

Urban energy planning procedure for sustainable development in the built environment: A review of available spatial approaches

*Original*

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Abstract: Urban and Regional Integrated Energy Planning is crucial to define transition strategies toward sustainable development and post-carbon cities; particularly, in the built environment sector which is one of the main responsible for energy consumption and carbon emissions. The paper aims at offering a systematic review of existing urban and regional energy planning approaches. This analysis is based on literature review. The reviewed papers are critically analyzed and discussed through a Meta-analysis and a SWOT analysis. The papers are classified in order to highlight the main research trends and to illustrate the most relevant characteristics of the principal approaches.

This critical analysis of the papers highlights the lack of an holistic and integrated framework which is able to take into account the large variety of dimensions related to sustainable planning. A major achievement of this study is to provide information on how the various existing approaches can be integrated to handle the entire planning procedure adequately.

The result provides a preliminary theoretical framework to integrate different approaches, identify the main barriers and future challenges in the field of research. This framework will help urban actors to develop energy planning projects, guiding them in the choice among a significant number of existing planning approaches.

# Urban Energy Planning Procedure for Sustainable Development in the Built Environment: A Review of Available Spatial Approaches

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## Abstract

Urban and Regional Integrated Energy Planning is crucial to define transition strategies toward sustainable development and post-carbon cities; particularly, in the built environment sector which is one of the main responsible for energy consumption and carbon emissions.

The paper aims at offering a systematic review of existing urban and regional energy planning approaches. This analysis is based on literature review. The reviewed papers are critically analyzed and discussed through a Meta-analysis and a SWOT analysis. The papers are classified in order to highlight the main research trends and to illustrate the most relevant characteristics of the principal approaches.

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## Key words

Urban and Regional Integrated Energy Planning, Built Environment, Energy Modeling, Spatial Decision Support System

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## 1 Introduction

In recent decades, urban areas have been recognized as major contributors to CO<sub>2</sub> emissions since they are responsible for more than 70% of energy-related emissions (International Energy Agency, 2008). 60-80% of final energy use is associated with urban areas (Grubler et al., 2012). Therefore, urban areas play a significant role in the transition toward zero energy buildings (International Energy Agency, 2016).

It has been recognized that transition toward a sustainable urban development requires the definition of a set of strategies taking into account national priorities and specific characteristics. For supporting the strategic long-term planning process of urban areas, an Integrated Energy Planning (IEP) has been developed since late '50s. During these years, various energy supply companies had to make appropriate decisions to solve the large growth of the energy demand (Herbst et al., 2012). Only from the 1990s, there was an increasing of sustainability concerns, shifting the IEP focus towards the relation between energy and environment (Fleiter et al., 2011).

Currently, Urban and Regional Integrated Energy Planning (UR-IEP) has been recognized as the new generation of IEP (Mirakyan et al., 2009). UR-IEP requires a comprehensive vision of urban sustainable energy policies and a strong co-operation between national and local governments. It involves multiple actors and different sectors, being a multidisciplinary and complex problem (Albeverio et al., 2008).

Setting up and maintaining an effective UR-IEP requires appropriate approaches to support decision makers in defining a policy development strategy. These approaches help decision makers to choose the “best” alternative between different scenarios. However, there is still not a well-recognized procedure and an integrated framework to support the UR-IEP. This fact leads to neglect some important aspects in current urban energy planning practices (Brandon and Lombardi, 2011).

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4 Due to the complexity of this research field, this paper aims at reviewing current spatial approaches,  
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6 which can be adopted in a urban planning development with specifically focus to the built environment.  
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9 Therefore, the research questions raised by this paper are as follows: Are current research studies able  
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11 to support the challenges provided by UR-IEP, taking into account the variety of all the sustainable  
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13 planning aspects? What are current challenges and barriers in this research field?  
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16 This study provides a systematic review of existing spatial urban energy planning approaches and built  
17  
18 environment applications. It presents a preliminary theoretical framework that will help evaluating how  
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20 UR-IEP issues are handled.  
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23 The major contributions of this study are: 1. to offer a systematic review of existing urban energy  
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25 planning approaches toward sustainable built environment development; 2. to highlight the most  
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27 relevant spatial approaches and their applications for supporting urban energy planning procedures; 3.  
28  
29 to provide a statistical analysis of the reviewed papers through a Meta-analysis in order to figure out  
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31 current research trends; 4. to provide a SWOT analysis of the different approaches for guiding and  
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33 supporting urban actors in choosing among the various reviewed approaches; 5. to identify the main  
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35 barriers and future challenges in the field, with the aim to help understanding how the UR-IEP can be  
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37 handled in future analysis.  
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41 Accordingly, this review is expected to be very useful for all urban actors including, in particular, new  
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43 practitioners, researchers and decision makers working in this topic.  
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47 The rest of the paper is organized as follows: Section 2 illustrates the systematic review methodology  
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49 adopted by the authors. Section 3 presents the state of the art and classifies the main approaches  
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51 currently used in urban energy planning. Section 4 provides the results of the paper through a Meta-  
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53 analysis and SWOT analysis. Furthermore, it discusses the significance of the findings and the barriers  
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55 in the research field. Finally, Section 5 provides the main remarks and highlights the necessary future  
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57 developments.  
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## 2 Systematic Review Methodology

This part illustrates the systematic literature reviews methodology, which has been adopted in this study for reviewing the journal articles and conference papers. According to (Prasara-A and Gheewala, 2016), this is structured as a four-stage analysis framework.

In the earliest stage of the review process, named “Literature search”, the Scopus database has been chosen to support the literature search. Moreover, conference papers and many different tools and applications developed by R&D projects have been scattered across different websites through Google search engine.

The second stage is the “Screening process”. In this, the review has been organized according to three<sup>1</sup> UR-IEP process phases, as presented in Section 2.1 , with the aim at illustrating an in-depth state of the art on available approaches, in the specific context. In each phase, the principal keywords have been used, in combination with the literature search.

As this paper focuses on the “UR-IEP for a Sustainable Development in the Built Environment”, which is a multi-disciplinary and multi-phases topic, the authors checked the relevant keyword combinations, as follows: Urban/ Building/ Energy Modelling/Multi-Criteria/Spatial/ Decision Support System/GIS/Energy System. The time period sets in the search engine for the academic publications is between 1970 and 2016.

In the third stage, “Selection of literature”, the abstract of all the references has been read in order to select and identify the most related studies to the topic. Furthermore, the full paper texts of those more appropriate papers have been included in the database. Finally, this selection of papers has been filtered by considering the following criteria: (i) English language papers; (ii) the study must be related to energy sustainable development; (iii) the approach presented in the paper must be “spatial” or “integrable spatial”. A total of 146 papers, ranging from 1970 to 2016, have been selected in this stage.

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<sup>1</sup> The authors excluded from the literature review the Phase IV “monitoring and implementation”, because it is not functional to the strategy definition.

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4 The fourth stage, named “Including literature”, consists in reading the 146 selected papers in order to  
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6 collect the information about existing approaches for supporting the UR-IEP in sustainable built  
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8 environment and urban development. In total, the 146 reviewed papers are composed by two groups as  
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10 follows: 66 papers that describe the state of art and theoretical background and 80 articles that show the  
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12 urban applications of the described approaches. The latter have been further included in a meta-  
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14 analysis as better described in Section 4.1. Figure 1 shows the flowchart of this systematic review  
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16 methodology.  
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## 23 **2.1 Basic Definitions**

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26 In this literature review, a description of the terminologies used is provided in this section.

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28 UR-IEP, Urban and Regional Integrated Energy Planning, is defined according to (Mirakyan et al.,  
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30 2009), as a long-term, model-based energy planning process. This is divided into the following four  
31  
32 major phases: Phase I: Preparation and orientations; Phase II: Model design and detailed analysis;  
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34 Phase III: Prioritization and decision; Phase IV: Implementation and monitoring.  
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40 As it has been specified, the focus of this paper is mainly the ‘Spatial’ or “Spatial-Integrable”  
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42 approaches of UR-IEP (see Figure 1. Flowchart of the systematic review outlining the study selection  
43  
44 process.

45  
46 Figure 2).

47  
48 Figure 1. Flowchart of the systematic review outlining the study selection process.

49  
50 Figure 2. UR-IEP Steps, adapted from (Mirakyan et al., 2009).

51  
52 The concept of sustainable development dates back to 1970s and since then it has been widely the  
53  
54 subject of public, private and academic sectors concerns, being the main effort of national and  
55  
56 international economic, social and environmental agendas (Brandon et al., 2016; Cosmi et al., 2015;  
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58 Iddrisu and Bhattacharyya, 2015). According to (Brandon and Lombardi, 2011) and (Rad, 2010),  
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4 sustainable development is a continuous process that is able to balance between all the environmental,  
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6 economic and social aspects related to a living environment, in order to improve, and not to impact  
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8 adversely, on present or future generations. A sustainable energy development means balancing energy  
9  
10 production and consumption, along with having the minimal impact on the environment and giving the  
11  
12 opportunity to employ social and economic activities (Hofman and Li, 2009).  
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16 Future scenarios analyses can be defined as a way to create and predict future alternatives and their  
17  
18 impacts, providing policy decisions framework (Miola, 2008; Mistry et al., 2014). The aim of future  
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20 studies is to support decision-making under uncertainty which is to be defined as indeterminacy  
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22 (Dreborg, 1996).  
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25  
26 In planning, “*scenario*” is a very commonly used term. In literature, scenarios have various  
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28 classifications (Börjeson et al., 2006; Marien, 2002; Rotmans et al., 2000) (see Table 1). Interestingly,  
29  
30 scenario analysis has been broadly used as an approach in the field of urban energy planning.  
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32  
33 In the next sub-sections the authors will review and introduce several approaches of UR-IEP that may  
34  
35 help to define different scenarios.  
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38 Table 1. Future scenarios classification according to (Banister and Stead, 2004; Börjeson et al., 2006).  
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### 42 **3 State of the Art of the Approaches used in Urban and Regional Energy Planning**

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45 This section provides a wide revision of existing urban energy planning approaches toward sustainable  
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47 built environment for each phase of the UR-IEP (See Figure 1. Flowchart of the systematic review  
48  
49 outlining the study selection process.

50  
51 Figure 2), highlighting the most relevant spatial approaches. In order to ease the reader to follow

52  
53 Section 3, a summary of major features of the reviewed papers is shown in Figure 3.

54  
55 Accordingly, Section 3 is organized in sub-section 3.1 “Preparation” which describes the preliminary

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57 UR-IEP phase where a supportive GIS database involving stakeholders should be defined in order to  
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59 proceed with phase II and III.  
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4 Sub-section 3.2 is the core of the UR-IEP and it illustrates different approaches regarding the “Detailed  
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6 Urban Energy Modelling”. It is divided into “3.2.1. Urban Building Energy”, focused on urban  
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8 building energy demand side, and “3.2.2. Urban Comprehensive Energy System Models”, focused on  
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10 urban energy demand and supply side. Both these two sub-sections pay special attention to GIS  
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12 integration.  
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15  
16 Finally, sub-section 3.3, entitled “Prioritization and Decisional Process” presents the last and  
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18 complementary phase of UR-IEP by illustrating some of the most important Multiple Criteria Spatial  
19  
20 (GIS) Decision Support System implemented for Urban Energy Planning.  
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23 Figure 3. Outline of Section 3  
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### 26 **3.1 Phase I-Preparation** 27

28 The Preparation Phase I is presented in order to introduce the preliminary required actions to create a  
29  
30 supportive base of data and information necessary to perform the next phases of the UR- IEP. Among a  
31  
32 number of possible actions involved in Phase I of UR-IEP, the most relevant ones include data  
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34 collection and stakeholders’ involvement processes (Mirakyan and De Guio, 2013).  
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37 Data collection consists in collecting the historical and current building stock data such as:  
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41 • socio-economic, demographic, and building data, which can be extracted from the National  
42  
43 Census database (e.g. population and prevailing buildings age);  
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- 46 • building stock geometrical, typological information, which can be extracted from the digital  
47  
48 cartographic buildings map of technical departments of the municipalities (e.g. base surface and  
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50 height);  
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- 53 • available real energy consumption data for a building stock (energy suppliers, surveys).  
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56 Some examples of the detailed studies regarding aforementioned data collection process in the field of  
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58 urban energy planning are (Caputo et al., 2013b; Tornberg and Thuvander, 2005). According to these  
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60 examples, the data collection process can be divided into (i) Geo-referenced data collection\_ the  
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4 collection of existing building-related data and, (ii) Non geo-referenced data collection\_ the collection  
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6 of existing data which should be later geo-referenced. A high data disaggregation may represent wider  
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8 possibilities of investigations, simultaneously very detailed data collection may be challenging and  
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10 time-consuming (Kelly, 2011).  
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14 In this phase the use of GIS is extremely useful to store, manage, and visualize a vast number of spatial  
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16 data for urban planning purposes. Through the representation of multiple layers, city development can  
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18 be represented), where each item is associated with a geometric entity in a proper system of coordinates  
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20 (Bugs et al., 2010). Particularly, the GIS allow geo-referencing all the available energy data in order to  
21  
22 develop energy consumptions models to fully characterize the building stock for the whole city. Figure  
23  
24 4 illustrates an example of the creation of a supportive GIS platform by overlapping multiple layers  
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26 (Torabi Moghadam et al., 2016b). Data need to be carefully elaborated and analysed in order to create a  
27  
28 strong supporting dataset (see Section 3.2).  
29  
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32  
33 Figure 4. Example of the creation of a supportive GIS platform for urban energy planning (Torabi Moghadam et al., 2016b) by  
34  
35 overlapping multiple layers, source EEB Project, case study: city of Settimo Torinese.  
36  
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38 The other fundamental action to be considered from the earlier phase of UR-IEP is the involvement of  
39  
40 stakeholders. This fact helps to obtain the existing data, determine relevant sustainable objectives, and  
41  
42 propose a common strategic vision (Bottero et al., 2015; Linnenluecke et al., 2016; Pelzer et al., 2015).  
43  
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45 In order to involve multiple stakeholders and experts in the planning procedure is necessary to organize  
46  
47 the collaborative events such as workshop organization, focus groups, questionnaire, and interviews.  
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50 The GIS supportive database aids the stakeholders to visualize the current urban energy situation and  
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52 therefore to reshape the sustainable objectives.  
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### **3.2 Phase II-Detailed Urban Building Energy Modelling**

This section aims at providing an overview of some of the existing building stock energy assessment approaches and their applications to predict building stock energy consumption, with a particular focus on GIS based methodologies.

As reported by Yu et al. ( 2011), existing studies with regards to energy consumption can be classified into two types: aggregate analysis (Lenzen et al., 2006; Unander et al., 2004; Zhang, 2004) and disaggregate analysis (Moll et al., 2005; Vringer and Blok, 1995). Two of the most comprehensive reviews have classified building energy modelling into “top-down” (aggregate) and “bottom-up” (disaggregate) (Kavgic et al., 2010; Swan and Ugursal, 2009).

