatory approaches. J. Clean. Prod. 106, 690–699.
King, D., 2010. Engineering a low carbon built environment: The discipline of Building Engineering Physics. Engineering 1–52.
Kirby, A., 2019. Transdisciplinarity and sustainability science: A response to Sakao and Brambila-Macias in the context of sustainable cities research. J. Clean. Prod. doi:10.1016/j.jclepro.2018.11.003
Kivimaa, P., Boon, W., Hyysalo, S., Klerkx, L., 2019. Towards a typology of intermediaries in sustainability transitions: A systematic review and a research agenda. Res. Policy. doi:10.1016/j.respol.2018.10.006
KlemeŠ, J.J., Kravanja, Z., Varbanov, P.S., Lam, H.L., 2013. Advanced multimedia engineering education in energy, process integration and optimisation. Appl. Energy 101, 33–40. doi:10.1016/j.apenergy.2012.01.039

Koirala, B.P., Koliou, E., Friege, J., Hakvoort, R.A., Herder, P.M., 2016. Energetic communities for community energy: A review of key issues and trends shaping integrated community energy systems. Renew. Sustain. Energy Rev. doi:10.1016/j.rser.2015.11.080
Kolokotsa, D., Diakaki, C., Grigoroudis, E., Stavrakakis, G., Kalaitzakis, K., 2009. Decision support methodologies on the energy efficiency and energy management in buildings. Adv. Build. Energy Res. 3, 121–146. doi:10.3763/aber.2009.0305
Kontokosta, C.E., 2016. Modeling the energy retrofit decision in commercial office buildings. Energy Build. 131, 1–20.
Koutsikouri, D., Austin, S., Dainty, A., 2008. Critical success factors in collaborative multi-disciplinary design projects. J. Eng. Des. Technol. 6, 198–226. doi:10.1108/17260530810918243
Kumbaroğlu, G., Madlener, R., 2012. Evaluation of economically optimal retrofit investment options for energy savings in buildings. Energy Build. 49, 327–334.
Kylili, A., Fokaides, P.A., Lopez Jimenez, P.A., 2016. Key Performance Indicators (KPIs) approach in buildings renovation for the sustainability of the built environment: A review. Renew. Sustain. Energy Rev. 56, 906–915.
Lawrence, T.M., Boudreau, M.-C., Helsen, L., Henze, G., Mohammadpour, J., Noonan, D., Patteeuw, D., Pless, S., Watson, R.T., 2016. Ten questions concerning integrating smart buildings into the smart grid. Build. Environ. 108, 273–283.
Lawrence, T.M., Watson, R.T., Boudreau, M.-C., Johnsen, K., Perry, J., Ding, L., 2012. A new paradigm for the design and management of building systems. Energy Build. 51, 56–63.
Li, J., Tharakan, P., Macdonald, D., Liang, X., 2013. Technological, economic and financial prospects of carbon dioxide capture in the cement industry. Energy Policy 61, 1377–1387.
Loftness, V., Aziz, A., Choi, J., Kampschroer, K., Powell, K., Atkinson, M., Heerwagen, J., 2009. The value of post-occupancy evaluation for building occupants and facility managers. Intell. Build. Int. 1, 249–268. doi:10.3763/inbi.2009.SI04
Lu, Y., Wu, Z., Chang, R., Li, Y., 2017. Building Information Modeling (BIM) for green buildings: A critical review and future directions. Autom. Constr. 83, 134–148.
Lund, P., 2012. Large-scale urban renewable electricity schemes - Integration and interfacing aspects, in: Energy Conversion and Management. doi:10.1016/j.enconman.2012.01.037
Ma, Z., Cooper, P., Daly, D., Ledo, L., 2012. Existing building retrofits: Methodology and state-of-the-art. Energy Build. 55, 889–902.
Magrini, A., Franco, G., 2016. The energy performance improvement of historic buildings and their environmental sustainability assessment. J. Cult. Herit. 21, 834–841.
Marasco, D.E., Kontokosta, C.E., 2016. Applications of machine learning methods to identifying and predicting building retrofit opportunities. Energy Build. 128, 431–441.
Martínez-Molina, A., Tort-Ausina, I., Cho, S., Vivancos, J.-L., 2016. Energy efficiency and thermal comfort in historic buildings: A review. Renew. Sustain. Energy Rev. 61, 70–85.
Mat, N., Cerceau, J., Shi, L., Park, H.S., Junqua, G., Lopez-Ferber, M., 2016. Socio-ecological transitions toward low-carbon port cities: Trends, changes and adaptation processes in Asia and Europe. J. Clean. Prod. doi:10.1016/j.jclepro.2015.04.058
Mauro, G.M., Hamdy, M., Vanoli, G.P., Bianco, N., Hensen, J.L.M., 2015. A new methodology for investigating the cost-optimality of energy retrofitting a building category. Energy Build. 107, 456–478.
Mayring, P., 2008. The qualitative content analysis process. J. Adv. Nurs. 62, 107–15. doi:10.1111/j.1365-2648.2007.04569.x
Mayring, P., 2000. Qualitative Content Analysis, in: Forum Qualitative Sozialforschung / Forum: Qualitative Social Research. p. v.1, n.2, pp.1–10. doi:10.1111/j.1365-2648.2007.04569.x
Mazzarella, L., 2015. Energy retrofit of historic and existing buildings. The legislative and regulatory point of view. Energy Build. 95, 23–31.
Mehaffy, M., 2013. Prospects for scenario-modelling urban design methodologies to achieve significant greenhouse gas emissions reductions. Urban Des. Int. 18, 313–324.
Menezes, A.C., Cripps, A., Bouchlaghem, D., Buswell, R., 2012. Predicted vs. actual energy performance of non-domestic buildings: Using post-occupancy evaluation data to reduce

