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

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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.
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1 Introduction

In recent decades, urban areas have been recognized as major contributors to CO_2 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).

Due to the complexity of this research field, this paper aims at reviewing current spatial approaches, which can be adopted in a urban planning development with specifically focus to the built environment. Therefore, the research questions raised by this paper are as follows: Are current research studies able to support the challenges provided by UR-IEP, taking into account the variety of all the sustainable planning aspects? What are current challenges and barriers in this research field?

This study provides a systematic review of existing spatial urban energy planning approaches and built environment applications. It presents a preliminary theoretical framework that will help evaluating how UR-IEP issues are handled.

The major contributions of this study are: 1. to offer a systematic review of existing urban energy planning approaches toward sustainable built environment development; 2. to highlight the most relevant spatial approaches and their applications for supporting urban energy planning procedures; 3. to provide a statistical analysis of the reviewed papers through a Meta-analysis in order to figure out current research trends; 4. to provide a SWOT analysis of the different approaches for guiding and supporting urban actors in choosing among the various reviewed approaches; 5. to identify the main barriers and future challenges in the field, with the aim to help understanding how the UR-IEP can be handled in future analysis.

Accordingly, this review is expected to be very useful for all urban actors including, in particular, new practitioners, researchers and decision makers working in this topic.

The rest of the paper is organized as follows: Section 2 illustrates the systematic review methodology adopted by the authors. Section 3 presents the state of the art and classifies the main approaches currently used in urban energy planning. Section 4 provides the results of the paper through a Meta-analysis and SWOT analysis. Furthermore, it discusses the significance of the findings and the barriers in the research field. Finally, Section 5 provides the main remarks and highlights the necessary future developments.

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 [1] 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.

[1] The authors excluded from the literature review the Phase IV "monitoring and implementation", because it is not functional to the strategy definition.

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

2.1 Basic Definitions

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

UR-IEP, Urban and Regional Integrated Energy Planning, is defined according to (Mirakyan et al., 2009), as a long-term, model-based energy planning process. This is divided into the following four major phases: Phase I: Preparation and orientations; Phase II: Model design and detailed analysis; Phase III: Prioritization and decision; Phase IV: Implementation and monitoring.

As it has been specified, the focus of this paper is mainly the ‘Spatial’ or “Spatial-Integrable” approaches of UR-IEP (see Figure 1. Flowchart of the systematic review outlining the study selection process.

Figure 2).

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

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

The concept of sustainable development dates back to 1970s and since then it has been widely the subject of public, private and academic sectors concerns, being the main effort of national and international economic, social and environmental agendas (Brandon et al., 2016; Cosmi et al., 2015; Iddrisu and Bhattacharyya, 2015). According to (Brandon and Lombardi, 2011) and (Rad, 2010), sustainable development is a continuous process that is able to balance between all the environmental, economic and social aspects related to a living environment, in order to improve, and not to impact adversely, on present or future generations. A sustainable energy development means balancing energy production and consumption, along with having the minimal impact on the environment and giving the opportunity to employ social and economic activities (Hofman and Li, 2009).

Future scenarios analyses can be defined as a way to create and predict future alternatives and their impacts, providing policy decisions framework (Miola, 2008; Mistry et al., 2014). The aim of future studies is to support decision-making under uncertainty which is to be defined as indeterminacy (Dreborg, 1996).

In planning, "*scenario"* is a very commonly used term. In literature, scenarios have various classifications (Börjeson et al., 2006; Marien, 2002; Rotmans et al., 2000) (see Table 1). Interestingly, scenario analysis has been broadly used as an approach in the field of urban energy planning.

In the next sub-sections the authors will review and introduce several approaches of UR-IEP that may help to define different scenarios.

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

3 State of the Art of the Approaches used in Urban and Regional Energy Planning

This section provides a wide revision of existing urban energy planning approaches toward sustainable built environment for each phase of the UR-IEP (See Figure 1. Flowchart of the systematic review outlining the study selection process.
Figure 2), highlighting the most relevant spatial approaches. In order to ease the reader to follow Section 3, a summary of major features of the reviewed papers is shown in Figure 3.

Accordingly, Section 3 is organized in sub-section 3.1 "Preparation" which describes the preliminary UR-IEP phase where a supportive GIS database involving stakeholders should be defined in order to proceed with phase II and III.