In literature, the top-down approach has been considered suitable for large-scale analysis and not for the identification of the possible improvements at building sector level at urban and regional levels (Hitchcock, 1993; Martinez Soto and Jentsch, 2016).

Bottom-up models are divided into two methodological groups with the aim of evaluating the energy consumption: Engineering or Building Physics and Statistical methods (Swan and Ugursal, 2009). The bottom-up models have been recognized as suitable for urban and regional analyses (MacGregor et al., 1993). In fact, modelling urban and regional energy systems calls for detail-based approaches (Mendes et al., 2011). Sub-section 3.2 aims at describing some of the most common energy models and tools divided into urban building energy modelling (Section 3.2.1) focused on urban building energy demand side and comprehensive energy system models focused on urban energy demand and supply side with a special attention on the building sector (Section 3.2.2).

#### **3.2.1 Urban Building Energy Modelling**

Building energy modelling relates to techniques matching statistics, data surveys and building physics analyses to estimate current and future energy consumption of the stock. Bottom-up building energy

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4 models are classified as buildings physics models, statistical models and the combination of both these  
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6 approaches (hybrid) (Kavgic et al., 2010; Oladokun and Odesola, 2015; Swan and Ugursal, 2009).

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8 They differ in calculation methodology, time and spatial resolution, disaggregation level of input data  
9  
10 and results. Even if previous reviews are focused on the same classification mentioned in this study,  
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12 some basic information is provided in order to understand if the methodologies can be applied at urban  
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14 scale and coupled with GIS. Quantitative estimations methodology provides a determination of energy  
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16 consumption for each building and thus permitting a better territorial control through a geo-referenced  
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18 model (Al-kheder et al., 2009; Favretto, 2000).  
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### 23 24 **3.2.1.1 Building physics or Engineering models**

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26 Building physics or Engineering methods are very detailed models based on traditional thermodynamic  
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28 relationships (Aydinalp-Koksal and Ugursal, 2008). They can be divided into (Swan and Ugursal,  
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30 2009):  
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35 • archetype method – it is based on the aggregation of buildings in representative classes clustered  
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37 according to key characteristics (Corgnati et al., 2013; Shimoda et al., 2004). The main difficulties  
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39 are related to the characterization of archetypes in order to be representative of a wide set of  
40  
41 buildings. The identification of archetypes implies the association of thermo-physical  
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43 characteristics to each building and consequently to use building simulation software for assessing  
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45 current and future energy consumption (Ballarini et al., 2014; Wan and Yik, 2004).  
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- 50  
51 • sample method – it considers the data collected from surveys and monitoring campaign used to  
52  
53 model the actual behaviour of the building stock. Limited applications of sample method have  
54  
55 been found at local level (Cheng and Steemers, 2011).  
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- 58  
59 • population distribution method – it is an accounting method reflecting energy consumption of  
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61 household appliances regarding the ownership saturation rate of appliances. Accordingly, it can be  
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4 suitable for building up the electric distribution load of an area or to estimate the energy  
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6 consumption of household appliances (Kadian et al., 2007a; Saidur et al., 2007).  
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10 In order to focus on spatial applications, the paper reviews the integration of building physics models  
11 with GIS methods. In particular, Fabbri et al. (2012) investigated the influence of typology factor in  
12 energy saving in heritage buildings. This study used GIS maps as a strong platform to link a different  
13 data and the building Energy Performance Certificate (EPC). Yamaguchi et al. (2007) proposed a new  
14 clustering modelling approach to define CO<sub>2</sub> reduction scenarios in the commercial sector. A  
15 simulation model capable of considering the various parameters affecting energy use and management  
16 is developed.  
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26 Another archetype approach is presented by Mattinen et al. (2014) in which a GIS-based calculation  
27 and visualization approach for energy use and greenhouse gas emissions for the residential stock has  
28 been developed. Jones et al. (2001) introduced Energy and Environmental Prediction model based on a  
29 GIS technique which provides additional information, based on a “*drive-pass*” survey, to archetypes.  
30 Caputo et al. (2013a) and Costa (2012) proposed a methodology in order to evaluate the energy  
31 performance of the built environment at city level.  
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41 Mastrucci et al. (2013) developed a dynamic thermal simulation and indoor thermal comfort analysis to  
42 support sustainable urban planning. Österbring et al. (2016) have proposed a methodology to describe  
43 the building-stock by integrating building characteristics from energy performance certificates,  
44 measured energy use and envelope areas from a GIS model. A GIS-based simulation model has been  
45 proposed by Li et al. (2016) in order to evaluate how building typology and urban morphology  
46 influence building energy consumption and CO<sub>2</sub> emissions. Delmastro et al. (2016) developed several  
47 long-term scenarios assessing the energy saving potential and the relative cost. Moreover, they spatially  
48 analysed the socio-economic feasibility of renovation measures.  
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4 To conclude this sub-section, although it might be possible to use the sample and population  
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6 distribution models at urban level, the most widespread method applicable for urban spatial analyses is  
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8 the archetype one. This method allows both short and long-term analysis and the possibility to create  
9  
10 energy retrofit scenarios).  
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### 13 14 **3.2.1.2 Statistical models** 15

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17 Statistical methods search for correlations between historical data on building energy use/external  
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19 conditions and buildings characteristics. They can be divided into regression analysis, conditional  
20  
21 demand analysis, and neural network.  
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- 24  
25 • Regression analyses fit the relation between energy consumption and its identified relevant drivers  
26  
27 (Dascalaki et al., 2010; Fracastoro and Serraino, 2011; Theodoridou et al., 2011). They do not  
28  
29 require very detailed data about the building, however, high amount of data is needed to develop  
30  
31 the model. Regression methods can be also suitable for assessing the retrofit potential of large  
32  
33 building stock as proposed by Walter and Sohn (2016).  
34  
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- 36  
37 • The Conditional Demand Analysis method (CDA) is a regression-based method suitable for  
38  
39 analysing large datasets. Due to the lack of flexibility, the analysis of energy conservation  
40  
41 measures on demand variation isn't allowed therefor this method will not be further considered in  
42  
43 this paper.  
44  
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47 • Neural network models (NN) study the relationship between a wide range of variables and  
48  
49 parameters based on a large training dataset. They have been largely used for prediction problems  
50  
51 at individual building level, but also at a larger scale (Aydinalp et al., 2004, 2002). This method is  
52  
53 suitable for the evaluation of energy consumption and the impact of socio-economic factors  
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55 (Aydinalp-Koksal and Ugursal, 2008), but they are not suitable for defining energy conservation  
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57 measures even if some applications exist (Krarti et al., 1998).  
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4 In order to focus on spatial applications of urban energy modelling technique, the paper reviews  
5  
6 the integration of statistical models with GIS methods. Recently, Dall’O et al. utilized GIS tools to  
7  
8 create a comprehensive building energy performance database using energy audits of sample  
9  
10 buildings, (Dall’O’ et al., 2012). Mutani and Vicentini (2013) have conducted a regression analysis  
11  
12 to correlate building energy consumption to building compactness and construction period. The  
13  
14 bottom-up GIS-based model for New York City is built by Howard et al. with the aim of  
15  
16 estimating the building sector energy end-use intensities (Howard et al., 2012). Yeo et al. (2013)  
17  
18 develop an urban demand forecasting system, with hourly resolution, based on a GIS database (E-  
19  
20 GIS DB) with 2D/3D visualization. The ongoing Zero Energy Buildings in Smart Urban Districts  
21  
22 proposes an integrating GIS and regression model with the Stakeholders Analysis, in order to later  
23  
24 integrate the Multi-Criteria Decision Analysis (Torabi Moghadam et al., 2016a).  
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31  
32 From the literature emerged that between the mentioned statistical approaches, the regression methods  
33  
34 have been coupled with GIS more than the other methods. These methods are appropriate for short-  
35  
36 term planning based on large data requirement and to create energy retrofit scenarios.  
37  
38

### 39 **3.2.1.3 Hybrid models**

40

41  
42 Hybrid models combine different methods in order to merge their strengths. These models have  
43  
44 performed well in case of the small sample, but according to Chalal et al. (2016) “*it could be possible*  
45  
46 *to utilize them in urban energy planning when certain parameters, especially the thermal ones, are*  
47  
48 *unattainable*”. These methods have been widely integrated with GIS in the literature. Particularly,  
49  
50 Tornber and Thuvander (2005) developed a model toward a sustainable management of the building  
51  
52 stock. In this study, a top- down approach is combined with a bottom-up approach to compensate the  
53  
54 lack of data and complete each other.  
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4 A methodology called EnerGIS has been proposed by Girardin et al. (2010) to support qualitative long-  
5  
6 term scenario analysis involving building renovation. EnerGIS is based on the pinch analysis and  
7  
8 statistical analysis. Ascione et al. (2013) suggested a new method for the calculation of the space  
9  
10 heating demand for buildings with aim at characterizing both winter and summer energy performances.  
11  
12 Their target was to promote efficient refurbishment solutions for existing buildings and effective design  
13  
14 for new ones.  
15  
16

17  
18 Mutani and Pairona (2014) proposed a hybrid approach (i.e. regression and archetype) to calculate the  
19  
20 energy consumption of residential building stock by starting from census information and real energy  
21  
22 consumption data.  
23  
24

25  
26 Concluding, in the review conducted by authors the archetype and regression models have been the  
27  
28 most used modelling techniques to perform spatial urban building energy modelling due to their  
29  
30 suitability for energy savings potential assessment.  
31  
32

### 33 **3.2.2 Urban Comprehensive Energy System Modelling**

34

35  
36 The building energy modelling approach (Section 3.2.1) may do not consider the effects of building  
37  
38 policies on the whole energy system (Bhattacharyya and Timilsina, 2010; Harrestrup and Svendsen,  
39  
40 2014). On the other hand, comprehensive energy system models aim at finding a suitable mix of energy  
41  
42 supply and demand choices to support the planning process from a cross-sectoral system perspective  
43  
44 (Nakata et al., 2011). The energy system is defined as the combination of processes for “acquiring and  
45  
46 using energy in a given society or economy” (Jaccard, 2005). The urban energy system includes all  
47  
48 what is physically sited in the administrative boundaries of a city plus all the traceable upstream flows  
49  
50 (Keirstead et al., 2012).  
51  
52

53  
54 Bottom-up comprehensive energy systems models are typically adopted for long-term runs (Herbst et  
55  
56 al., 2012). The application of a comprehensive energy system models at urban and regional levels has  
57  
58 been introduced from 2000 in Steidle et al. (2000). Compared to large scale applications, urban  
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4 comprehensive energy system models require a higher focus on end-uses at a disaggregated level.

5  
6 In this study, models and tools are classified according to Connolly et al. (2010) and Timmerman et al.  
7  
8 (2014) in Scenario, Simulation and Hybrid. It should be stated that, besides this classification, any  
9  
10 individual model can have characteristics belonging to different model types making the categorization  
11  
12 ambiguous (Hourcade et al., 2006).  
13  
14

### 15 16 **3.2.2.1 Scenario models and tools**

17  
18 Scenario tools “usually combine a series of years into a long- term  
19  
20 scenario” and “typically function in time-steps of 1 year and combine such annual results  
21  
22 into a scenario of typically 20–50 years” (Connolly et al., 2010). These models and tools determine the  
23  
24 optimum set of technologies necessary to achieve, under fixed constrains, a specific goal/target. They  
25  
26 usually choose the mathematical approach of linear programming (LP), which means the optimization,  
27  
28 under certain constraints, of a linear equation objective function.  
29  
30

31  
32 Urban models based on linear programming approach exist and can be coupled with GIS tools. A GIS  
33  
34 application of LP method has been implemented by Brownsword et al. (2005) to simulate spatial  
35  
36 changes in energy demand profiles. Jennings et al. (2013) implemented an energy system model to  
37  
38 support urban stakeholders in their choice among several building technologies. One of the main  
39  
40 conclusions is to assess the long-term allocation of investments among several alternatives measures in  
41  
42 both demand side and supply side. Other urban models based on LP have been developed by Farzaneh  
43  
44 et al. (2016) to address the urban electric deficiency and by Huang and Yu (2014) for the optimization  
45  
46 of the urban heating energy system.  
47  
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49  
50 Furthermore, there are many existing tools based on LP optimization that can be applied in urban areas.  
51  
52 In particular, authors highlight the Integrated MARKAL-EFOM System (TIMES) developed by the  
53  
54 Energy Technology System Analysis Program. TIMES is a multi-scale economic model generator  
55  
56 suitable for medium (20-50 years) or long-term (up to 100 years) analysis (Loulou et al., 2005). It  
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4 allows creating user defined time-slices (Lewis, 2008; Vaillancourt et al., 2007). TIMES may require  
5  
6 complementary interfaces for the simplification the input/output data management (VEDA or  
7  
8 ANSWER). A recent spatial analysis based on TIMES can be referred to the InSMART project  
9  
10 (InSmart, 2015).  
11

12  
13  
14 Another important scenario tool based on LP-optimization techniques is the Open Source Energy  
15  
16 Modelling System (OSEMOSYS) where the structure of time-periods is not multi-year, but a single  
17  
18 year structure (Timmerman et al., 2014), with particular attention on the capability of modelling Smart  
19  
20 Grids (Howells et al., 2011; Welsch et al. 2012). To the best of the authors, any urban application of  
21  
22 OSEMOSYS exists in current literature, but the structure of the model allows to be scaled for urban  
23  
24 and regional analyses.  
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### 28 **3.2.2.2 Simulation models and tools**

29  
30  
31 Simulation tools “simulate the operation of a given energy system to supply a given set of energy  
32  
33 demands” and “are operated in hourly time-steps over a one-year time-period”.

34  
35  
36 As reviewed by Mendes et al. (2011), starting from the concepts of micro-grids and distributed  
37  
38 generation some models have been developed. The Hybrid Optimization Model for Electric  
39  
40 Renewables (HOMER) is an open source energy system simulation model, which searches for the best  
41  
42 mix of technologies able to minimize the total life cycle cost. Some applications of HOMER can be  
43  
44 found in Bahramara et al. (2016) and in the (NREL, 2016). It can be integrated with the Village Power  
45  
46 Optimization of Renewable (ViPOR) to design the distribution grid of a local area. ViPOR requires a  
47  
48 GIS import of spatial data, but can only be used for electric analysis, neglecting the thermal aspect.  
49

50  
51  
52 Another model focused on distributed generation is the Distributed Energy Resources Customer  
53  
54 Adoption Model (DER-CAM). It is based on Mixed-Integer Linear Programming optimization  
55  
56 techniques (Siddiqui et al., 2001). It aims at finding the most suitable combination of technological  
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58 solution, their relevant size and operational profiles. A link with GIS tools to catch layout constraints  
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4 and site new tech has been proposed by (Edwards et al., 2002). With similar purpose and approach, the  
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6 Economic Evaluation of Micro-grids (EAM) has been developed by (Asano and Bando, 2006).