the performance gap. Appl. Energy 97, 355–364. doi:10.1016/j.apenergy.2011.11.075
Mills, E., 2003. Climate change, insurance and the buildings sector: technological synergisms between adaptation and mitigation. Build. Res. Inf. 31, 257–277.
Moffatt, S., Kohler, N., 2008. Conceptualizing the built environment as a social-ecological system. Build. Res. Inf. 36, 248–268. doi:10.1080/09613210801928131
Mohareb, E., Hashemi, A., Shahrestani, M., Sunikka-Blank, M., 2017. Retrofit Planning for the Performance Gap: Results of a Workshop on Addressing Energy, Health and Comfort Needs in a Protected Building. energies 10, 1–17.
Monetti, V., Fabrizio, E., Filippi, M., 2015. Impact of low investment strategies for space heating control: Application of thermostatic radiators valves to an old residential building. Energy Build. 95, 202–210.
Munarim, U., Ghisi, E., 2016. Environmental feasibility of heritage buildings rehabilitation. Renew. Sustain. Energy Rev. 58, 235–249.
Neto, A.H., Fiorelli, F.A.S., 2008. Comparison between detailed model simulation and artificial neural network for forecasting building energy consumption. Energy Build. 40, 2169–2176. doi:10.1016/j.enbuild.2008.06.013
Novak, J.D., Cañas, A.J., 2004. Building on New Constructivist Ideas & CmapTools to Create a New Model for Education. Concept Maps Theory, Methodol. Technol. Proc. First Int. Conf. Concept Mapp. 1, 469–476.
Ochoa, C.E., Capeluto, I.G., 2015. Decision methodology for the development of an expert system applied in an adaptable energy retrofit fa?ade system for residential buildings. Renew. Energy 78, 498–508.
Olubunmi, O.A., Xia, P.B., Skitmore, M., 2016. Green building incentives: A review. Renew. Sustain. Energy Rev. 59, 1611–1621.
Oti, A.H., Kurul, E., Cheung, F., Tah, J.H.M., 2016. A framework for the utilization of Building Management System data in building information models for building design and operation. Autom. Constr. 72, 195–210. doi:10.1016/j.autcon.2016.08.043
Parker, J., Hardy, A., Glew, D., Gorse, C., 2017. A methodology for creating building energy model occupancy schedules using personal location metadata. Energy Build. 150, 211–223.
Parra, D., Swierczynski, M., Stroe, D.I., Norman, S.A., Abdon, A., Worlitschek, J., O'doherty, T., Rodrigues, L., Gillott, M., Zhang, X., Bauer, C., Patel, M.K., 2017. An interdisciplinary review of energy storage for communities: Challenges and perspectives. Renew. Sustain. Energy Rev. 79, 730–749.
Peck, P., Parker, T., 2016. The 'Sustainable Energy Concept' – making sense of norms and co-evolution within a large research facility's energy strategy. J. Clean. Prod. 123, 137–154.
Pérez-Urrestarazu, Luis Fernández-Cañero, Rafael Franco-Salas, A., Egea, G., 2016. Vertical Greening Systems and Sustainable Cities. J. Urban Technol. 1–21.
Petri, I., Beach, T., Rezgui, Y., Wilson, I.E., Li, H., 2014. Engaging construction stakeholders with sustainability through a knowledge harvesting platform. Comput. Ind. 65, 449–469.
Peuportier, B., Thiers, S., Guiavarch, A., 2013. Eco-design of buildings using thermal simulation and life cycle assessment. J. Clean. Prod. 39, 73–78.
Pinder, J., Iii, R.S., Saker, J., 2013. Stakeholder perspectives on developing more adaptable buildings. Constr. Manag. Econ. 31, 440–459.
Rhodes, J.D., Gorman, W.H., Upshaw, C.R., Webber, M.E., 2015. Using BEopt (EnergyPlus) with energy audits and surveys to predict actual residential energy usage. Energy Build. 86, 808–816.
Roberti, F., Oberegger, U.F., Lucchi, E., Troi, A., 2017. Energy retrofit and conservation of a historic building using multi-objective optimization and an analytic hierarchy process. Energy Build. 138, 1–10.
Robertson, S., 2016. A longitudinal quantitative–qualitative systems approach to the study of transitions toward a low carbon society. J. Clean. Prod. doi:10.1016/j.jclepro.2015.04.074
Rovers, R., 2014. New energy retrofit concept: 'renovation trains' for mass housing. Build. Res. Inf. 1–11.
Rydin, Y., Guy, S., Goodier, C., Chmutina, K., Devine-Wright, P., Wiersma, B., 2015. The