Sub-section 3.2 is the core of the UR-IEP and it illustrates different approaches regarding the “Detailed Urban Energy Modelling”. It is divided into “3.2.1. Urban Building Energy”, focused on urban building energy demand side, and “3.2.2. Urban Comprehensive Energy System Models”, focused on urban energy demand and supply side. Both these two sub-sections pay special attention to GIS integration.

Finally, sub-section 3.3, entitled “Prioritization and Decisional Process” presents the last and complementary phase of UR-IEP by illustrating some of the most important Multiple Criteria Spatial (GIS) Decision Support System implemented for Urban Energy Planning.

Figure 3. Outline of Section 3

3.1 Phase I-Preparation

The Preparation Phase I is presented in order to introduce the preliminary required actions to create a supportive base of data and information necessary to perform the next phases of the UR- IEP. Among a number of possible actions involved in Phase I of UR-IEP, the most relevant ones include data collection and stakeholders’ involvement processes (Mirakyan and De Guio, 2013).

Data collection consists in collecting the historical and current building stock data such as:

- socio-economic, demographic, and building data, which can be extracted from the National Census database (e.g. population and prevailing buildings age);
- building stock geometrical, typological information, which can be extracted from the digital cartographic buildings map of technical departments of the municipalities (e.g. base surface and height);
- available real energy consumption data for a building stock (energy suppliers, surveys).

Some examples of the detailed studies regarding aforementioned data collection process in the field of urban energy planning are (Caputo et al., 2013b; Tornberg and Thuvander, 2005). According to these examples, the data collection process can be divided into (i) Geo-referenced data collection_ the collection of existing building-related data and, (ii) Non geo-referenced data collection_ the collection of existing data which should be later geo-referenced. A high data disaggregation may represent wider possibilities of investigations, simultaneously very detailed data collection may be challenging and time-consuming (Kelly, 2011).

In this phase the use of GIS is extremely useful to store, manage, and visualize a vast number of spatial data for urban planning purposes. Through the representation of multiple layers, city development can be represented), where each item is associated with a geometric entity in a proper system of coordinates (Bugs et al., 2010). Particularly, the GIS allow geo-referencing all the available energy data in order to develop energy consumptions models to fully characterize the building stock for the whole city. Figure 4 illustrates an example of the creation of a supportive GIS platform by overlapping multiple layers (Torabi Moghadam et al., 2016b). Data need to be carefully elaborated and analysed in order to create a strong supporting dataset (see Section 3.2).

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.

The other fundamental action to be considered from the earlier phase of UR-IEP is the involvement of stakeholders. This fact helps to obtain the existing data, determine relevant sustainable objectives, and propose a common strategic vision (Bottero et al., 2015; Linnenluecke et al., 2016; Pelzer et al., 2015). In order to involve multiple stakeholders and experts in the planning procedure is necessary to organize the collaborative events such as workshop organization, focus groups, questionnaire, and interviews. The GIS supportive database aids the stakeholders to visualize the current urban energy situation and therefore to reshape the sustainable objectives.

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 models are classified as buildings physics models, statistical models and the combination of both these approaches (hybrid) (Kavgic et al., 2010; Oladokun and Odesola, 2015; Swan and Ugursal, 2009). They differ in calculation methodology, time and spatial resolution, disaggregation level of input data and results. Even if previous reviews are focused on the same classification mentioned in this study, some basic information is provided in order to understand if the methodologies can be applied at urban scale and coupled with GIS. Quantitative estimations methodology provides a determination of energy consumption for each building and thus permitting a better territorial control through a geo-referenced model (Al-kheder et al., 2009; Favretto, 2000).

3.2.1.1 Building physics or Engineering models

Building physics or Engineering methods are very detailed models based on traditional thermodynamic relationships (Aydinalp-Koksal and Ugursal, 2008). They can be divided into (Swan and Ugursal, 2009):

- archetype method – it is based on the aggregation of buildings in representative classes clustered according to key characteristics (Corgnati et al., 2013; Shimoda et al., 2004). The main difficulties are related to the characterization of archetypes in order to be representative of a wide set of buildings. The identification of archetypes implies the association of thermo-physical characteristics to each building and consequently to use building simulation software for assessing current and future energy consumption (Ballarini et al., 2014; Wan and Yik, 2004).
- sample method – it considers the data collected from surveys and monitoring campaign used to model the actual behaviour of the building stock. Limited applications of sample method have been found at local level (Cheng and Steemers, 2011).
- population distribution method – it is an accounting method reflecting energy consumption of household appliances regarding the ownership saturation rate of appliances. Accordingly, it can be

suitable for building up the electric distribution load of an area or to estimate the energy consumption of household appliances (Kadian et al., 2007a; Saidur et al., 2007).