7  
8  
9 One of the most widespread simulation models is EnergyPLAN. It is a deterministic input/output  
10  
11 simulation model that has been built up for modelling the energy system at both national and regional  
12  
13 scales (Ma et al., 2014; Østergaard, 2013). The model has been designed to analyse regulation  
14  
15 strategies of complex energy systems (Lund, 2007; Østergaard, 2015).

### 18 19 **3.2.2.3 Hybrid tool**

20  
21 Considering the limitations of single approaches, hybrid models have been developed to combine  
22  
23 scenario models with simulation models (Timmerman et al., 2014). An example of hybrid tool is the  
24  
25 Long-range Energy Alternatives Planning (LEAP) which comes from OSEMOsSys (Heaps, 2016). It  
26  
27 describes both demand and supply side of the energy system considering all the economic sectors,  
28  
29 tracking the environmental impact of each technological choice. It has been widely applied in recent  
30  
31 years at both national (Bautista, 2012) and urban and regional levels for comprehensive energy  
32  
33 planning purposes (Kadian et al., 2007b; Nojedehe et al., 2016; Winkler et al., 2006). The time horizon  
34  
35 of LEAP is unlimited and characterized by a series of years, split into time slices.

36  
37 Comprehensive energy system analyses aren't widely used for UR\_ IEP yet, however, they can be used  
38  
39 to perform spatial urban building energy analyses.

40  
41 Table 2 summarizes the most important characteristics of the described tools of (Section 3.2.2) in order  
42  
43 to facilitate the readers to choose the most appropriate one for their research.

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45  
46 Table 2. Comprehensive energy system tools and models characteristics

## 47 48 49 50 51 52 53 **3.3 Phase III-Prioritization and decisional process**

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57 Due to uncertainties, technology diversity and conflicting interests of actors, the prioritization and  
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59 decision process should be integrated into the UR-IEP procedure (Mirakyan and De Guio, 2013).

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4 As it can be observed in Section 3, energy and environmental analyses have traditionally considered a  
5  
6 single measurement criterion, as costs benefit maximization, to make their decisions (Greening and  
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8 Bernow, 2004). However the conflicting and multidimensionality concept of long-term urban  
9  
10 sustainable development matters cannot be relied on just a single criterion. Moreover, UR-IEP should  
11  
12 be sustained by collaborative and inclusive processes since cities are dynamic living organisms that are  
13  
14 continuously evolving (Lombardi and Ferretti, 2015). In this regard, it is necessary the use of the  
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16 appropriate tools and methods to address complex interactions of energy planning problems.  
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21 Multi-Criteria Decision Analysis (MCDA) is an integrated form of a sustainability evaluation. It  
22  
23 provides well-established decision support tools for energy development because of the multi-  
24  
25 dimensionality of the sustainability goal (Wang et al., 2009a). However, MCDA approach cannot make  
26  
27 the actual decisions by itself, but it should aid decision makers to make better decisions. A huge  
28  
29 number of MCDA models and approaches are available in the literature (Herbert A Simon, 1977;  
30  
31 Simon, 1960).  
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36 The general MCDA process in sustainable decision-making is shown in Figure 5 according to (Pohekar  
37  
38 and Ramachandran, 2004; Sharifi and Rodriguez, 2002; Wang et al., 2009a). As it can be seen in  
39  
40 Figure 5 , generally, the first phase in MCDA consists in formulating the problem and alternatives for  
41  
42 sustainable energy decision-making problem, setting the evaluation sustainable criteria and normalizing  
43  
44 both quantitative and qualitative criteria data. Afterward, criteria weights are defined to show their  
45  
46 impact performance. It is then necessary to structure the model and the evaluation matrix (acceptable  
47  
48 criteria and alternatives matrix). Finally, after selecting the appropriate method, it can assess and  
49  
50 evaluate the alternatives in order to rank/sort/choice/describe them. To ensure the consistency of the  
51  
52 obtained result, a sensitivity analysis should be performed.  
53  
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57  
58 Figure 5. MCDA process in sustainable energy decision-making, elaborated from (Pohekar and Ramachandran, 2004; Sharifi and  
59  
60 Rodriguez, 2002; H.A. Simon, 1977; Wang et al., 2009b).  
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4 So far, there are a number of MCDA review methods in the literature regarding the sustainable energy  
5  
6 planning. The most comprehensive review of Decision Analysis in energy and environment modelling  
7  
8 was presented by Huang et al. (1995). The study conducted by Greening and Bernow (2004) has  
9  
10 surveyed the application of MCDA methods. The importance of MCDA methods and energy-related  
11  
12 environmental studies have been underlined also by Zhou et al. (2006). In this survey, more than 250  
13  
14 studies have been reviewed in order to classify the MCDA methods according to the application type  
15  
16 and methods. Furthermore, the literature review conducted by Løken (2007) has emphasized that  
17  
18 energy planning is a suitable field for the use of MCDA. Pohekar and Ramachandran (2004) have  
19  
20 reviewed the application areas of MCDA in energy planning. They found out that the commonly  
21  
22 applied MCDA methods are multi-objective optimization, AHP, PROMETHEE, ELECTRE, MAUT,  
23  
24 fuzzy methods and decision support systems (DSS). DSS are interactive computer aided methods  
25  
26 which can support the decision makers in the collaborative, participative, criteria/alternatives selection  
27  
28 procedure (Pohekar and Ramachandran, 2004).  
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35 Although the MCDA aims at presenting the most suitable plan, it should fulfil the understanding of the  
36  
37 multi-criteria complex situation by supporting the interactive planning, helping people to express their  
38  
39 value judgments, and documenting the values and the alternatives of each recommendation (Mirakyan  
40  
41 and De Guio, 2013). However, since the energy consumption at the built environment is influenced by  
42  
43 many different features, urban energy planners, and decision makers need proper MCDA tools to  
44  
45 identify potential areas where improvement is necessary (Chalal et al., 2016). This requires data  
46  
47 visualization of the geographical locations of alternatives. McHarg was the first one who used maps to  
48  
49 make decisions (McHarg, 1969). The use of maps in decision-making processes has been defined in  
50  
51 1991(Charlton and Ellis, 1991). GIS produces thematic maps and performs spatial operations, while  
52  
53 Multi-criteria methods translate these maps into value maps (Arciniegas et al., 2011).  
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4 Due to this reason, in the last two decades, a lot of geospatial data processing have been done to gain  
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6 information for decision making processes and many spatial decision problems gave rise to the GIS-  
7  
8 based multi-criteria spatial decision support system (MC-SDSS) (Malczewski, 2006). Interestingly,  
9  
10 these two tools take advantage of each other (Laaribi et al., 1996). According to Chakhar and Martel  
11  
12 (2003) the components of the SDSS are :(i) acquire, manage and store the spatially-referenced data, (ii)  
13  
14 perform the analysis of spatial problems, and (iii) provide to the decision maker and/or analysts an  
15  
16 interactive, convivial and adequate environment to perform an effective visual decision-aid activity.  
17  
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20  
21 The main advantage of MC-SDSS is the fact that the decision makers are able to express and exert their  
22  
23 preferences with respect to evaluation criteria and/or alternatives, and consequently, get back feedback  
24  
25 in order to increase the decision makers trust in the results. Moreover, they are powerful visualization  
26  
27 tools through which maps become a '*visual index*' in order to offer solutions to the planners to optimize  
28  
29 the conditions (Andrienko and Andrienko, 1999; Chakhar, S; Martel, 2003; Jankowski et al., 2001).  
30  
31

32  
33 Some of the existing SDSS/MC-SDSS tools related to sustainable energy planning are presented.  
34

35  
36 Among SDSS, MEU (Urban Energy Management) (Rager et al., 2013) is a web-based platform, which  
37  
38 integrates with CitySim (Robinson et al., 2009) to develop different energy demand and supply  
39  
40 scenarios, including GIS-based visualization of the results. It permits to continuously monitor annual  
41  
42 energy flows, consumptions and related actions (Puerto et al., 2015).  
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45  
46 Another open source SDSS tool for scenario development and simulation for the city scale is UrbanSim  
47  
48 (Waddell, 2007). It is an integrated platform to share data, design alternative plans, simulate the  
49  
50 impacts of those plans over time, and visualize outcomes in 3D. This platform analyses the impacts of  
51  
52 alternative scenarios, adopts UrbanCanvas for interactive design, UrbanSim Commons to share data on  
53  
54 the cloud. This tool is not specifically produced for the building sector; however, it is used to evaluate  
55  
56 alternative transportation and land use plans taking into account the building stock evolution.  
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4 Additional example is DIMMER (District Information Modelling and Management for Energy  
5  
6 Reduction) Dashboard/Portal\_(Lombardi et al., 2014). It is an open platform for existing and real-time  
7  
8 data processing and visualization to support decision making by energy managers and public  
9  
10 authorities, monitoring district energy data. DIMMER integrates Building Information Model (BIM),  
11  
12 System Information Model (SIM) and Geographic Information System (GIS).  
13

14  
15  
16 InViTo (Interactive Visualisation Tool) (Pensa and Masala, 2014) is an interactive SDSS web interface  
17  
18 to support users in the exploration of spatial data. The tool aims at providing a structured framework to  
19  
20 aid users in accessing and interrogating a geo-referenced spatial thematic database. InViTo works with  
21  
22 GIS database and relies on free and open web technologies such as Google Maps and Google Fusion  
23  
24 Tables.  
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27  
28 An ongoing project to support decision makers and other stakeholders towards ‘Smart’ City is  
29  
30 INDICATE\_(MELIA et al., 2015). It aims at developing a SDSS interactive cloud-based tool, which  
31  
32 will provide a dynamic assessment of the interactions between buildings, electricity grid, renewable  
33  
34 technologies and Information Communication Technologies (ICT).  
35  
36

37  
38 The integration of SDSS tools with MCDA (MC-SDSS)\_has been widely applied in the field of urban  
39  
40 energy planning, especially in the siting of renewable energy technologies in land use. Few tools have  
41  
42 been developed for energy analysis in the built environment but they can potentially be adapted for it.  
43  
44

45 In this section, both are considered.  
46

47  
48 For example, CommunityVIZ\_(Kwartler and Bernard, 2001) is an ArcGIS extension decision support  
49  
50 system for community planning, which allows to provide different interactive visualization and  
51  
52 understand their potential impacts (Lieske and Hamerlinck, 2013). It consists of two components: i.  
53  
54 Scenario 360 for communication, analysis, and engagement; ii. Scenario 3D for three-dimensional  
55  
56 visualization. It could be integrated into energy analysis and planning (Novak et al., 2012).  
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4 FASUDIR-IDST (Friendly and Affordable Sustainable Urban District Retrofitting-Development of  
5  
6 Decision Support Tool)\_(Barbano et al., 2015) is an interactive decision support tool to analyse the  
7  
8 effect of the building retrofitting strategies on the sustainability of the urban district. It features a 3D  
9  
10 graphical user interface, in order to facilitate the interaction between the multiple stakeholders involved  
11  
12 in the decision-making process.  
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15  
16 Another example is AHP in ArcGIS. It is a very strong ArcGIS extension which determines a criteria  
17  
18 weight considering the well-known Analytic Hierarchy Process (AHP) (Saaty, 1980).  
19  
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21 Table 3 summarizes the most important characteristics of the explained tools of (Section 3.3) in order  
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23 to facilitate the readers to choose the most appropriate one for their research and applications.  
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27 Table 3. SDSS and MC-SDSS tools characteristics  
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## 30 31 **4 Results**

32  
33 This section provides a meta-analysis and SWOT analysis for providing information and insights on  
34  
35 how the various UR-IEP approaches can be integrated to handle the entire planning procedure.  
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37

### 38 **4.1 Meta-analysis of previous literature**

39  
40 Over the 146 articles, 80 papers on the UR-IEP application have been identified. These papers have  
41  
42 been classified based on three criteria for the purpose of presenting results effectively: the year of  
43  
44 publication, the level of integration of UR-IEP phases and the types of combination of methodology.  
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48 In Figure 6, the results of the meta-analysis are shown.  
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50  
51 Figure 6. Meta-analysis of previous papers  
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- 53 • The level of integration. Phase I is always integrated with the other UR-IEP phases since it is  
54 the necessary basis of the entire planning procedure. Phase II is the most widespread phase,  
55 involving a total of 70 papers out of 80, accounting for 87,5% (27 papers integrate Phase I with  
56 Phase II, 36 papers belong to Phase II only and only 7 papers include all the Phases). Since  
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4 Phase III is the prioritization and decisional process, complementary to the other Phases, it is  
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6 required to be integrated. The Figure shows that 17 papers (21,25%) are referred to Phase I, of  
7  
8 which 10 papers integrate Phase I and III while 7 papers integrate all the Phases. The most  
9  
10 important finding, relevant to be highlighted, is that the full integration of the different Phases is  
11  
12 reported by only 8,75% of the papers (7 papers).  
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- 16  
17 • Methods (shape of the bullets in Figure 6). According to the previous studies, the possible  
18  
19 combinations of methodologies have been classified in: (i) Methodology isolationism: one  
20  
21 method for one paradigm; (ii) Methodology enhancement: enhancing a methodology by  
22  
23 exploiting other methodologies; (iii) Methodology combination: combining methodologies in a  
24  
25 unique intervention; (iv) Multi-methodology: combining parts of different methodologies  
26  
27 (Mirakyan and De Guio, 2013); (Mingers and Brocklesby, 1997). A total of 36 papers (45%),  
28  
29 which are classified in Phase II by a circle shape (○), perform the methodology isolationism by  
30  
31 proposing urban energy modelling approach without integration. 35 of reviewed papers  
32  
33 (43,75%), shaped as a triangle (Δ), belong to Methodology enhancement classification since  
34  
35 they enhanced the proposed approach by using GIS tools. Further, regarding to the  
36  
37 Methodology combination shaped as a square (□), 6 papers (7,5%) have combined their  
38  
39 approaches in a unique intervention. Finally, the remaining 3 papers (3,75%) shaped as (\*),  
40  
41 have combined different parts of different methodologies in a Multi-methodology.  
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- 50 • Year of publication (colour of the bullets in Figure 6). The most important output from this  
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52 analysis is that the UR-IEP is a very recent research topic. In fact, 78 papers (97,5%) have been  
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54 published after 2000, red and blue bullets. Two other papers are older, but still relevant for the  
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56 survey field.  
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4 In comparing the reviewed papers based on the three aforementioned criteria, this meta-analysis first  
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6 recognises that in urban energy planning the number of papers that fully integrate the UR-IEP Phases  
7  
8 are very few and very recent.  
9

10  
11 Finally, one can say that although there are several examples of urban energy planning approaches  
12  
13 there is still not a well-recognised procedure and an integrated method to face the UR-IEP.  
14  
15