financial entanglements of local energy projects. Geoforum 59, 1–11.
Saber, H.H., Maref, W., Gnanamurugan, G., Nicholls, M., 2015. Energy retrofit using vacuum insulation panels: An alternative solution for enhancing the thermal performance of wood-frame walls. J. Build. Phys. 39, 35–68.
Sakao, T., Brambila-Macias, S.A., 2018. Do we share an understanding of transdisciplinarity in environmental sustainability research? J. Clean. Prod. doi:10.1016/j.jclepro.2017.09.226
Salter, A., Gann, D., 2003. Sources of ideas for innovation in engineering design. Res. Policy. doi:10.1016/S0048-7333(02)00119-1
Santamouris, M., Dascalaki, E., 2002. Passive retrofitting of office buildings to improve their energy performance and indoor environment: The OFFICE project. Build. Environ. 37, 575–578. doi:10.1016/S0360-1323(02)00004-5
Santangelo, A., Tondelli, S., 2017. Occupant behaviour and building renovation of the social housing stock: Current and future challenges. Energy Build. 145, 276–283.
Sauter, R., Watson, J., 2007. Strategies for the deployment of micro-generation: Implications for social acceptance. Energy Policy 35, 2770–2779. doi:10.1016/j.enpol.2006.12.006
Senel Solmaz, A., Halicioglu, F.H., Gunhan, S., 2016. An approach for making optimal decisions in building energy efficiency retrofit projects. Indoor Built Environ.
Shakouri, M., Lee, H.W., Choi, K., 2015. PACPIM: New decision-support model of optimized portfolio analysis for community-based photovoltaic investment. Appl. Energy 156, 607–617.
Shao, Y., Geyer, P., Lang, W., 2014. Integrating requirement analysis and multi-objective optimization for office building energy retrofit strategies. Energy Build. 82, 356–368.
Shen, L., He, B., Jiao, L., Song, X., Zhang, X., 2016. Research on the development of main policy instruments for improving building energy-efficiency. J. Clean. Prod. 112, 1789–1803.
Si, J., Marjanovic-Halburd, L., Nasiri, F., Bell, S., 2016. Assessment of building-integrated green technologies: A review and case study on applications of Multi-Criteria Decision Making (MCDM) method. Sustain. Cities Soc. 27, 106–115.
Sibilla, M., 2017. A meaningful mapping approach for the complex design. Int. J. Des. Sci. Technol. 23, 41–78.
Sibilla, M., Kurul, E., 2018. Distributed Renewable and Interactive Energy Systems in Urban Environments. TECHNE J. Technol. Archit. Environ. I, 33–39.
Silva, P.C.P., Almeida, M., Bragança, L., Mesquita, V., 2013. Development of prefabricated retrofit module towards nearly zero energy buildings. Energy Build. 56, 115–125.
Simpson, S., Banfill, P., Haines, V., Mallaband, B., Mitchell, V., 2014. Energy-led domestic retrofit: impact of the intervention sequence. Build. Res. Inf. 1–19.
Smith, A., Voß, J.P., Grin, J., 2010. Innovation studies and sustainability transitions: The allure of the multi-level perspective and its challenges. Res. Policy. doi:10.1016/j.respol.2010.01.023
Smith, K.M., Svendsen, S., 2015. Development of a plastic rotary heat exchanger for room-based ventilation in existing apartments. Energy Build. 107, 1–10.
Soares, N., Bastos, J., Pereira, L.D., Soares, A., Amaral, A.R., Asadi, E., Rodrigues, E., Lamas, F.B., Monteiro, H., Lopes, M.A.R., Gaspar, A.R., 2017. A review on current advances in the energy and environmental performance of buildings towards a more sustainable built environment. Renew. Sustain. Energy Rev. 77, 845–860.
Sovacool, B.K., Watts, C., 2009. Going Completely Renewable: Is It Possible (Let Alone Desirable)? Electr. J. doi:10.1016/j.tej.2009.03.011
Strauss, A., Corbin, J., 1990. Grounded theory procedures and techniques. Basics Qual. Res. 19. doi:10.4135/9781452230153
Süsser, D., Döring, M., Ratter, B.M.W., 2017. Harvesting energy: Place and local entrepreneurship in community-based renewable energy transition. Energy Policy 101, 332–341.
Suzuki, H., Dastur, A., Moffatt, S., Yabuki, N., Maruyama, H., 2010. Eco2 Cities. doi:10.1596/978-0-8213-8046-8
Tadeu, S.F., Alexandre, R.F., Tadeu, A.J.B., Antunes, C.H., Sim?es, N.A. V, Silva, P.P. Da,

2016. A comparison between cost optimality and return on investment for energy retrofit in buildings-A real options perspective. Sustain. Cities Soc. 21, 12–25.
Tariku, F., Kumaran, K., Fazio, P., 2015. Application of a Whole-Building Hygrothermal model in energy, durability, and indoor humidity retrofit design. J. Build. Phys. 39, 3–34.
Terés-Zubiaga, J., Campos-Celador, A., González-Pino, I., Diarce, G., 2016. The role of the design and operation of individual heating systems for the energy retrofits of residential buildings. Energy Convers. Manag. 126, 736–747.
Theodosiou, T., Tsikaloudaki, K., Tsoka, S., Chastas, P., 2019. Thermal bridging problems on advanced cladding systems and smart building facades. J. Clean. Prod. doi:10.1016/j.jclepro.2018.12.286
Thomsen, K.E., Rose, J., M?rck, O., Jensen, S. ?stergaard, ?stergaard, I., Knudsen, H.N., Bergs?e, N.C., 2016. Energy consumption and indoor climate in a residential building before and after comprehensive energy retrofitting. Energy Build. 123, 8–16.
Torres-Ramírez, M., García-Domingo, B., Aguilera, J., De La Casa, J., 2014. Video-sharing educational tool applied to the teaching in renewable energy subjects. Comput. Educ. 73, 160–177. doi:10.1016/j.compedu.2013.12.014
Tovarović, J.Č., Ivanović-Šekularac, Jelena Šekularac, N., 2017. Renovation of existing glass facade in order to implement energy efficiency and media facade. Energy Build. 152, 653–666.
Tranfield, D., Denyer, D., Smart, P., 2003. Towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Review. Br. J. Manag. 14, 207–222. doi:10.1111/1467-8551.00375
Trencher, G., Cast?n Broto, V., Takagi, T., Sprigings, Z., Nishida, Y., Yarime, M., 2016. Innovative policy practices to advance building energy efficiency and retrofitting: Approaches, impacts and challenges in ten C40 cities. Environ. Sci. Policy 66, 353–365.
Tuohy, P.G., Murphy, G.B., 2015. Closing the gap in building performance: Learning from BIM benchmark industries. Archit. Sci. Rev. 58, 47–56. doi:10.1080/00038628.2014.975780
Van Der Schoor, T., Scholtens, B., 2015. Power to the people: Local community initiatives and the transition to sustainable energy. Renew. Sustain. Energy Rev. 43, 666–675. doi:10.1016/j.rser.2014.10.089
van Krugten, L.T.F., Hermans, L.M.C., Havinga, L.C., Pereira Roders, A.R., Schellen, H.L., 2016. Raising the energy performance of historical dwellings. Manag. Environ. Qual. 27, 740–755.
Vilches, A., Barrios Padura, Á., Molina Huelva, M., 2017. Retrofitting of homes for people in fuel poverty: Approach based on household thermal comfort. Energy Policy 100, 283–291.
Vlasova, L., Gram-Hanssen, K., 2014. Incorporating inhabitants' everyday practices into domestic retrofits. Build. Res. Inf. 1–13.
Volk, R., Stengel, J., Schultmann, F., 2014. Building Information Modeling (BIM) for existing buildings — Literature review and future needs. Autom. Constr. 38, 109–127.
Voytenko, Y., McCormick, K., Evans, J., Schliwa, G., 2016. Urban living labs for sustainability and low carbon cities in Europe: Towards a research agenda. J. Clean. Prod. 123, 45–54. doi:10.1016/j.jclepro.2015.08.053
Walker, G., 2008. What are the barriers and incentives for community-owned means of energy production and use? Energy Policy 36, 4401–4405. doi:10.1016/j.enpol.2008.09.032
Wang, N., Phelan, P.E., Gonzalez, J., Harris, C., Henze, G.P., Hutchinson, R., Langevin, J., Lazarus, M.A., Nelson, B., Pyke, C., Roth, K., Rouse, D., Sawyer, K., Selkowitz, S., 2017. Ten questions concerning future buildings beyond zero energy and carbon neutrality. Build. Environ. 119, 169–182.
Wang, P., Gong, G., Wang, Y., Li, L., 2014. Thermodynamic investigation of building integrated energy efficiency for building retrofit. Energy Build. 77, 139–148.
Webb, A.L., 2017. Energy retrofits in historic and traditional buildings: A review of problems and methods. Renew. Sustain. Energy Rev. 77, 748–759.
Whyte, J., Gann, D., Salter, A., Whyte, J., Gann, D., Salter, A., 2003. Design Quality Indicator as a tool for thinking. Build. Res. Inf. 31, 318–333. doi:10.1080/0961321032000107564