## 16 **4.2 SWOT analysis**

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18  
19 From this review, it has emerged that a broad range of available individual approaches for sustainable  
20  
21 urban energy planning exists (see Figure 6). A SWOT analysis is presented in Figure 7 to discuss the  
22  
23 main strengths, weaknesses, opportunities and threats of each available spatial approach described in  
24  
25 previous sections.  
26  
27

28 Figure 7. SWOT analysis related to the presented approaches.  
29

30 Under the headings of Figure 7 the following considerations are derived:  
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- 33  
34 • Phase II/Urban Building Energy Modelling: detailed information on the building stock  
35  
36 and its retrofit potential can be derived, also relevant for design purposes. Among these  
37  
38 models, the choice between archetype and regression methods mostly depends on data  
39  
40 availability (i.e. structural data for archetype and real consumption data for regression)  
41  
42 and the willingness to explore retrofit solutions (archetype) or to forecast energy  
43  
44 consumption (regression).  
45  
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- 47  
48 • Phase II/Urban Comprehensive Energy System modelling: interdependencies between  
49  
50 the building sector and the other sectors can be captured, but a lower level of data on the  
51  
52 component descriptions is required. Simulation tools are mainly concentrated on the  
53  
54 feasibility and operation of renewable energy applications, distributed generation and  
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56 smart micro-grid with a high time resolution. However, scenario tools are mostly used  
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4 for creating long-term investment strategies to fulfil government targets at the minimum  
5  
6 system cost. In this case, the time resolution is lower in comparison to simulation tools.  
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- 9
- 10 • Phase III/Spatial Decision Support Systems: tool to build alternative actions, to express  
11 different and conflicting objectives, and to explore the different aspects that can  
12 influence final decisions. In addition, these tools can take into account both quantitative  
13 and qualitative aspects, considering all sustainability pillars. In this regard, a huge  
14 amount of data is required to compute all different aspects (i.e. social, environmental  
15 and economic). In some of these tools the MC methods are integrated into their  
16 application (MC-SDSS), and for the others, the MC analysis should be integrated  
17 exogenously (SDSS). This means that, once the scenarios are defined in the SDSS, the  
18 MC analysis will be performed separately.  
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33 From the SWOT analysis, urban energy planners can recognize how the weaknesses of the different  
34 approaches can be rectified by the strengths of others. Accordingly, the urban actors can realize which  
35 approach could be proper for their planning purposes. Therefore, the presented SWOT analysis may  
36 guide and support urban actors in the choices among the summarized individual approaches by  
37 highlighting the main characteristics. Furthermore, the SWOT analysis is extremely helpful to urban  
38 energy planners and decision makers since models become useful when the users are aware of the  
39 models' advantages and limitations in order to make effective decisions (Cheng and Steemers, 2011).  
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### 50 **4.3 Major findings**

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52 After presenting the results of the systematic review, in the following section the major findings are  
53 summarized to give new insights for future research and extend existing research.  
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57 Taking into account the aforementioned considerations emerging from meta-analysis and SWOT  
58 analysis, Figure 8**Error! Reference source not found.** shows which approaches are suitable for  
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4 creating the different scenarios explained in Section 2.1. Moreover, this figure illustrates the possible  
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6 integration of different methods to help the urban actors in performing the whole UR-IEP procedure.  
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11 Figure 8, Approaches suitability for creating future scenarios and integrating with other phases. The barred bullets mean the possible  
12  
13 integration methods in Phase II in order to improve one of them.  
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16 As shown in Figure 8, Phase I must be integrated with all other phases in a spatial framework due to  
17  
18 the necessity of handling a large volume of data (i.e. the building energy demands and the relative  
19  
20 retrofit potential) to improve significantly the quality of planning and decision-making processes.  
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24 In Phase II, it is possible to interlink more than one method when it is deemed necessary. For instance,  
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26 the output of the Archetype models could be used as the input of comprehensive energy system models  
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28 (e.g. energy requirement of a building typology and retrofit solutions).  
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31 Phase III should be integrated with all the methodologies of Phase I and II to support a collaborative  
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33 process, to better visualize the structure of group decision problems, and organize communication  
34  
35 among participants. Therefore, in order to obtain an effective UR-IEP, decision making for  
36  
37 sustainability should be broadened to include the participation of stakeholders. In this context,  
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39 collaborative SDSS and MC/SDSS based on spatial knowledge and on expert systems are more  
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41 appropriate to tackle the problem.  
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46 Existing tools are very effective in modelling energy consumption but not very effective in structuring  
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48 urban planning problems.  
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51 The authors point out some of the most relevant findings of the review and some insights for future  
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53 research developments. The major findings cover three points:  
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- 55 1. Urban energy planning has to take into consideration an integrated approach: considering that  
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57 energy planning is complex and multi-disciplinary, from the in-depth analysis of the state of the  
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59 art, the main challenge for future research is to integrate the existing different methodologies in  
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4 an agreed structure in order to enhance the quality and robustness of the planning results. In  
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6 fact, although the research field of energy planning has become progressively important at  
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8 urban and regional scales, performing the entire energy planning process by integrating  
9  
10 different approaches is still not a common practice. The discussion so far underlines that the  
11  
12 advantage of integrating different approaches is due to their complementarity in fulfilling  
13  
14 different tasks of the process. Indeed, the preparation of the GIS supportive database allows to  
15  
16 manage and visualize the territorial and socio-economic spatial peculiarities (Phase I); energy  
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18 modelling tools allow to quantitatively analyse the current and future sustainable built  
19  
20 environment evolution (Phase II); while MC-SDSS allows to involve the different actors in the  
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22 decision process and to analyse and choose between the different strategies obtained from the  
23  
24 energy modelling parts (Phase III).  
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32 2. An integrated urban and regional energy planning is an opportunity through which it is possible  
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34 to contribute towards a greater sustainability. The whole process is essential to guarantee a  
35  
36 future sustainable urban transformation by: investing responsibly in alternative consumption  
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38 patterns and greener strategies; speeding the decision-making process through participation and  
39  
40 intuitive visualization; strengthening the collaboration and relationship between research and  
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42 private and public local authorities; leading to various new commercial consequences for the  
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44 environment, economy and society at the national level down to the city level; offering the  
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46 opportunities of engaging stakeholders in the planning process by establishing a shared  
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48 framework between them.  
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54 3. The integrated procedure of urban energy planning faces several barriers. One limitation is  
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56 related to the necessity of changing traditional thinking that may lead users to be discouraged  
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58 since it requires integrating a wide range and diversity of disciplines. Moreover, a high level of  
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4 expertise is required to combine the different methods and to simultaneously handle the  
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6 different sustainability aspects. A second barrier is related to the evaluation process difficulties  
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8 that may be time consuming and certainly costly. This fact emerges from the need of high-level  
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10 data (quantity and quality) and expertise for the assessment processes. Furthermore, the  
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12 availability and reliability of large standardized databases and public data sources is limited at  
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14 the local level. This issue is very challenging since the data is not always open-source and  
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16 updated. Furthermore, the data collection process requires new instruments (e.g. smart meters)  
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18 and new physical resources to analyse them. Finally, there is a necessity to synthesize the  
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20 planning procedure in order to be understandable to decision-makers. This fact is crucial since it  
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22 provides new opportunities for collaboration between non-experts and experts.  
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## 29 **5 Conclusion and future developments**

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32 This study has drawn on an understanding of UR-IEP towards a more sustainable development of the  
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34 built environment. In this paper, a systematic review of the available spatial approaches for performing  
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36 UR-IEP has been proposed. The conclusion attempts to answer the proposed research question in the  
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38 Introduction section. The systematic review showed that many spatial energy modelling approaches  
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40 have been recently developed. Nevertheless, a unique UR-IEP framework is not available or agreed on  
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42 among the several experts and scientific disciplines dealing with sustainable energy planning. From the  
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44 proposed meta-analysis it can be highlighted how the great majority of current approaches do not  
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46 integrate all the phases of UR-IEP. Consequently, not all planning aspects are taken into account in  
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48 conventional practices for guiding policies along sustainable development paths.  
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54 Hence, the authors suggest reinforcing the collaboration between different research disciplines dealing  
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56 with socio-economic, institutional and technical aspects with attention to spatial issues. In order to  
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58 understand how to structure the UR-IEP, it is important to analyse how it is possible to implement the  
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60 interaction among the different stakeholders, how to select different approaches and how to choose  
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4 them considering the decision context peculiarities and the type of planning project. From this  
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6 perspective, the proposed SWOT analysis is useful for all urban actors including, in particular, the new  
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8 practitioner, researchers and decision makers, in understanding the most important characteristics of the  
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10 available approaches for the different planning phases.  
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14 Although the approaches have not yet been integrated in order to cover and accomplish all of UR-IEP,  
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16 it is important to push future research and practice to take into account the integration process.  
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19 Extensive research should be focused on overcoming the barriers identified in the discussion section for  
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21 developing more integrated techniques of various planning approaches related to sustainable urban  
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23 planning horizons. This will allow the possibility to explore urban energy transition strategies in the  
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25 spatial planning field according to sustainable development.  
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28 The ultimate aim of this research is to highlight the potential of existing approaches to be combined in  
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30 order to cover all the UR-IEP phases and to reduce the current uncertainty faced by decision-makers at  
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32 the urban energy planning level. As a preliminary theoretical framework, the outcome helps urban  
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34 actors to (re)develop energy planning projects, guiding them in the choice among a significant number  
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36 of existing planning approaches. Finally, the theoretical framework represents a significant step  
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38 forward in evaluating the built environment in the context of a sustainable urban development. It also  
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40 has the potential of allowing an understanding and evaluation of the concept of sustainable UR-IEP  
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42 over time.  
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#### 54 55 **References**

56  
57 Al-kheder, S., Haddad, N., Fakhoury, L., Baqaen, S., 2009. A GIS analysis of the impact of modern  
58  
59 practices and polices on the urban heritage of Irbid, Jordan. *Cities* 26, 81–92.  
60  
61  
62  
63  
64  
65

- 1  
2  
3  
4 Albeverio, S., Andrey, D., Giordano, P., Vancheri, A., 2008. The dynamics of complex urban systems.  
5  
6 Accademia di Architettura.  
7  
8  
9 Andrienko, G.L., Andrienko, N. V., 1999. Interactive maps for visual data exploration. International  
10  
11 Journal of Geographical Information Science 13, 355–374.  
12  
13  
14 Arciniegas, G., Janssen, R., Omtzigt, N., 2011. Map-based multicriteria analysis to support interactive  
15  
16 land use allocation. International Journal of Geographical Information Science 25, 1931–1947.  
17  
18  
19 Asano, H., Bando, S., 2006. Load fluctuation analysis of commercial and residential customers for  
20  
21 operation planning of a hybrid photovoltaic and cogeneration system. IEEE power engineering  
22  
23 society general meeting 1–6.  
24  
25  
26 Ascione, F., De Masi, R.F., de Rossi, F., Fistola, R., Sasso, M., Vanoli, G.P., 2013. Analysis and  
27  
28 diagnosis of the energy performance of buildings and districts: Methodology, validation and  
29  
30 development of Urban Energy Maps. Cities 35, 270–283.  
31  
32  
33 Aydinalp-Koksal, M., Ugursal, V.I., 2008. Comparison of neural network, conditional demand  
34  
35 analysis, and engineering approaches for modelling end-use energy consumption in the residential  
36  
37 sector. Applied Energy 85, 271–296.  
38  
39  
40 Aydinalp, M., Ugursal, V.I., Fung, A.S., 2004. APPLIED Modelling of the space and domestic 79,  
41  
42 159–178.  
43  
44  
45 Aydinalp, M., Ugursal, V.I., Fung, A.S., 2002. Modelling of the appliance , lighting , and space-  
46  
47 cooling energy consumptions in the residential sector using neural networks 71, 87–110.  
48  
49  
50 Bahramara, S., Moghaddam, M.P., Haghifam, M.R., 2016. Optimal planning of hybrid renewable  
51  
52 energy systems using HOMER: A review. Renewable and Sustainable Energy Reviews 62, 609–  
53  
54 620.  
55  
56  
57 Ballarini, I., Corgnati, S.P., Corrado, V., 2014. Use of reference buildings to assess the energy saving  
58  
59 potentials of the residential building stock : The experience of TABULA project. Energy Policy  
60  
61  
62  
63  
64  
65

1  
2  
3  
4 68, 273–284.  
5

6 Banister, D., Stead, D., 2004. Impact of information and communications technology on transport.  
7  
8 Transport Reviews 24, 611–632.  
9

10 Barbano, G., Mitter, P., Zukowska, E.A., 2015. FASUDIR IDST baseline.  
11

12  
13  
14 Bautista, S., 2012. A sustainable scenario for Venezuelan power generation sector in 2050 and its costs.  
15  
16 Energy Policy 44, 331–340.  
17

18  
19 Bhattacharyya, S.C., Timilsina, G.R., 2010. A review of energy system models. International Journal of  
20  
21 Energy Sector Management 4, 494–518.  
22

23  
24 Börjeson, L., Höjer, M., Dreborg, K.-H., Ekvall, T., Finnveden, G., 2006. Scenario types and  
25  
26 techniques: Towards a user's guide. Futures 38, 723–739.  
27

28  
29 Bottero, M., Ferretti, V., Figueira, J.R., Greco, S., Roy, B., 2015. Dealing with a multiple criteria  
30  
31 environmental problem with interaction effects between criteria through an extension of the  
32  
33 Electre III method. European Journal of Operational Research 245, 837–850.  
34

35  
36 Brandon, P., Lombardi, P., Shen, G., 2016. Future challenge in sustainable urban development. Wiley,  
37  
38 London.  
39

40  
41 Brandon, P.S., Lombardi, P., 2011. Evaluating sustainable development in the built environment,  
42  
43 SECOND EDITION. A John Wiley & Sons, Ltd., Publication.  
44

45  
46 Brownsword, R.A., Fleming, P.D., Powell, J.C., Pearsall, N., 2005. Sustainable cities - Modelling  
47  
48 urban energy supply and demand. Applied Energy 82, 167–180.  
49

50  
51 Bugs, G., Granell, C., Fonts, O., Huerta, J., Painho, M., 2010. An assessment of Public Participation  
52  
53 GIS and Web 2.0 technologies in urban planning practice in Canela, Brazil. Cities 27, 172–181.  
54

55  
56 Caputo, P., Costa, G., Ferrari, S., 2013a. A supporting method for defining energy strategies in the  
57  
58 building sector at urban scale. Energy Policy 55, 261–270.  
59

60  
61 Caputo, P., Costa, G., Zanutto, V., 2013b. A methodology for defining electricity demand in energy  
62  
63  
64  
65

1  
2  
3  
4 simulations referred to the italian context. *Energies* 6, 6274–6292.  
5

6 Chakhar, S; Martel, J.-M., 2003. Enhancing Geographical Information Systems Capabilities with  
7  
8 Multi-Criteria Evaluation Functions. *Journal of Geographic Information and Decision Analysis* 7,  
9  
10 47–71.  
11  
12

13 Chakhar, S., Martel, J.-M., 2003. Enhancing Geographical Information Systems Capabilities with  
14  
15 Multi-Criteria Evaluation Functions. *Journal of Geographic Information and Decision Analysis* 7,  
16  
17 47–71.  
18  
19

20 Chalal, M.L., Benachir, M., White, M., Shrahily, R., 2016. Energy planning and forecasting approaches  
21  
22 for supporting physical improvement strategies in the building sector : A review. *Renewable and*  
23  
24 *Sustainable Energy Reviews* 64, 761–776.  
25  
26

27 Charlton, M., Ellis, S., 1991. GIS in planning. *Journal of Environmental Planning and Management* 34,  
28  
29 20–26.  
30  
31

32 Cheng, V., Steemers, K., 2011. Modelling domestic energy consumption at district scale: A tool to  
33  
34 support national and local energy policies. *Environmental Modelling and Software* 26, 1186–  
35  
36 1198.  
37  
38

39 Connolly, D., Lund, H., Mathiesen, B. V, Leahy, M., 2010. A review of computer tools for analysing  
40  
41 the integration of renewable energy into various energy systems. *Applied Energy* 87, 1059–1082.  
42  
43

44 Corgnati, S.P., Fabrizio, E., Filippi, M., Monetti, V., 2013. Reference buildings for cost optimal  
45  
46 analysis: Method of definition and application. *Applied Energy* 102, 983–993.  
47  
48

49 Cosmi, C., Dvarionenė, J., Marques, I., Di Leo, S., Gecevičius, G., Gurauskienė, I., Mendes, G.,  
50  
51 Selada, C., 2015. A holistic approach to sustainable energy development at regional level: The  
52  
53 RENERGY self-assessment methodology. *Renewable and Sustainable Energy Reviews* 49, 693–  
54  
55 707.  
56  
57

58 Costa, G., 2012. A methodology for assessing energy performance of a large scale building stock.  
59  
60  
61  
62  
63  
64  
65

1  
2  
3  
4 Milano.

5  
6 Dall'O', G., Galante, A., Torri, M., 2012. A methodology for the energy performance classification of  
7 residential building stock on an urban scale. *Energy and Buildings* 48, 211–219.

8  
9  
10  
11 Dascalaki, E.G., Droutsa, K., Gaglia, A.G., Kontoyiannidis, S., Balaras, C.A., 2010. Data collection  
12 and Analysis of the building stock and its energy performance-An example for Hellenic buildings.  
13  
14  
15  
16  
17 *Energy and Buildings* 42, 1231–1237.

18  
19 Delmastro, C., Mutani, G., Corgnati, S.P., 2016. A supporting method for selecting cost-optimal energy  
20 retrofit policies for residential buildings at the urban scale. *Energy Policy* 99, 42–56.

21  
22  
23 Dreborg, K.H., 1996. Essence of backcasting. *Futures* 28, 813–828.

24  
25  
26 Edwards, J.L., Marnay, C., Bartholomew, E., Ouaglal, B., Siddiq, A.S., Lacomme, K.S.H., 2002.

27  
28 Assessment of  $\mu$ Grid Distributed Energy Resource Potential Using DER-CAM and GIS. LBNL.

29  
30  
31 Fabbri, K., Zuppiroli, M., Ambrogio, K., 2012. Heritage buildings and energy performance: Mapping  
32 with GIS tools. *Energy and Buildings* 48, 137–145.

33  
34  
35  
36 Farzaneh, H., Doll, C.N.H., Puppim De Oliveira, J.A., 2016. An integrated supply-demand model for  
37 the optimization of energy flow in the urban system. *Journal of Cleaner Production* 114, 269–285.

38  
39  
40 Favretto, A., 2000. Nuovi strumenti per l'analisi geografica. I GIS - Favretto Andrea - Libro - Patron -  
41  
42 Geografia dello sviluppo territoriale - IBS. bolgna.

43  
44  
45  
46 Fleiter, T., Worrell, E., Eichhammer, W., 2011. Barriers to energy efficiency in industrial bottom-up  
47 energy demand models - A review. *Renewable and Sustainable Energy Reviews* 15, 3099–3111.

48  
49  
50  
51 Fracastoro, G.V., Serraino, M., 2011. A methodology for assessing the energy performance of large  
52 scale building stocks and possible applications. *Energy and Buildings* 43, 844–852.

53  
54  
55  
56  
57 Girardin, L., Marechal, F., Dubuis, M., Calame-Darbellay, N., Favrat, D., 2010. EnerGis: A  
58 geographical information based system for the evaluation of integrated energy conversion systems  
59 in urban areas. *Energy* 35, 830–840.  
60  
61  
62  
63  
64  
65

- 1  
2  
3  
4 Greening, L.A., Bernow, S., 2004. Design of coordinated energy and environmental policies: Use of  
5  
6 multi-criteria decision-making. *Energy Policy* 32, 721–735.  
7  
8  
9 Grubler, A., Bai, X., Buettner, T., Dhakal, S., Fisk, D.J., Ichinose, T., 2012. Urban Energy Systems.  
10  
11 Global Energy Assessment (GEA) Toward a Sustainable Future 1307–1400.  
12  
13  
14 Harrestrup, M., Svendsen, S., 2014. Heat planning for fossil-fuel-free district heating areas with  
15  
16 extensive end-use heat savings: A case study of the Copenhagen district heating area in Denmark.  
17  
18  
19 *Energy Policy* 68, 294–305.  
20  
21 Heaps, 2016. Long-range Energy Alternatives Planning (LEAP) system. Stockholm Environment  
22  
23 Institute. Somerville, MA, USA.  
24  
25  
26 Herbst, A., Toro, F., Reitze, F., Jochem, E., 2012. Introduction to energy systems modelling. *Swiss*  
27  
28 *journal of economics and statistics* 148, 111–135.  
29  
30  
31 Hitchcock, G., 1993. An integrated framework for energy use and behaviour in the domestic sector.  
32  
33  
34 *Energy and Buildings* 20, 151–157.  
35  
36 Hofman, K., Li, X., 2009. Canada's energy perspectives and policies for sustainable development.  
37  
38  
39 *Applied Energy* 86, 407–415.  
40  
41 Hourcade, J.C., Jaccard, M.K., Bataille, C., Gherzi, F., 2006. Hybrid modelling: New answers to old  
42  
43 challenges. *The Energy Journal, International Association for Energy Economics* 2(S), 1–12.  
44  
45  
46 Howard, B., Parshall, L., Thompson, J., Hammer, S., Dickinson, J., Modi, V., 2012. Spatial distribution  
47  
48 of urban building energy consumption by end use. *Energy and Buildings* 45, 141–151.  
49  
50  
51 Howells, M., Rogner, H., Strachan, N., Heaps, C., Huntington, H., Kypreos, S., Hughes, A., Silveira,  
52  
53 S., DeCarolis, J., Bazillian, M., Roehrl, A., 2011. OSeMOSYS: The Open Source Energy  
54  
55 Modelling System. An introduction to its ethos, structure and development. *Energy Policy* 39,  
56  
57 5850–5870.  
58  
59  
60 Huang, J.P., Poh, K.L., Ang, B.W., 1995. Decision analysis in energy and environmental modelling.  
61  
62  
63  
64  
65

1  
2  
3  
4 Energy 20, 843–855.  
5

6 Huang, Z., Yu, H., 2014. Approach for integrated optimization of community heating system at urban  
7 detailed planning stage. *Energy and Buildings* 77, 103–111.  
8

9 Iddrisu, I., Bhattacharyya, S.C., 2015. Sustainable Energy Development Index: A multi-dimensional  
10 indicator for measuring sustainable energy development. *Renewable and Sustainable Energy*  
11 *Reviews* 50, 513–530.  
12  
13

14 IEA, 2016. *Energy Technology Perspectives (Executive Summary)*. Iea 371. doi:10.1787/energy\_tech-  
15 2014-en  
16

17 InSmart, 2015. <http://www.insmartenergy.com/> (accessed 15.06.17).  
18

19 International Energy Agency, 2008. *World energy outlook*, IEA, Paris, France.  
20

21 Jaccard, M., 2005. Sustainable fossil fuels: the unusual suspect in the quest for clean and enduring  
22 energy.  
23

24 Jankowski, P., Andrienko, N., Andrienko, G., 2001. Map-centered exploratory approach to multiple  
25 criteria spatial decision making. *International Journal of Geographical Information Science* 2001,  
26 2.  
27

28 Jennings, M., Munuera, L., Minka McInerney, 2013. Energy modelling to support local authorities in  
29 the transition towards greater energy efficiency of building stock : a case study in North London.  
30 *ECEEE Summer Study Proceedings* 44, 943–948.  
31

32 Jones, P.J., Lannon, S., Williams, J., 2001. *Modelling Building Energy Use At Urban Scale*. Seventh  
33 International IBPSA Conference 175–180.  
34

35 Kadian, R., Dahiya, R.P., Garg, H.P., 2007a. Energy-related emissions and mitigation opportunities  
36 from the household sector in Delhi 35, 6195–6211.  
37

38 Kadian, R., Dahiya, R.P., Garg, H.P., 2007b. Energy-related emissions and mitigation opportunities  
39 from the household sector in Delhi. *Energy Policy* 35, 6195–6211.  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60  
61  
62  
63  
64  
65

- 1  
2  
3  
4 Kavgic, M., Mavrogianni, A., Mumovic, D., Summerfield, A., Stevanovic, Z., Djurovic-petrovic, M.,  
5  
6 2010. A review of bottom-up building stock models for energy consumption in the residential  
7  
8 sector. *Building and Environment* 45, 1683–1697.  
9
- 10  
11 Keirstead, J., Jennings, M., Sivakumar, A., 2012. A review of urban energy system models :  
12  
13 Approaches , challenges and opportunities. *Renewable and Sustainable Energy Reviews* 16, 3847–  
14  
15 3866.  
16  
17
- 18  
19 Kelly, S., 2011. Do homes that are more energy efficient consume less energy?: A structural equation  
20  
21 model for England’s residential sector.  
22
- 23  
24 Krarti, M., Kreider, J., Cohen, D., Curtiss, P., 1998. Estimation of energy saving for building retrofits  
25  
26 using neural networks. *J solar energ eng* 120, 211–216.  
27
- 28  
29 Kwartler, M., Bernard, R.N., 2001. *CommunityViz: An Integrated Planning Support System*. Planning  
30  
31 Support Systems integrating geographic information systems models and visualization tools.  
32
- 33  
34 Laaribi, A., Chevallier, J.J., Martel, J.M., 1996. A spatial decision aid: A multicriterion evaluation  
35  
36 approach. *Computers, Environment and Urban Systems* 20, 351–366.  
37
- 38  
39 Lenzen, M., Wier, M., Cohen, C., Hayami, H., Pachauri, S., Schaeffer, R., 2006. A comparative  
40  
41 multivariate analysis of household energy. *Energy* 31, 181–207.  
42
- 43  
44 Lewis, C., 2008. *Linear Programming: Theory and Application*. Whitman College.  
45
- 46  
47 Li, Z., Quan, S.J., Yang, P.P.J., 2016. Energy performance simulation for planning a low carbon  
48  
49 neighborhood urban district: A case study in the city of Macau. *Habitat International* 53, 206–214.  
50
- 51  
52 Lieske, S.N., Hamerlinck, J.D., 2013. *Integrating Planning Support Systems and Multicriteria*  
53  
54 *Evaluation for Energy Facility Site Suitability Evaluation*. URISA Journal.  
55
- 56  
57 Linnenluecke, M.K., Verreyne, M.-L., de Villiers Scheepers, M.J., Venter, C., 2016. A review of  
58  
59 collaborative planning approaches for transformative change towards a sustainable future. *Journal*  
60  
61 *of Cleaner Production* 142, 1–13.  
62  
63  
64  
65

- 1  
2  
3  
4 Løken, E., 2007. Use of multicriteria decision analysis methods for energy planning problems.  
5  
6 Renewable and Sustainable Energy Reviews 11, 1584–1595.  
7  
8  
9 Lombardi, P., Acquaviva, A., Macii, E., Osello, A., Patti, E., Sonetti, G., 2014. Web and cloud  
10  
11 management for building energy reduction: toward a smart district information modelling, in: Sun,  
12  
13 Z. (Ed.), Demand-Driven Web Services: Theory, Technologies, and Applications. IGI Global,  
14  
15 Pennsylvania, USA, pp. 340–355.  
16  
17  
18 Lombardi, P., Ferretti, V., 2015. New Spatial Urban Decision Support Systems for Sustainable Urban  
19  
20 and Regional Development. Smart and sustainable built environment 4, 45–66.  
21  
22  
23 Loulou, R., Remne, U., Kanudia, A., Lehtila, A., Goldstein, G., 2005. Documentation for the TIMES  
24  
25 Model.  
26  
27  
28 Lund, H., 2007. Renewable energy strategies for sustainable development. Energy 32, 912–919.  
29  
30  
31 Ma, T., Ostergaard, P.A., Lund, H., Yang, H., Lu, L., 2014. An energy system model for Hong Kong in  
32  
33 2020. Energy 68, 301–310.  
34  
35  
36 MacGregor, W.A., Hamdullahpur, F., Ugursal, V.I., 1993. Space heating using small-scale fluidized  
37  
38 beds: A technoeconomic evaluation. International Journal of Energy Research 17, 445–466.  
39  
40  
41 Malczewski, J., 2006. GIS - based multicriteria decision analysis : a survey of the literature 20, 703–  
42  
43 726.  
44  
45  
46 Marien, M., 2002. Futures studies in the 21st century: A reality-based view. Futures 34, 261–281.  
47  
48  
49 Martinez Soto, A., Jentsch, M.F., 2016. Comparison of prediction models for determining energy  
50  
51 demand in the residential sector of a country. Energy and Buildings 128, 38–55.  
52  
53  
54 Mastrucci, A., Baume, O., Stazi, F., Salvucci, S., Leopold, U., Bianche, V.B., 2013. A GIS-based  
55  
56 approach to estimate energy savings and indoor thermal comfort for urban housing stock  
57  
58 retrofitting. Università Politecnica Delle Marche, Resource Centre For Environmental  
59  
60 Technologies .  
61  
62  
63  
64  
65