Wiek, A., Walter, A.I., 2009. A transdisciplinary approach for formalized integrated planning and decision-making in complex systems. Eur. J. Oper. Res. 197, 360–370. doi:10.1016/j.ejor.2008.06.013

Wu, R., Mavromatidis, G., Orehounig, K., Carmeliet, J., 2017. Multiobjective optimisation of energy systems and building envelope retrofit in a residential community. Appl. Energy 190, 634–649.

Wu, Z., Wang, B., Xia, X., 2016. Large-scale building energy efficiency retrofit: Concept, model and control. Energy 109, 456–465.

Xing, Y., Hewitt, N., Griffiths, P., 2011. Zero carbon buildings refurbishment - A Hierarchical pathway. Renew. Sustain. Energy Rev. 15, 3229–3236. doi:10.1016/j.rser.2011.04.020

Xu, X., Taylor, J.E., Pisello, A.L., 2014. Network synergy effect: Establishing a synergy between building network and peer network energy conservation effects. Energy Build. 68, 312–320.

Yalcintas, M., 2008. Energy-savings predictions for building-equipment retrofits. Energy Build. 40, 2111–2120. doi:10.1016/j.enbuild.2008.06.008

Yan, D., O'brien, W., Hong, T., Feng, X., Burak Gunay, H., Tahmasebi, F., Mahdavi, A., 2015. Occupant behavior modeling for building performance simulation: Current state and future challenges. Energy Build. 107, 264–278.

Yang, X., Ergan, S., Knox, K., 2015. Requirements of Integrated Design Teams While Evaluating Advanced Energy Retrofit Design Options in Immersive Virtual Environments. Buildings 5, 1302–1320.

Young, J., Brans, M., 2017. Analysis of factors affecting a shift in a local energy system towards 100% renewable energy community. J. Clean. Prod.

Yushchenko, A., Patel, M.K., 2017. Cost-effectiveness of energy efficiency programs: How to better understand and improve from multiple stakeholder perspectives? Energy Policy 108, 538–550.

Zeleny, M., 2012. High Technology and barriers to innovation: from globalization to relocalization. Int. J. Inf. Technol. Decis. Mak. 11, 441–456. doi:10.1142/S021962201240010X

Zeleny, M., 2009. Technology and high technology: support net and barriers to innovation. Acta Mech. Slovaca.

Zeleny, M., 1986. High technology management. Hum. Syst. Manag. 6, 109–120. doi:10.3233/HSM-1986-6203

Appendix 1 – word frequency analysis

World	Count	Weighted Percentage (%)	Source	Line of Research	Category:
environment	182	0.64	(Cajot et al. 2017), (Gregório and Seixas 2017), (Becchio et al. 2016) , (Z. Wu, Wang, and Xia 2016), (Magrini and Franco 2016), (Gupta et al. 2015), (Mazzarella 2015), (Jennings, Fisk, and Shah 2014), (Dixon and Eames 2013), (Mehaffy 2013), (Bai 2007)	From Building Retrofit to Urban Retrofit	ER and Low Carbon City Transition
innovation	148	0.52			
local	123	0.43			
regime	91	0.32			
consumption	88	0.31			
community	87	0.31			
culture	85	0.30			
urban	82	0.29			
policies	69	0.24			
insulation	58	0.2			
planning	324	0.96	(Gianfrate et al. 2017), (van Krugten et al. 2016), (Broto 2015), (Cosmi et al. 2015), (Dall'O' et al. 2013), (Head 2010), (Kelly, 2010), (A. Smith, Voß, and Grin 2010), (Moffatt and Kohler 2008)	Technical and Social Integration	
urban	216	0.64			
consumption	196	0.58			
data	131	0.39			
climate	88	0.26			
cultural	84	0.25			
investment	63	0.19			
integrated	54	0.16			
policies	50	0.15			
resilience	46	0.14			
community	147	0.68	(Fonseca et al. 2016), (Glackin and Dionisio 2016), (Dixon et al. 2014), (Eames et al. 2013),(Mills 2003)	Disruptive and Sustainable Local Technologies	
planning	66	0.31			
change	60	0.28			
regeneration	59	0.27			
industry	48	0.22			
disruptive	48	0.22			
urban	46	0.21			
environment	46	0.21			
participation	42	0.19			
innovation	41	0.19			
community	147	0.68			

World	Count	Weighted Percentage (%)	Source	Line of Research	Category:
data	454	0.89	(Cao et al. 2017), (Heidarinejad et al. 2017), (R. Wu et al. 2017), (Alwan 2016), (García Kerdan et al. 2016), (Marasco and Kontokosta 2016), (Munarim and Ghisi 2016), (Bomberg, Gibson, and Zhang 2015), (De Lieto Vollaro et al. 2015), (Dineen, Rogan, and Ó Gallachóir 2015), (Hsu 2015), (Fawcett and Killip 2014), (Wang et al. 2014), (de Wilde and Tian 2012), (Heo, Choudhary, and	Energy Modelling Process	ER and Information Modelling Process
consumption	350	0.68			
insulation	158	0.31			
environment	137	0.27			
simulation	130	0.25			
option	104	0.20			
calibration	90	0.18			
investment	66	0.13			
uncertainties	59	0.12			
optimisation	56	0.11			