- 1  
2  
3  
4 Mattinen, M.K., Heljo, J., Vihola, J., Kurvinen, A., Lehtoranta, S., Nissinen, A., 2014. Modelling and  
5  
6 visualization of residential sector energy consumption and greenhouse gas emissions. *Journal of*  
7  
8 *Cleaner Production* 81, 70–80.  
9  
10  
11 McHarg, I., 1969. *Design with nature*. Published for the American Museum of Natural History [by] the  
12  
13 Natural History Press, Garden City N.Y.  
14  
15  
16 MELIA, A., NOLAN, E., Kerrigan, R., 2015. INDICATE: towards the development of a virtual city  
17  
18 model using a 3D model of Dundalk city. *Proceedings of International* 925–930.  
19  
20  
21 Mendes, G., Ioakimidis, C., Ferrão, P., 2011. On the planning and analysis of Integrated Community  
22  
23 Energy Systems: A review and survey of available tools. *Renewable and Sustainable Energy*  
24  
25 *Reviews* 15, 4836–4854.  
26  
27  
28 Mingers, J., Brocklesby, J., 1997. Multimethodology: Towards Theory and Practice for Mixing  
29  
30 Methodologies. *International Journal of Management Science* 25, 489–509.  
31  
32  
33 Miola, A., 2008. Backcasting approach for sustainable mobility, *Communities*.  
34  
35  
36 Mirakyan, A., De Guio, R., 2013. Integrated energy planning in cities and territories: A review of  
37  
38 methods and tools. *Renewable and Sustainable Energy Reviews* 22, 289–297.  
39  
40  
41 Mirakyan, A., Lelait, L., Khomenko, N., Kaikov, I., 2009. Methodological Framework for the analysis  
42  
43 and development of a sustainable, integrated, regional energy plan – A French region case study.  
44  
45  
46 Mistry, J., Tschirhart, C., Verwer, C., Glastra, R., Davis, O., Jafferally, D., Haynes, L., Benjamin, R.,  
47  
48 Albert, G., Xavier, R., Bovolo, I., Berardi, A., 2014. Our common future? Cross-scalar scenario  
49  
50 analysis for social-ecological sustainability of the Guiana Shield, South America. *Environmental*  
51  
52 *Science and Policy* 44, 126–148.  
53  
54  
55 Moll, H.C., Noorman, K.J., Kok, R., Engstr, R., Throne-holst, H., Clark, C., 2005. Pursuing More  
56  
57 Sustainable Consumption by Analyzing Household Metabolism in European Countries and Cities  
58  
59 9, 259–275.  
60  
61  
62  
63  
64  
65

- 1  
2  
3  
4 Mutani, G., Vicentini, G., 2013. *Tecnica con software geografico libero . Il caso studio di Torino*  
5  
6 *Tecnica.*  
7  
8  
9 Mutani, G., Pairona, M., 2014. *Un modello per valutare il consumo energetico per la climatizzazione*  
10 *invernale degli edifici residenziali : il caso studio di Torino.*  
11  
12  
13  
14 Nakata, T., Silva, D., Rodionov, M., 2011. *Application of energy system models for designing a low-*  
15 *carbon society. Progress in Energy and Combustion Science 37, 462–502.*  
16  
17  
18  
19 Nojehdehi, P., Heidari, M., Ataei, A., Nedaei, M., Kurdestani, E., 2016. *Environmental assessment of*  
20 *energy production from landfill gas plants by using Long-range Energy Alternative Planning*  
21 *(LEAP) and IPCC methane estimation methods: A case study of Tehran. Sustainable Energy*  
22 *Technologies and Assessments 16, 33–42.*  
23  
24  
25  
26  
27  
28  
29 Novak, E., Snyder, K., Newman, D., 2012. *Chula Vista Research Project: Integrating Energy Analysis*  
30 *and Planning at the Neighborhood Scale. The Future of Cities and Regions, Springer 245–60.*  
31  
32  
33  
34 NREL, 2016. NREL [WWW Document]. URL <http://www.nrel.gov/>  
35  
36  
37  
38 Oladokun, M.G., Odesola, I.A., 2015. *Gulf Organisation for Research and Development Household*  
39 *energy consumption and carbon emissions for sustainable cities – A critical review of modelling*  
40 *approaches. International Journal of Sustainable Built Environment 4, 231–247.*  
41  
42  
43  
44 Österbring, M., Mata, É., Thuvander, L., Mangold, M., Johnsson, F., Wallbaum, H., 2016. *A*  
45 *differentiated description of building-stocks for a georeferenced urban bottom-up building-stock*  
46 *model. Energy and Buildings 120, 78–84.*  
47  
48  
49  
50  
51 Østergaard, P.A., 2013. *Wind power integration in Aalborg Municipality using compression heat*  
52 *pumps and geothermal absorption heat pumps. Energy 49, 502–508.*  
53  
54  
55  
56 Østergaard, P.A.Ø., 2015. *Reviewing EnergyPLAN simulations and performance indicator applications*  
57 *in EnergyPLAN simulations. Applied Energy 154, 921–933.*  
58  
59  
60  
61 Pelzer, P., Arciniegas, G., Geertman, S., Lenferink, S., 2015. *Planning Support Systems and Task-*  
62  
63  
64  
65

- 1  
2  
3  
4 Technology Fit: a Comparative Case Study. *Applied Spatial Analysis and Policy* 8, 155–175.  
5  
6  
7 Pensa, S., Masala, E., 2014. InViTo: An Interactive Visualisation Tool to Support Spatial Decision  
8  
9 Processes, in: *Technologies for Urban and Spatial Planning*. p. 19.  
10  
11 Pohekar, S.D., Ramachandran, M., 2004. Application of multi-criteria decision making to sustainable  
12  
13 energy planning - A review. *Renewable and Sustainable Energy Reviews* 8, 365–381.  
14  
15  
16 Prasara-A, J., Gheewala, S.H., 2016. Sustainable utilization of rice husk ash from power plants: A  
17  
18 review. *Journal of Cleaner Production*.  
19  
20  
21 Puerto, P., Pernet, M., Capezzali, M., 2015. Towards pre-dimensioning of natural gas networks on a  
22  
23 web-platform 0–15.  
24  
25  
26 Rad, F.D., 2010. Application of Local Energy Indicators in Municipal Energy Planning : A New  
27  
28 Approach Towards Sustainability 48–59.  
29  
30  
31 Rager, J., Rebeix, D., Marechal, F., Cherix, G., Capezzali, M., Maréchal, F., Rager, J., 2013. MEU: An  
32  
33 urban energy management tool for communities and multi-energy utilities. *Cisbat 2013* 897–902.  
34  
35  
36 Robinson, D., Haldi, F., Kämpf, J.H., Leroux, P., Perez, D., Rasheed, a, Wilke, U., 2009. CITYSIM:  
37  
38 Comprehensive Micro-Simulation Of Resource Flows For Sustainable Urban Planning.  
39  
40 International IBPSA Conference 1083–1090.  
41  
42  
43 Rotmans, J., Van Asselt, M., Anastasi, C., Greeuw, S., Mellors, J., Peters, S., Rothman, D., Rijkens, N.,  
44  
45 2000. Visions for a sustainable Europe. *Futures* 32, 809–831.  
46  
47  
48 Saaty, T.L., 1980. *The Analytic Hierarchy Process*. New York.  
49  
50  
51 Saidur, R., Masjuki, H.H., Jamaluddin, M.Y., 2007. An application of energy and exergy analysis in  
52  
53 residential sector of Malaysia. *Energy Policy* 35, 1050–1063.  
54  
55  
56 Sharifi, M. a, Rodriguez, E., 2002. Design and development of a planning support system for policy  
57  
58 formulation in water resources rehabilitation: the case of Alcazar De San Juan District in Aquifer  
59  
60 23, La Mancha, Spain. *Journal of Hydroinformatics [J. Hydroinf.]*. 4, 157–176.  
61  
62  
63  
64  
65

- 1  
2  
3  
4 Shimoda, Y., Fujii, T., Morikawa, T., Mizuno, M., 2004. Residential end-use energy simulation at city  
5  
6 scale 39, 959–967.  
7  
8  
9 Siddiqui, A.S., Marnay, C., Hamachi, K.S., Rubio, F.J., 2001. Customer adoption of small-scale on-site  
10  
11 power generation. LBNL.  
12  
13  
14 Simon, H.A., 1977. Models of discovery : and other topics in the methods of science.  
15  
16 Simon, H.A., 1977. The New Science of Management Decision. Prentice Hall PTR.  
17  
18  
19 Simon, H.A., 1960. The new science of management decision. New York ; Evanston : Harper and Row.  
20  
21 Steidle, T., Schlenzig, C., Cuomo, V., Macchiato, M., Lavagno, E., Rydèn, B., Willemsen, S., Grevers,  
22  
23 W., 2000. Advanced Local Energy Planning, a guidebook, Communities.  
24  
25  
26 Swan, L.G., Ugursal, V.I., 2009. Modelling of end-use energy consumption in the residential sector: A  
27  
28 review of modelling techniques. Renewable and Sustainable Energy Reviews 13, 1819–1835.  
29  
30  
31 Theodoridou, I., Papadopoulos, A.M., Hegger, M., 2011. Statistical analysis of the Greek residential  
32  
33 building stock. Energy and Buildings 43, 2422–2428.  
34  
35  
36 Timmerman, J., Vandeveld, L., Van Eetvelde, G., 2014. Towards low carbon business park energy  
37  
38 systems: Classification of techno-economic energy models. Energy 75, 68–80.  
39  
40  
41 Torabi Moghadam, S., Lombardi, P., Mutani, G., 2016a. A mixed methodology for defining a new  
42  
43 spatial decision analysis towards low carbon cities, In Press. Procedia Engineering.  
44  
45  
46 Torabi Moghadam, S., Mutani, G., Lombardi, P., 2016b. GIS-Based Energy Consumption Model at the  
47  
48 Urban Scale for the Building Stock, in: Bertoldi, P. (Ed.), JRC Conference and Workshop Reports.  
49  
50 European Union, Luxembourg, pp. 56–63.  
51  
52  
53 Tornberg, J., Thuvander, L., 2005. A GIS energy model for the building stock of Goteborg. 2005 Esri  
54  
55 International User Conference.  
56  
57  
58 Unander, F., Etestøl, I., Ting, M., Schipper, L., 2004. Residential energy use: An international  
59  
60 perspective on long-term trends in Denmark, Norway and Sweden. Energy Policy 32, 1395–1404.  
61  
62  
63  
64  
65

- 1  
2  
3  
4 Vaillancourt, K., Labriet, M., Loulou, R., Waaub, J., 2007. The role of nuclear energy in long-term  
5  
6 climate scenarios: An analysis with the World-TIMES model. *Les Cahiers du GERAD G 29*.  
7  
8  
9 Vringer, K., Blok, K., 1995. The direct and indirect energy requirements of households in the  
10  
11 Netherlands. *Energy Policy* 23, 893–910.  
12  
13  
14 Waddell, P., 2007. UrbanSim: Modelling urban development for land use, transportation, and  
15  
16 environmental planning. *Journal of the American Planning Association*.  
17  
18  
19 Walter, T., Sohn, M., 2016. A Regression-based approach to estimating retrofit savings using the  
20  
21 Building Performance Database. *Applied Energy* 179, 996–1005.  
22  
23  
24 Wan, K.S.Y., Yik, F.H.W., 2004. Representative building design and internal load patterns for  
25  
26 modelling energy use in residential buildings in Hong Kong. *Applied Energy* 77, 69–85.  
27  
28  
29 Wang, J.J., Jing, Y.Y., Zhang, C.F., Zhao, J.H., 2009a. Review on multi-criteria decision analysis aid in  
30  
31 sustainable energy decision-making. *Renewable and Sustainable Energy Reviews* 13, 2263–2278.  
32  
33  
34 Wang, J.J., Jing, Y.Y., Zhang, C.F., Zhao, J.H., 2009b. Review on multi-criteria decision analysis aid  
35  
36 in sustainable energy decision-making. *Renewable and Sustainable Energy Reviews* 13, 2263–  
37  
38 2278.  
39  
40  
41 Welsch, M., Howells, M., Bazilian, M., DeCarolis, J.F., Hermann, S., Rogner, H.H., 2012. Modelling  
42  
43 elements of Smart Grids - Enhancing the OSeMOSYS (Open Source Energy Modelling System)  
44  
45 code. *Energy* 46, 3z37e350.  
46  
47  
48 Winkler, H., Borchers, M., Hughes, A., Visagie, E., Heinrich, G., 2006. Policies and scenarios for Cape  
49  
50 Town ' s energy future: Options for sustainable city energy development. *Journal of Energy in*  
51  
52 *Southern Africa* 17, 28–41.  
53  
54  
55 Yamaguchi, Y., Shimoda, Y., Mizuno, M., 2007. Proposal of a modelling approach considering urban  
56  
57 form for evaluation of city level energy management. *Energy and Buildings* 39, 580–592.  
58  
59  
60 Yeo, I., Yoon, S., Yee, J., 2013. Development of an urban energy demand forecasting system to  
61  
62  
63  
64  
65

1  
2  
3  
4  
5  
6  
7  
8  
9  
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52  
53  
54  
55  
56  
57  
58  
59  
60  
61  
62  
63  
64  
65

support environmentally friendly urban planning. *Applied Energy* 110, 304–317.

Yu, B., Zhang, J., Fujiwara, A., 2011. Representing in-home and out-of-home energy consumption behavior in Beijing. *Energy Policy* 39, 4168–4177.

Zhang, Q., 2004. Residential energy consumption in China and its comparison with Japan , Canada , and USA. *Energy and Buildings* 36, 1217–1225.

Zhou, P., Ang, B.W., Poh, K.L., 2006. Decision analysis in energy and environmental modelling: An update. *Energy* 31, 2604–2621.

Highlights:

- A systematic review of existing building energy planning approaches is offered;
- The most relevant spatial urban approaches are highlighted;
- The reviewed papers are analyzed through a Meta-analysis and a SWOT analysis;
- A lack of an integrated framework considering all planning dimensions is revealed;
- A preliminary theoretical framework to integrate different approaches is provided;
- The main barriers and future challenges in the research field are identified.

Figure1

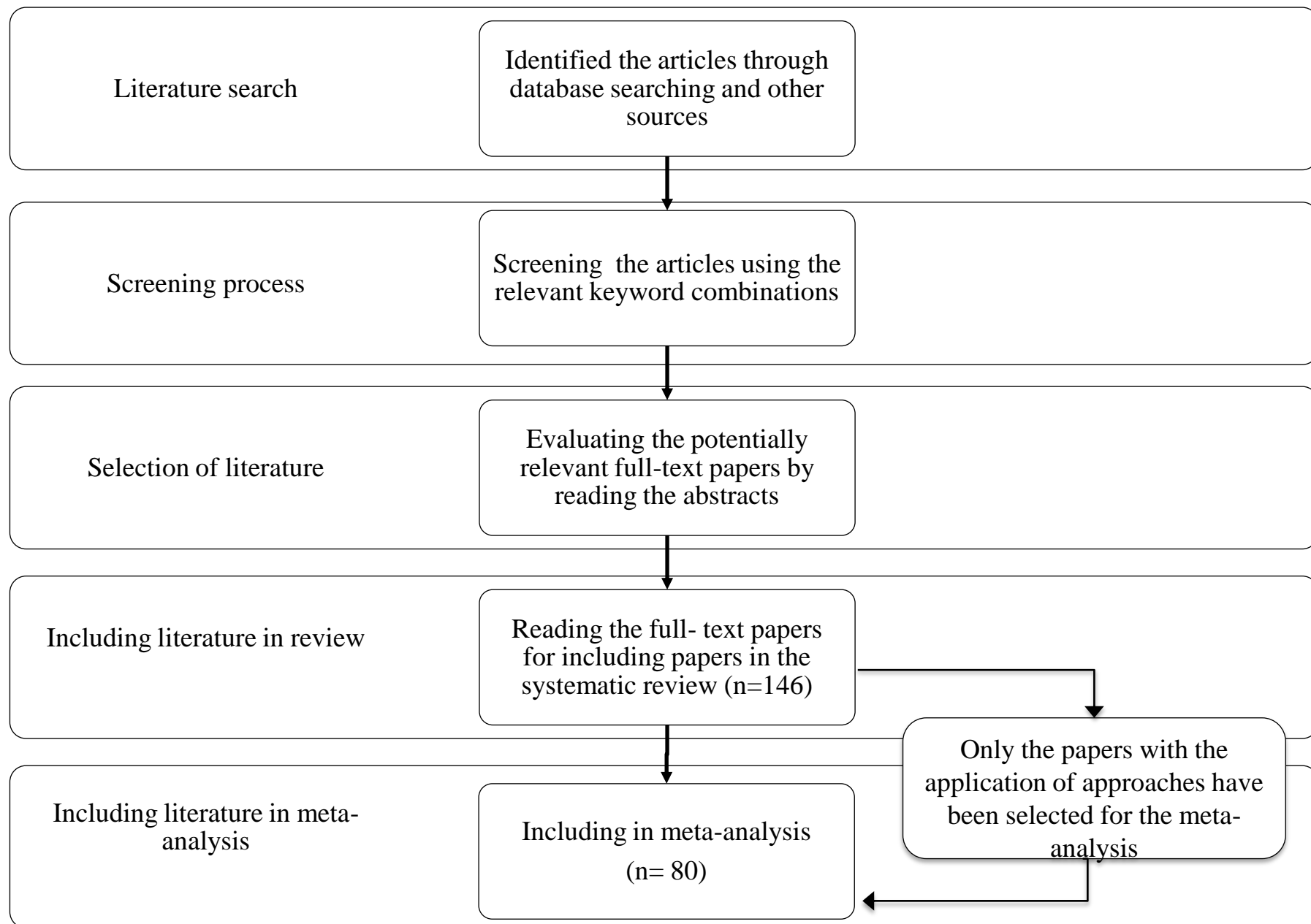


Figure 1. Flowchart of the systematic review outlining the study selection process

Figure2

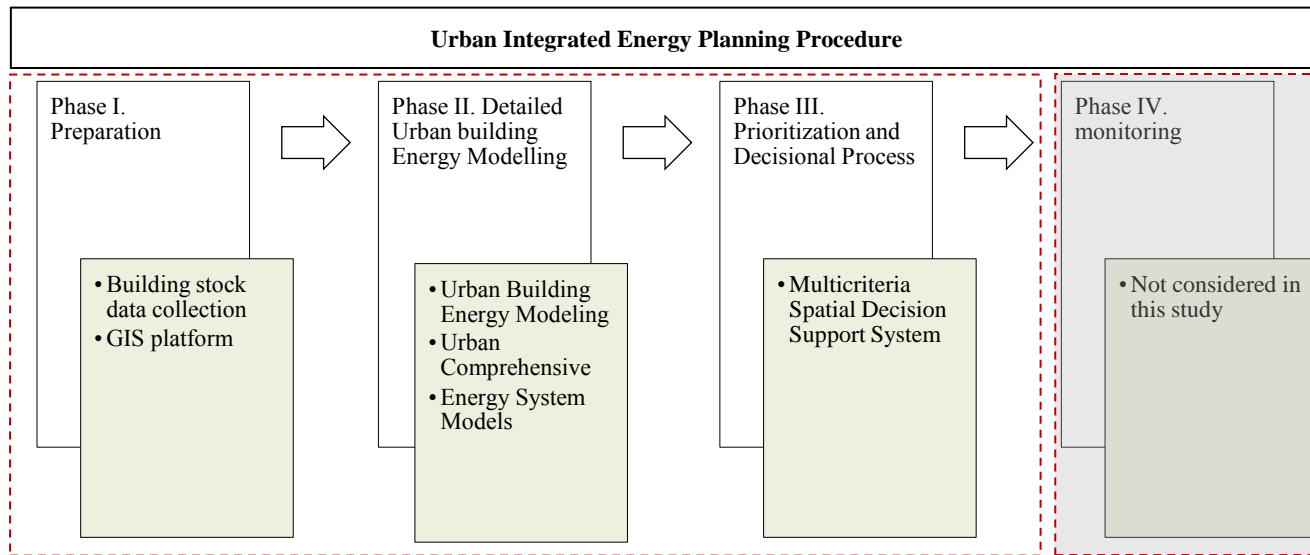


Figure 2. UR-IEP Steps, adapted from (Mirakyan et al. 2009).

Figure3

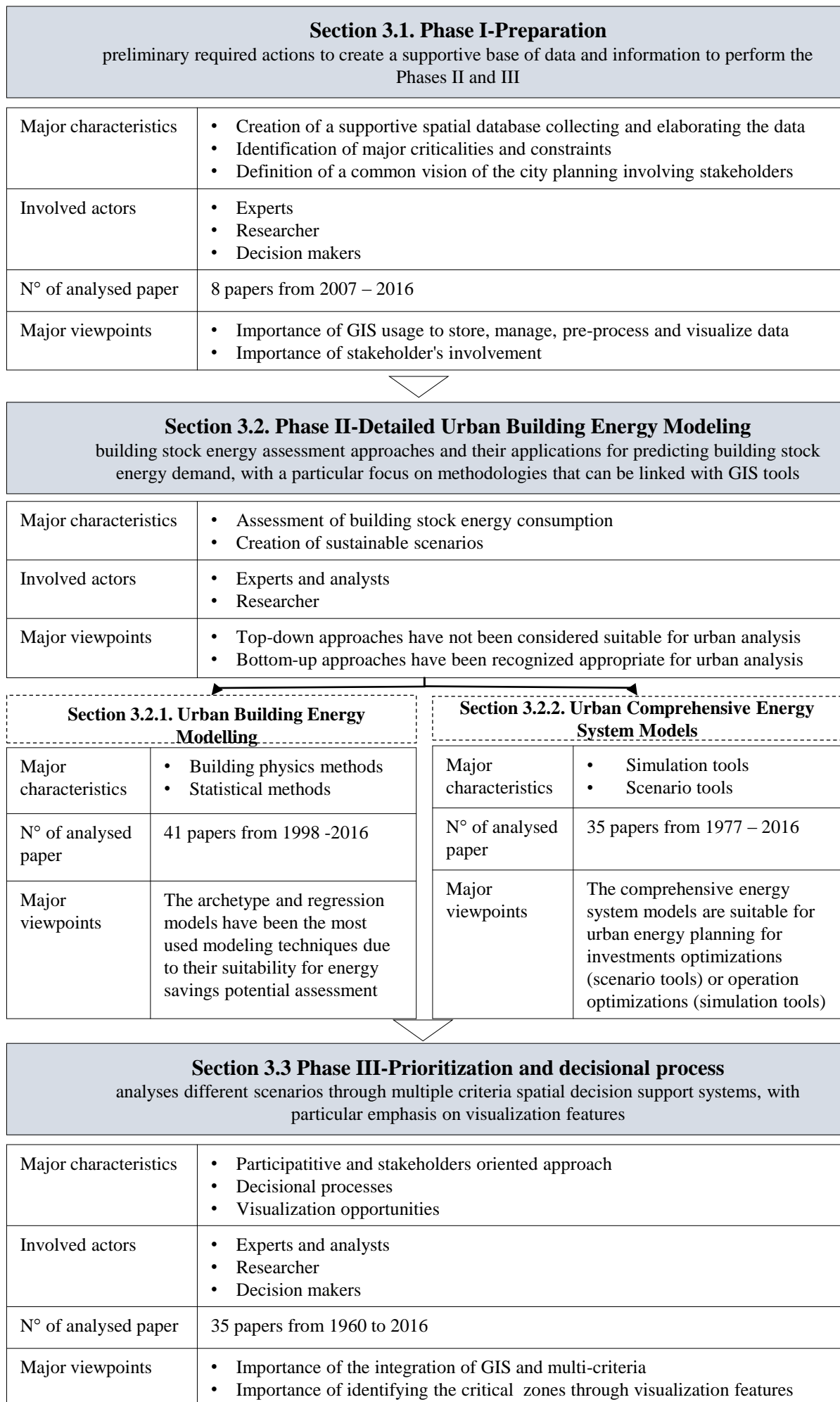


Figure 3. Outline of Section 3

Figure4

Figure 4. Example of the creation of a supportive GIS platform for urban energy planning (Torabi Moghadam et al., 2016b) by overlapping multiple layers, source EEB Project, case study: city of Settimo Torinese.

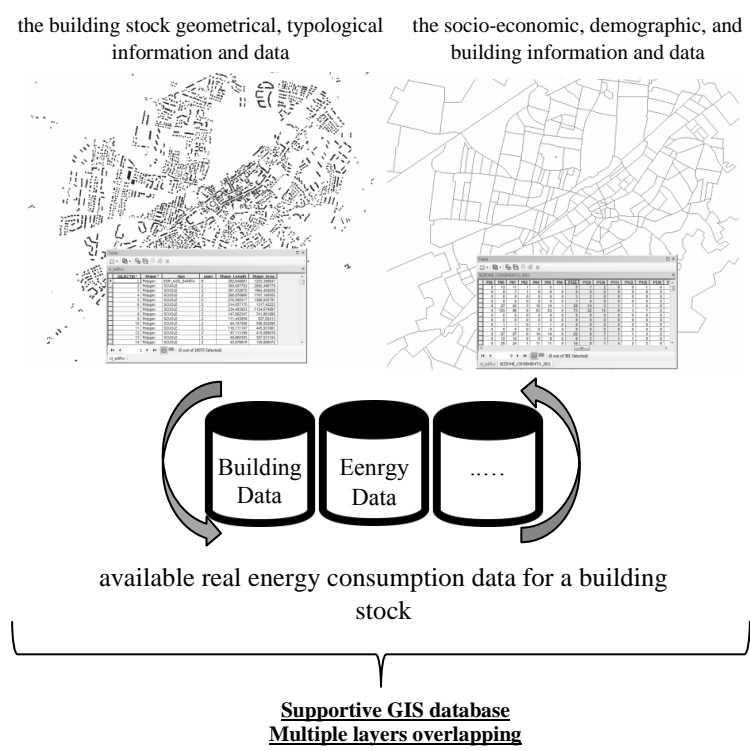


Figure 5

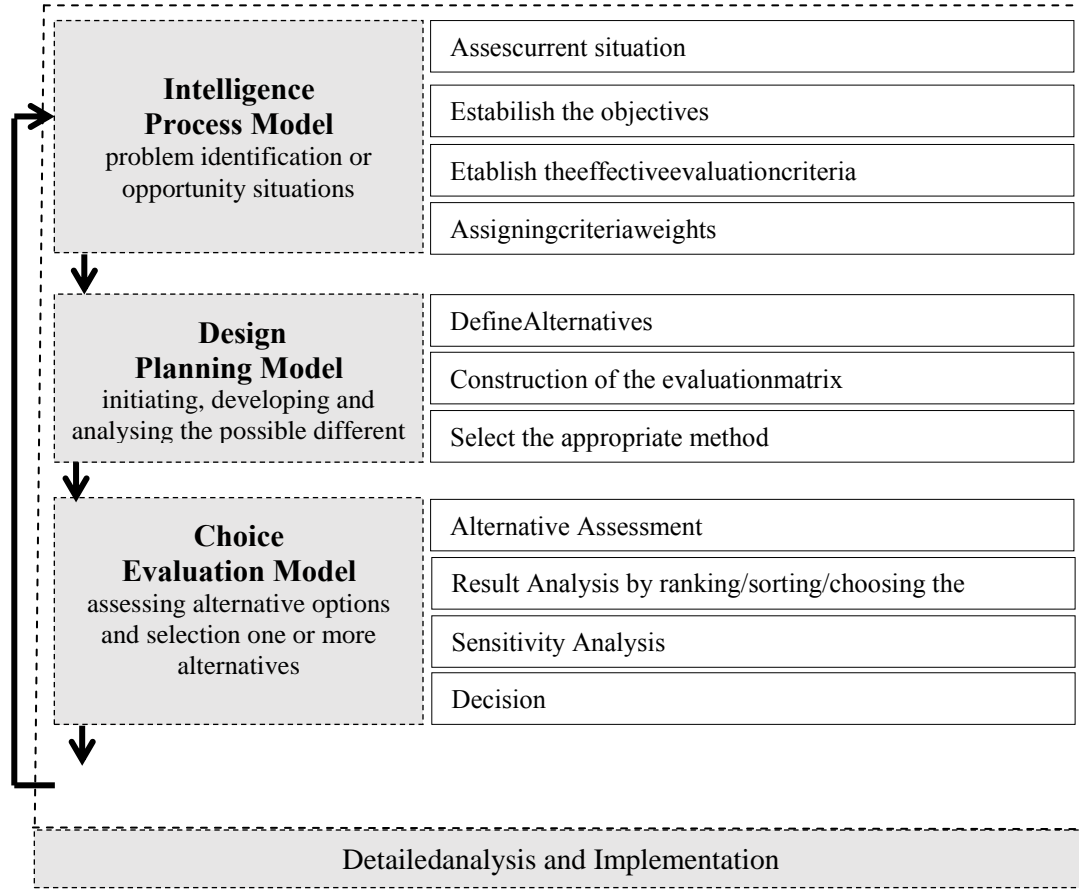


Figure 5. MCDA process in sustainable energy decision-making, elaborated from (Pohekar and Ramachandran, 2004; Sharifi and Rodriguez, 2002; H.A. Simon, 1977; Wang et al., 2009b).