			Augenbroe 2012), (Lawrence et al. 2012)		
data	666	1.78	(Mohareb et al. 2017), (Roberti et al. 2017), (Parker et al. 2017), (Gupta and Gregg 2016), (Tianzhen Hong et al. 2016), (Terés-Zubiaga et al. 2016), (Yan et al. 2015), (Rhodes et al. 2015), (Tianzhen Hong et al. 2014), (Chuah, Raghunathan, and Jha 2013), (Neto and Fiorelli 2008), (Yalcintas 2008), (Bazjanac 2004)	Occupant Behaviour Modelling	
consumption	350	0.93			
behaviour	285	0.76			
occupant	203	0.54			
metadata	78	0.21			
insulation	74	0.20			
profile	69	0.18			
schedule	61	0.16			
environment	54	0.14			
simulation	54	0.14			
simulation	121	0.91	(Fedoruk et al. 2015), (Beccali et al. 2013), (Peuportier, Thiers, and Guiavarch 2013), (Ardente et al. 2011), (Dong, Kennedy, and Pressnail 2005)	Life Cycle Analysis Modelling	
consumption	108	0.82			
insulation	105	0.79			
environment	40	0.30			
integrated	34	0.26			
performace	32	0.24			
indicator	30	0.23			
forecast	26	0.20			
assessment	27	0.20			
pollution	24	0.18			

World	Count	Weighted Percentage (%)	Source	Line of Research	Category:
consumption	236	0.49	(Ascione, Bianco, De Masi, et al. 2017), (Ascione, Bianco, De Stasio, et al. 2017), (Broderick et al. 2017), (Tadeu et al. 2016), (Tariku, Kumaran, and Fazio 2015), (Shao, Geyer, and Lang 2014), (Taehoon Hong et al. 2014), (Xu, Taylor, and Pisello 2014), (Kumbaroğlu and Madlener 2012), (Kanapeckiene et al. 2011), (Diakaki et al. 2010), (Diakaki, Grigoroudis, and Kolokotsa 2008) (Ascione, Bianco, De Masi, et al. 2017), (Ascione, Bianco, De Stasio, et al. 2017), (Broderick et al. 2017), (Tadeu et al. 2016), (Tariku, Kumaran, and Fazio 2015), (Shao, Geyer, and Lang 2014), (Taehoon Hong et al. 2014), (Xu, Taylor, and Pisello 2014), (Kumbaroğlu and Madlener 2012), (Kanapeckiene et al. 2011), (Diakaki et al. 2010), (Diakaki, Grigoroudis, and Kolokotsa 2008)	Multi-Attribute Information	ER and Decision-Making Process
insulation	219	0.45			
cost	200	0.41			
environment	90	0.19			
optimization	83	0.17			
mechanism	52	0.11			
financial	49	0.10			
choices	47	0.10			
consideration	47	0.10			
overhang	44	0.09			
consumption	298	0.67	(Yushchenko and Patel 2017), (Vilches, Barrios	Bottom-up Methodology	
data	262	0.59			

incentive	125	0.28	Padura, and Molina Huelva 2017), (Delmastro, Mutani, and Corgnati 2016), (Kontokosta 2016), (Shen et al. 2016), (Trencher et al. 2016), (Senel Solmaz, Halicioglu, and Gunhan 2016), (Mauro et al. 2015), (Yang, Ergan, and Knox 2015), (Vlasova and Gram-Hanssen 2014), (Asadi et al. 2011), (Kolokotsa et al. 2009)		
environment	114	0.26			
policies	109	0.25			
insulation	108	0.24			
investment	81	0.18			
criteria	74	0.17			
optimization	72	0.16			
Inhabitant	72	0.16			
consumption	62	0.39	(Ahmed et al. 2015), (Shakouri, Lee, and Choi 2015), (Asadi et al. 2014), (Ballarini, Corgnati and Corrado, 2014), (Eriksson et al. 2014)	Economic and Socio-Technical Factors	
community	45	0.29			
investment	38	0.24			
optimization	38	0.24			
typology	31	0.20			
balancing	29	0.18			
integration	23	0.15			
environment	22	0.14			
planning	22	0.14			
economy	18	0.11			

World	**Count**	**Weighted Percentage (%)**	**Source**	**Line of Research**	**Category:**
insulation	95	0.39	(Tovarović and Ivanović-Šekularac, Jelena Šekularac 2017), (Berardi 2016), (Pérez-Urrestarazu, Luis Fernández-Cañero, Rafael Franco-Salas and Egea 2016), (Aste et al. 2015), (Saber et al. 2015), (Ascione et al. 2014)	Innovative Building Materials	ER and Innovative Technical Solutions
consumption	69	0.28			
environment	62	0.26			
thermal (heat)	49	0.20			
climates	48	0.20			
facade	48	0.20			
microclimate	47	0.19			
properties	16	0.07			
inertia	6	0.02			
planning	6	0.02			
insulation	215	0.52	(Carlos 2017), (Eliopoulou and Mantziou 2017), (Biyanto et al. 2016), (Cuce 2016), (Evola and Margani 2016), (Hengstberger et al. 2016), (Si et al. 2016), (Giovanardi et al. 2015), (Monetti, Fabrizio, and Filippi 2015), (K. M. Smith and Svendsen 2015), (Capeluto and Ochoa 2014), (Moran *et al.*, 2014), (Häkkinen 2012), (Halawa 2009), (Hestnes and Kofoed 2002), (Santamouris and Dascalaki 2002)	Passive, Active and Smart Technologies	
data	145	0.35			
consumption	116	0.28			
environment	73	0.18			
integrated	73	0.18			
simulation	64	0.16			
configuration	59	0.14			
investment	48	0.12			
control	47	0.11			
bioclimatic	44	0.11			
insulation	178	0.79	(Carbonaro et al. 2016), (Thomsen et al. 2016), (Li et al. 2013), (Ochoa and Capeluto	Shifting the Industry	
façade	139	0.62			
consumption	74	0.33			
plaster	73	0.32			

integrated	54	0.24	2015), (Rovers 2014), (Silva et al. 2013), (Xing, Hewitt, and Griffiths 2011), (Aouad, Ozorhon, and Abbott 2010)
investment	36	0.16	
industry	35	0.15	
research	24	0.11	
prefabricated	21	0.09	
material	16	0.07	

World	Count	Weighted Percentage (%)	Source	Line of Research	Category:
local	470	1.47	(Süsser, Döring, and Ratter 2017), (Koirala et al. 2016), (Koirala et al. 2016), (Peck and Parker 2016), (Rydin et al. 2015), (Gough 2015), (Van Der Schoor and Scholtens 2015), (Simpson et al. 2014), (Sauter and Watson 2007)	Integrated Community Energy System	ER and Energy and Environmental Awareness
community	391	1.22			
integrated	77	0.24			
decentralised	61	0.19			
consumers	56	0.17			
changes	53	0.17			
financial	51	0.16			
municipality	51	0.16			
knowledge	50	0.16			
entrepreneurs	30	0.09			
community	112	1.17	(Santangelo and Tondelli 2017), (Berry et al. 2014), (Jenkins 2010), (Walker 2008)	Comfort and Quality of Life	
consumption	65	0.68			
local	51	0.53			
social	45	0.47			
income	29	0.30			
comfortable	25	0.26			
environment	25	0.26			
policy	25	0.26			
instruments	22	0.23			
knowledge	21	0.22			
planning	59	0.26	(Voytenko et al. 2016), (Kersten et al. 2015), (Petri et al. 2014), (Joss, Cowley, and Tomozeiu 2013), (KlemeŠ et al. 2013), (Glad, 2012)	Socio-Technological Learning Process	
local	53	0.24			
innovation	51	0.23			
participatory	44	0.20			
integration	43	0.19			
education	29	0.13			
network	28	0.12			
experiments	16	0.07			
universities	14	0.06			
knowledge	12	0.05			

Appendix 2 – Recording Unit – Pattern: scope detected

Line of Research	References	Recording Unit – Pattern: scope detected
From Building Retorift R to Urban Retrofit	(Cajot *et al.*, 2017)	interrelated challenges and obstacles which hinder efficient urban energy planning.
	(Gregório and Seixas, 2017)	holistic approach at a neighbourhood scale, instead of the traditional individual building scale
	(Becchio *et al.*, 2016)	new emerging concept of "Post-Carbon City" and its main influencing factors regarding the building sector.
	(Wu, Wang and Xia, 2016)	large-scale Building energy efficiency retrofit analysis
	(Magrini and Franco, 2016)	relationships between ER issues and cultural heritage ones as high level of complexity the society is called to face.
	(Gupta *et al.*, 2015)	retrofit programmes in order to reduce the gap between intent and outcome.
	(Mazzarella, 2015)	the gap between historic building and energy retrofit.
	(Jennings, Fisk and Shah, 2014)	retrofit problems at urban scale providing solutions for the selection and operation of complex energy systems.
	(Dixon and Eames, 2013)	mitigation and adaptation responses to climate change along with the allied threats of environmental degradation.
	(Mehaffy, 2013)	variables of urban morphology and their role in the generation of greenhouse gas emissions.
	(Bai, 2007)	obstacles that impede cities from addressing global environmental concerns.
Technical and Social Integration.	(Gianfrate *et al.*, 2017)	relationship between technological advancements and knowledge in energy retrofitting with social needs and habits.
	(van Krugten *et al.*, 2016)	the knowledge gap of the current energy performance of historical dwellings.
	(Broto, 2015)	an analysis of contradictions in urban low carbon transitions as engines of change.
	(Cosmi *et al.*, 2015)	a holistic approach in order to enhance the energy systems in terms of policy background, energy uses and infrastructures.
	(Dall'O' *et al.*,	a methodology that integrates multi-criteria analysis in order to support Public

	2013)	Administration/Local Authorities in programming Action Plans
	(Head, 2010)	the role of Adaptation as a core concept of twentieth-century cultural ecology.
	(Kelly, 2010)	the engineering challenge associated with energy security, climate change and sustainable consumption of existing buildings.
	(Smith, Voß and Grin, 2010)	the multi-level perspective of socio-technical transitions.
	(Moffatt and Kohler, 2008)	a unified theory of the built environment as a complex social–ecological system, where multiple-related metabolisms interact at different scales
Disruptive and Sustainable local technologies	(Fonseca *et al.*, 2016)	a computational framework for the analysis and optimization of energy systems in neighbourhoods and city districts.
	(Glackin and Dionisio, 2016)	a new methodology for community engagement in the urban regeneration process introducing the so called: 'deep engagement'.
	(Dixon *et al.*, 2014)	the importance to identify 'disruptive' and 'sustaining' technologies which may contribute to city-based sustainability transitions
	(Eames *et al.*, 2013)	the complex urban transitions under a multiple socio-technical 'regimes', scales and domains within a participatory process.
	(Mills, 2003)	an integration of sustainable energy considerations with risk-management objectives, underlining a more proactive coordination among groups.

Low carbon city transition category and lines of research

Line of Research	References	Recording Unit – Pattern: scope detected
Energy modelling process	(Cao *et al.*, 2017)	an automatic geometry modelling procedure of existing building facades in order to recover their semantic structure for reuse in the BEM process.
	(Heidarinejad *et al.*, 2017)	a procedure to rapidly create urban scale reduced order building energy models
	(Wu *et al.*, 2017)	a method for a multi-objective and simultaneous optimisation of building energy systems and retrofit
	(Alwan, 2016)	a systematic framework for maintenance and refurbishment in domestic housing sector for utilising BIM processes.
	(García Kerdan *et al.*, 2016)	a systematic framework that uses exergoeconomic theory integrated into 'building energy retrofit' (BER) design.
	(Marasco and Kontokosta, 2016)	the ways to utilize available data to target ECMs across a city's entire building stock