Figure6

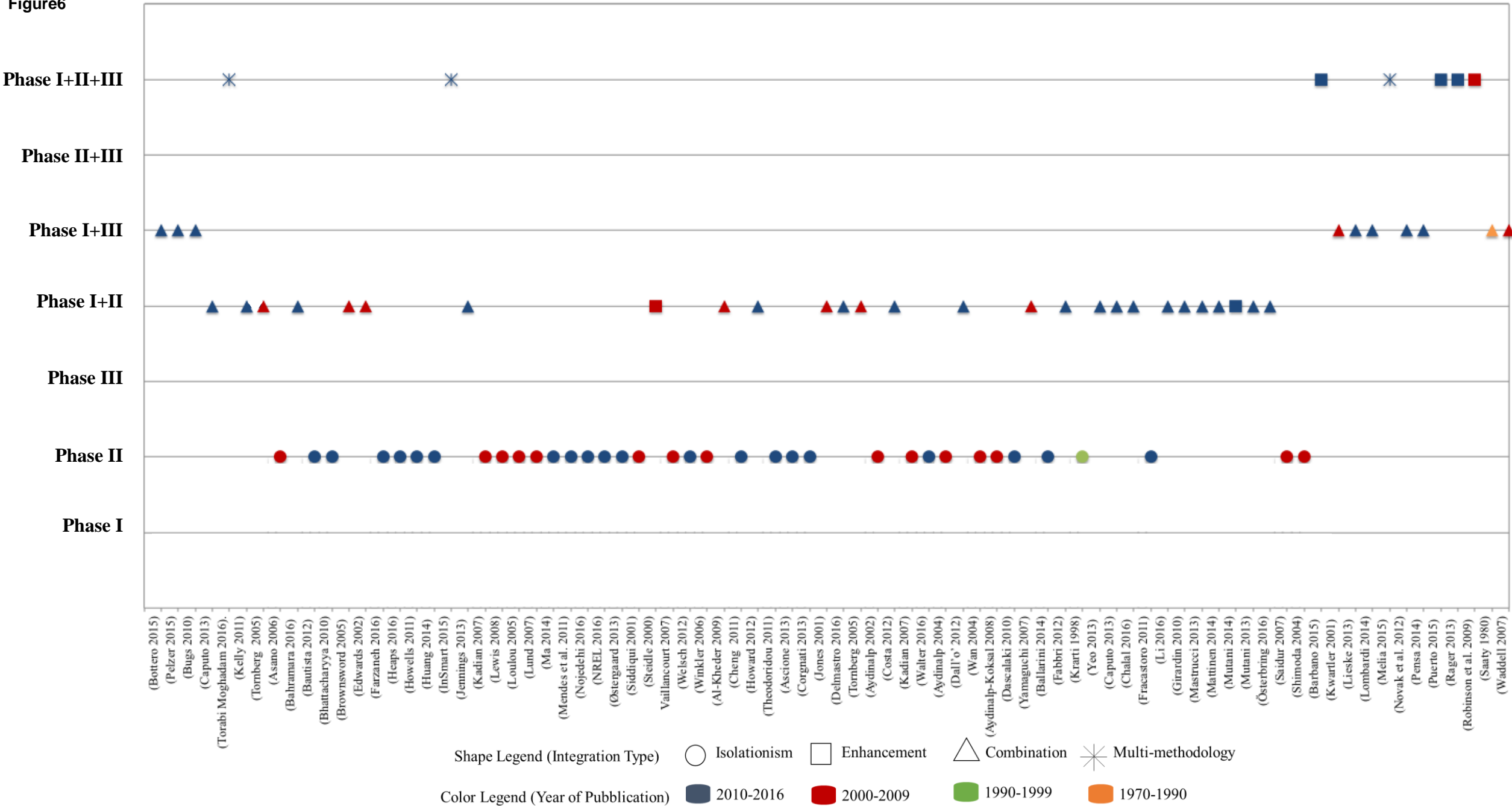


Figure 6. Meta-analysis of previous papers

Figure7

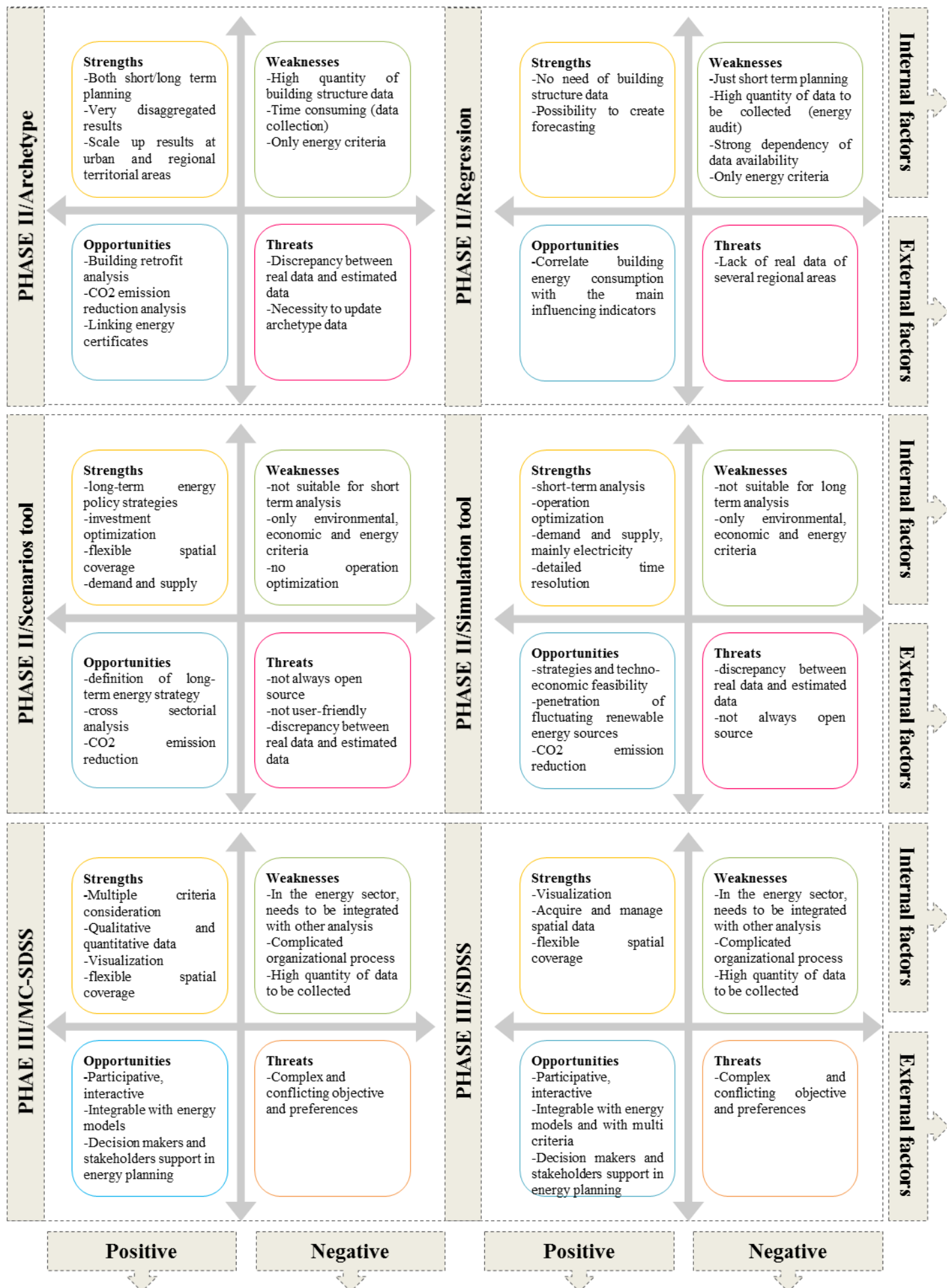


Figure 7. SWOT analysis related to the presented approaches

Figure8

## Scenarios Type

## Integration Possibility

SUITABILITY FOR CREATING FUTURE SCENARIOS	Approaches	Phase I	Phase II	Phase III
PREDICTIVE , EXPLORATIVE, NORMATIVE	● PREPARATION	●	● ● ● ●	●
PREDICTIVE	● REGRESSION	●	● <del>●</del>	●
PREDICTIVE , EXPLORATIVE, NORMATIVE	● ARCHETYPE	●	<del>●</del> ● ● ●	●
PREDICTIVE , EXPLORATIVE	● SIMULATION	●	● ● <del>●</del>	●
EXPLORATIVE, NORMATIVE	● SCENARIOS	●	● <del>●</del> ●	●
PREDICTIVE , EXPLORATIVE, NORMATIVE	● MC-SDSS/SDSS	●	● ● ● ●	●

Figure 8, Approaches suitability for creating future scenarios and integrating with other phases. The barred bullets mean the possible integration methods in Phase II in order to improve one of them.

Table1

Scenarios type	Quantitative/ Qualitative	Time-frame	Main Techniques		
			Generating	Integrating	Consistency
<b>PREDICTIVE_ What will happen? (Probable futures)</b>					
Forecasts	Typically quantitative, sometimes qualitative	Often short	Surveys, Workshops, Original Delphi method	Time series analysis, Explanatory modelling, Optimising modelling	-
What-if	Typically quantitative, sometimes qualitative	Often short	Surveys, Workshops, Delphi method	Explanatory modelling, Optimising modelling	-
<b>EXPLORATIVE_ What can happen? (Possible futures)</b>					
External	Typically quantitative, qualitatively possible	Often long	Surveys, Workshops, Delphi method	Explanatory modelling, Optimising modelling	Morphological field analysis, Cross impact
Strategic	Quantitative and qualitative	Often long	Surveys, Workshops, Delphi methods	Explanatory modelling, Optimising modelling	Morphological field analysis
<b>NORMATIVE_ How can a certain target be reached? (Preferable futures)</b>					
Preserving	Typically quantitative	Often long	Surveys; workshops. Transforming	Optimising modelling	Morphological field analysis
Transforming	Typically quantitative with qualitative elements	Often very long	Surveys; workshops, Backcasting Delphi.	-	Morphological field analysis

Table 1. Future scenarios classification according to (Börjeson et al. 2006); (Banister &amp; Stead 2004).

Table 2. Comprehensive energy system tools and models' characteristics

Name of the tool	TIMES	OSEMOSyS	ENERGYPLAN	DER-CAM	EAM	HOMER	LEAP
Developer	ETSAP	KTH, Stockholm Environmental Institute, IAEA, Energy Research Centre of UK	Dep. of Development and Planning, Aalborg University, DENMARK	LBNL	University of Tokyo	National Renewable Energy Laboratory	Stockholm Environment Institute
Open Source	No	Yes	Yes	Yes, but requires GAMS	Not available to public	Yes	Dependent on type of users
Objective	Long-term energy policy strategies investigation (cost-optimum mix of technologies)	Long-term energy policy strategies investigation (lowest net present value of energy services)	Analysing regulation strategies of complex energy systems, including high penetration of fluctuating renewable energy sources	Evaluate techno-economic feasibility and dispatch optimization of distributed generation systems.	Finding the appropriate size of a microgrid to be economically feasible	Searching the best mix of technologies to meet the local requirements able to minimize the total life cycle cost	Energy policy analysis and climate change mitigation assessment
Type of tool	Scenario/ partial equilibrium	Scenario	Input/output simulation model	Simulation	Simulation	Simulation	Hybrid
Approach	Linear Optimization - MILP/GAMS-CPLEX	Deterministic linear optimisation	Analytical programming	MILP/GAMS-CPLEX	MINLP	Accounting	Accounting/ Simulation
Type of optimization*	Investment	Investment	Operation	Operation and investments	Operation and investments	Operation and investments	Operation and investments
Spatial Coverage	User defined: National/Regional/Local/Multi-Country	User defined: local, national, global	User defined: local, national	Local level	Local level	Local level	User defined: local, national, global
Covered Sectors	Energy System (demand and supply) and Energy Trading	Energy system (demand and supply, mostly for electricity sector)	Energy system (demand and supply)	Heat and Electricity, distributed generation, micro-grids	Heat and Electricity, distributed generation, micro-grids	Heat and Electricity, distributed generation, micro-grids	Energy system (demand and supply), environment
Activities disaggregation	User-defined	User-defined	Pre-defined	User-defined	Pre-defined	Pre-defined	User-defined
Time resolution	Medium to long-term analysis user defined time steps	Medium to long term, user-defined time-step	Short-term, 1 year time period and 1 hour time step	Short-term, 1 year time period and 1 hour time step	Short-term, 1 year time period and 1 hour time step	Short-term, 1 year time period and user defined time step (1 minute minimum)	Medium to long-term (20-50 years), user defined time steps

\*Mendes et al, 2011 define operation optimization tools that “optimize the operation of some given energy system” (typically are simulation tools) and investment optimization tools that “optimize the investments in an energy system” (typically are scenario tools).

Table 3. SDSS and MC-SDSS tools characteristics

	SDSS					MC-SDSS		
<b>Name of the tool</b>	DIMMER Dashboard	InViTo	INDICATE	MEU	UrbanSim	CommunityViz	FASUDIR-IDST	ArcGIS with AHP
<b>Developer</b>	DIMMER Project Team (European project)	SiTI Istituto Superiore sui Sistemi Territoriali per l'Innovazione	INDICATE Project Team (European project)	LESO-PB	Urban Analytics Lab	Orton Family Foundation+Placeways	Fasudir project Team	Saaty
<b>Open Source</b>	Yes	Yes	No	Yes	Yes	No	No	No
<b>Objective</b>	District energy saving	Guide users in building their spatial knowledge by dynamic maps	Support stakeholders in the transition towards smart cities	Urbanenergy management	Community Planning Tool	Visualize, analyze and communicate about planning decisions	Define different retrofitting scenarios with regards to sustainable KPI	Spatial Analysis
<b>Visualization</b>	2D-3D	2D	2D-3D	2D-3D		2D-3D	2D-3D	2D-3D
<b>Approach</b>	Participative Collaboration	Open collaborative web tools	Participative Collaboration	direct collaborative framework	simulation, visualization, and shared open data	Collaborative decision-making	Collaborative stakeholders	data integration and collaborative
<b>Method</b>	Dynamic monitoring, management of energy consumption	Interactive visualization tool	Interactive Decision Support and Information Exchange Platform	link to CitySim	scenario development and simulation	Dynamic Scenario tool	Retrofitting Scenarios tool	Pairwise-Comparison
<b>Spatial Coverage</b>	Building and District	Cities and regions	City and neighbourhood	Urban district	community/urban	Cities and regions (large and small)	District and neighborhood	user-dependent
<b>Type of tool</b>	WebGIS Dashboard	Web platform	Platform	ArcGIS based web platform	Software based on Python data	ArcGIS Extension	Web based software	ArcGIS extension
<b>Time resolution</b>	Real-time	-	-	Hourly	Short/long term	Time-scope	Long-term	User-dependent
<b>Link</b>	<a href="http://www.dimmerproject.eu/">http://www.dimmerproject.eu/</a>	<a href="http://invito.urbanbox.it/">http://invito.urbanbox.it/</a>	<a href="http://www.indicate-smartcities.eu/">http://www.indicate-smartcities.eu/</a>	<a href="http://meu.epfl.ch/">http://meu.epfl.ch/</a>	<a href="http://www.urbansim.com/urbansim/">http://www.urbansim.com/urbansim/</a>	<a href="http://placeways.com/communityviz/">http://placeways.com/communityviz/</a>	<a href="http://fasudir.eu/">http://fasudir.eu/</a>	<a href="http://www.spatial.reidlands.edu/sds/ontology/?n=SDSSTool:ArcGIS-AHP">http://www.spatial.reidlands.edu/sds/ontology/?n=SDSSTool:ArcGIS-AHP</a>