	(Munarim and Ghisi, 2016)	a prospect of environmental indicators to evaluate the feasibility of architectural rehabilitation
	(Bomberg, Gibson and Zhang, 2015)	the need for an active role for building physics in the development of near-zero energy buildings.
	(De Lieto Vollaro *et al.*, 2015)	computerized procedures to calculate in an accurate way the annual energy demand taking in consideration the inertial properties of the structure
	(Dineen, Rogan and Ó Gallachóir, 2015)	a novel bottom up approach to modelling the energy savings potential of energy efficiency improvement measures.
	(Hsu, 2015)	interactions between technical and non-technical parameters for further analysis, policy development and targeting Data
	(Fawcett and Killip, 2014)	an alternative model of low carbon retrofit whereby improvements happen step by step over several years.
	(Wang *et al.*, 2014)	the building integrated energy efficiency taking into account the economic and energy efficiency of building envelope and cooling and heating resource
	(de Wilde and Tian, 2012)	the use of building performance simulation to quantify the risks that climate change poses to the thermal performance of buildings, and to their critical functions.
	(Heo, Choudhary and Augenbroe, 2012)	a scalable, probabilistic methodology that can support large scale investments in energy retrofit of buildings while accounting for uncertainty.
	(Lawrence *et al.*, 2012)	the concept of Facilities Management and Modeling as a new form of information systems to apply the principles of Energy Informatics to increasing energy efficiency in building operations.
Occupant behaviour modelling	(Mohareb *et al.*, 2017)	retrofit measures taking into account how to balance energy and comfort needs.
	(Roberti *et al.*, 2017)	a methodology that permits finding and comparing optimal retrofits for historic buildings in a trans-disciplinary and quantitative way.
	(Parker *et al.*, 2017)	a protocol for extracting and using freely available metadata to create occupancy schedules that are used as inputs for dynamic simulation models.

	(Gupta and Gregg, 2016)	a socio-technical building performance evaluation approach to assess the pre- and post- actual performance of two discrete deep low energy retrofits.
	(Hong *et al.*, 2016)	the most recent advances and current obstacles in modelling occupant behaviour and quantifying its impact on building energy use.
	(Terés-Zubiaga *et al.*, 2016)	the occupants' behaviour and the rebound effect, which show significant differences on energy consumption values.
	(Yan *et al.*, 2015)	the obstacles and future needs and directions of occupant behaviour modelling.
	(Rhodes *et al.*, 2015)	how energy efficiency retrofits and operational changes can influence a building's total and temporal energy use.
	(Tianzhen Hong *et al.*, 2014)	a new holistic approach powered by building performance data and analytics.
	(Chuah, Raghunathan and Jha, 2013)	retrofit modules with which the user can quickly and easily generate building models to perform retrofit comparison simulations.
	(Neto and Fiorelli, 2008)	a comparison between a simple model based on artificial neural network and a model that is based on physical principles.
	(Yalcintas, 2008)	a model that estimates energy savings from retrofit projects. A comparison between before and after the retrofits was used to develop the method.
	(Bazjanac, 2004)	to increase the quality of building energy simulation through simultaneous interaction of multiple design and simulation tools.
Life Cycle Analysis Modelling	(Fedoruk *et al.*, 2015)	the 'performance gap' between designed and actual energy performance of buildings taking into account different stages of a building life cycle.
	(Beccali *et al.*, 2013)	the strong interplay among all the phases of a building life-cycle.
	(Peuportier, Thiers and Guiavarch, 2013)	the implications of life cycle assessment in thermal analysis.
	(Ardente *et al.*, 2011)	the role of the life cycle approach for selecting the most effective options during the design and implementation of retrofit actions.
	(Dong, Kennedy and Pressnail,	to compare demolishing and rebuilding action from the life cycle environmental and economic analyses point of view.

2005)	

Building information modelling process category and lines of research

Line of Research	References	Recording Unit – Pattern: scope detected
Multi-attribute information	(Ascione, Bianco, De Masi, *et al.*, 2017)	a multi-objective approach to find robust cost-optimal energy retrofit solutions and to assess their resilience to global warming.
	(Ascione, Bianco, De Stasio, *et al.*, 2017)	how to predict building energy performance with low computational times and good reliability.
	(Broderick *et al.*, 2017)	the importance of characterising indoor air quality post energy retrofits within the overall building energy performance.
	(Tadeu *et al.*, 2016)	a multi-objective optimization approach to identify the minimum global cost and primary energy needs
	(Tariku, Kumaran and Fazio, 2015)	a whole-building hygro-thermal model, which is used for evaluation of various retrofit design parameters
	(Shao, Geyer and Lang, 2014)	a model-based method to support design teams in making informed multi-criteria decisions for energy-efficiency solutions
	(Taehoon Hong *et al.*, 2014)	to develop a decision support model for establishing the optimal energy retrofit strategy.
	(Xu, Taylor and Pisello, 2014)	energy saving potential as results of a network synergy effect.
	(Kumbaroğlu and Madlener, 2012)	a techno-economic evaluation method for the energy retrofit of buildings.
	(Kanapeckiene *et al.*, 2011)	a Multi-Attribute Decision-Making methods in order to prioritize the alternatives of comparative projects quite accurately
	(Diakaki *et al.*, 2010)	a methodology to define a optimal solution taking into account multiple and usually competitive objectives
	(Diakaki, Grigoroudis and Kolokotsa, 2008)	the feasibility of multi-objective optimization techniques to the problem of the improvement of the energy efficiency in buildings.
Bottom-up methodolog	(Yushchenko and Patel, 2017)	the existing practices of cost-effectiveness analysis and propose a modified methodology that allows considering perspectives of different stakeholders
	(Vilches, Barrios Padura and Molina Huelva, 2017)	a methodology to choose the most appropriate retrofit measure in a context of fuel poverty.
	(Delmastro, Mutani and Corgnati, 2016)	a new bottom-up methodology to aid decision-makers in the energy planning process
	(Kontokosta, 2016)	the effects of ownership type, tenant demand, and real estate market location on building energy retrofit decisions in the commercial office sector.
	(Shen *et al.*, 2016)	policy instrument as key to drive improving energy-efficiency in building sectors.
	(Trencher *et al.*, 2016)	programmes to advance energy efficiency and retrofitting of existing.
	(Senel Solmaz, Halicioglu and Gunhan, 2016)	an optimization-based decision support approach to determine the optimal energy efficiency retrofit options in existing buildings.
	(Mauro *et al.*, 2015)	a novel methodology aimed at supporting robust cost-optimal energy retrofit solutions for building categories.
	(Yang, Ergan and Knox, 2015)	integrated design teams when evaluating retrofit options in immersive virtual environments.
	(Vlasova and	the success of energy-focused retrofit projects is conditioned by their

	Gram-Hanssen, 2014)	compatibility with the everyday practices of the families living
	(Asadi *et al.*, 2011)	a multi-objective optimization model to assist stakeholders in the definition of ER intervention measures
	(Kolokotsa *et al.*, 2009)	the decision support processes towards energy efficiency and improvement of the environmental quality in buildings.
Economic and socio-technical factors	(Ahmed *et al.*, 2015)	systematic methodology to support the decision-making process for the integration of various improvement options
	(Shakouri, Lee and Choi, 2015)	a quantitative decision-support model for Community-based PV Investment Model
	(Asadi *et al.*, 2014)	a multi-objective optimization model using genetic algorithm and artificial neural network to quantitatively assess technology choices
	(Ballarini, Corgnati and Corrado, 2014)	a methodology for the identification of reference buildings aimed at creating a harmonised structure for "European Building Typologies"
	(Eriksson *et al.*, 2014)	a heritage impact assessment methodology to enable such a balancing process in a well-structured and systematic way

Decision-making process category and lines of research

Line of Research	References	Recording Unit – Pattern: scope detected
Innovative building materials	(Tovarović and Ivanović-Šekularac, Jelena Šekularac, 2017)	Special attention was paid to the implementation of media technologies and final effects on energy balance of glass façade.
	(Berardi, 2016)	the benefits on the local microclimate and the building energy saving resulting from green roof retrofits.
	(Pérez-Urrestarazu, Luis Fernández-Cañero, Rafael Franco-Salas and Egea, 2016)	vertical greening systems as structures that allow vegetation to spread over a building facade or interior wall.
	(Aste *et al.*, 2015)	the importance of the dynamic thermal properties as one of the design parameters.
	(Saber *et al.*, 2015)	the steady-state and transient thermal performance of three wall assemblies.
	(Ascione *et al.*, 2014)	a phase change materials integrated in the building exterior envelope.
..., active and smart techn ologie	(Carlos, 2017)	how passive air heating system can be improved in order to collect more solar heat.

	(Eliopoulou and Mantziou, 2017)	the relationships between basic architectural features and energy performance.
	(Biyanto *et al.*, 2016)	the performance of heat exchanger.
	(Cuce, 2016)	news PV glazing products.
	(Evola and Margani, 2016)	the energy and economic profitability of renovating residential buildings through the integration of PV panels on facades.
	(Hengstberger *et al.*, 2016)	the thermal comfort in buildings with facade integrated solar thermal collectors.
	(Si *et al.*, 2016)	a selection of green technologies where multiple criteria exist and interrelate.
	(Giovanardi *et al.*, 2015)	the concept and design of a modular unglazed solar thermal façade component for facilitating the installation of active solar façade
	(Monetti, Fabrizio and Filippi, 2015)	the application of space heating control devices such as thermostatic radiators valves on an old existing multi-family building.
	(Smith and Svendsen, 2015)	an experiment application of a short plastic rotary heat exchanger.
	(Capeluto and Ochoa, 2014)	a simplified methodology to identify preferred strategies and combinations for the early design stages of such system
	(Moran *et al.*, 2014)	the use of the Passive House Planning Package modelling tool to assess the potential for retrofit adaptation measures.
	(Häkkinen, 2012)	the method for the analysis of refurbishment concepts.
	(Halawa, 2009)	bioclimatic concepts, principles and strategies for large-scale buildings for the purposes of advanced renovation.
	(Hestnes and Kofoed, 2002)	passive solar and energy efficient retrofitting measures in office buildings.
	(Santamouris and Dascalaki, 2002)	global retrofitting strategies in order to promote successful and cost-effective implementation of passive solar measures.
Renovation of building sector	(Carbonaro *et al.*, 2016)	a joint research project involving manufacturers and research centers, adopting an integrated multi-objective design process
	(Thomsen *et al.*, 2016)	the tenants' overall satisfaction with the retrofitting process and the results of the retrofitting.
	(Li *et al.*, 2013)	the economic and financial issues in deploying CO2 capture in the cement

	industry.
(Ochoa and Capeluto, 2015)	a methodology with integrative approach between energy and economic aspects.
(Rovers, 2014)	an application of standardized process in order to improve ER actions.
(Silva *et al.*, 2013)	a new prefabricated retrofit module solution for the facades of existing buildings.
(Xing, Hewitt and Griffiths, 2011)	a range of technologies for building refurbishment in a sequential manner.
(Aouad, Ozorhon and Abbott, 2010)	the role of universities in working with industry to promote innovation

Innovative technical solutions category and lines of research

Line of Research	References	Recording Unit – Pattern: scope detected
Integrated Community energy system	(Süsser, Döring and Ratter, 2017)	the multifaceted interplay between place, local entrepreneurship and 'community renewable energy'.
	(Koirala *et al.*, 2016)	a model-based framework to assess the distributed energy resources-consumer adoption model.
	(Peck and Parker, 2016)	how organisations may implement renewable energies and improve energy efficiency.
	(Rydin *et al.*, 2015)	local energy initiatives identifying barriers, drivers and incentives to explain their emergence (or not).
	(Gough, 2015)	the complementarity of liveability and sustainability at a theoretical level but recognizes that linkage in practice is complex
	(Van Der Schoor and Scholtens, 2015)	the transition towards renewable and sustainable energy focusing on what is happening at the local community level.
	(Simpson *et al.*, 2014)	the variation in operational performance due to the intervention sequence.
	(Sauter and Watson, 2007)	social acceptance of renewable energy innovation
Comfort and Quality of life	(Santangelo and Tondelli, 2017)	the existing energy policy instruments and the current analysis methods in relation to occupant behaviour.
	(Berry *et al.*, 2014)	the level of householders' knowledge on smart technologies.
	(Jenkins, 2010)	the problem of installing non-cost effective measure.
	(Walker, 2008)	the meaning of "community-owned production and use"
Socio-technological learning process	(Voytenko *et al.*, 2016)	how the Urban Living Lab concept is being operationalised in contemporary urban governance for sustainability and low carbon cities.
	(Kersten *et al.*, 2015)	methods to transfer technological knowledge among residents
	(Petri *et al.*, 2014)	a web-based platform solution that provides integrated access to sustainability resources in the form of interactive, user-oriented services
	(Joss, Cowley and Tomozeiu, 2013)	the 'ubiquitous eco-city' paradigm with strong local contextualisation and social sustainability measures
	(KlemeŠ *et al.*, 2013)	the development of methods and tools, multimedia internet-based teaching and learning programs for future practitioners.
	Glad, 2012)	a socio-technical approach, based on social learning theory in order to examine the energy system transition.

Energy and environmental awareness category and lines of research