In order to focus on spatial applications, the paper reviews the integration of building physics models with GIS methods. In particular, Fabbri et al. (2012) investigated the influence of typology factor in energy saving in heritage buildings. This study used GIS maps as a strong platform to link a different data and the building Energy Performance Certificate (EPC). Yamaguchi et al. (2007) proposed a new clustering modelling approach to define CO_2 reduction scenarios in the commercial sector. A simulation model capable of considering the various parameters affecting energy use and management is developed.

Another archetype approach is presented by Mattinen et al. (2014) in which a GIS-based calculation and visualization approach for energy use and greenhouse gas emissions for the residential stock has been developed. Jones et al. (2001) introduced Energy and Environmental Prediction model based on a GIS technique which provides additional information, based on a "*drive-pass*" survey, to archetypes. Caputo et al. (2013a) and Costa (2012) proposed a methodology in order to evaluate the energy performance of the built environment at city level.

Mastrucci et al. (2013) developed a dynamic thermal simulation and indoor thermal comfort analysis to support sustainable urban planning. Österbring et al. (2016) have proposed a methodology to describe the building-stock by integrating building characteristics from energy performance certificates, measured energy use and envelope areas from a GIS model. A GIS-based simulation model has been proposed by Li et al. (2016) in order to evaluate how building typology and urban morphology influence building energy consumption and CO_2 emissions. Delmastro et al. (2016) developed several long-term scenarios assessing the energy saving potential and the relative cost. Moreover, they spatially analysed the socio-economic feasibility of renovation measures.

To conclude this sub-section, although it might be possible to use the sample and population distribution models at urban level, the most widespread method applicable for urban spatial analyses is the archetype one. This method allows both short and long-term analysis and the possibility to create energy retrofit scenarios).

3.2.1.2 Statistical models

Statistical methods search for correlations between historical data on building energy use/external conditions and buildings characteristics. They can be divided into regression analysis, conditional demand analysis, and neural network.

- Regression analyses fit the relation between energy consumption and its identified relevant drivers (Dascalaki et al., 2010; Fracastoro and Serraino, 2011; Theodoridou et al., 2011). They do not require very detailed data about the building, however, high amount of data is needed to develop the model. Regression methods can be also suitable for assessing the retrofit potential of large building stock as proposed by Walter and Sohn (2016).
- The Conditional Demand Analysis method (CDA) is a regression-based method suitable for analysing large datasets. Due to the lack of flexibility, the analysis of energy conservation measures on demand variation isn't allowed therefor this method will not be further considered in this paper.
- Neural network models (NN) study the relationship between a wide range of variables and parameters based on a large training dataset. They have been largely used for prediction problems at individual building level, but also at a larger scale (Aydinalp et al., 2004, 2002). This method is suitable for the evaluation of energy consumption and the impact of socio-economic factors (Aydinalp-Koksal and Ugursal, 2008), but they are not suitable for defining energy conservation measures even if some applications exist (Krarti et al., 1998).

In order to focus on spatial applications of urban energy modelling technique, the paper reviews the integration of statistical models with GIS methods. Recently, Dall'O et al. utilized GIS tools to create a comprehensive building energy performance database using energy audits of sample buildings, (Dall'O' et al., 2012). Mutani and Vicentini (2013) have conducted a regression analysis to correlate building energy consumption to building compactness and construction period. The bottom-up GIS-based model for New York City is built by Howard et al. with the aim of estimating the building sector energy end-use intensities (Howard et al., 2012). Yeo et al. (2013) develop an urban demand forecasting system, with hourly resolution, based on a GIS database (E-GIS DB) with 2D/3D visualization. The ongoing Zero Energy Buildings in Smart Urban Districts proposes an integrating GIS and regression model with the Stakeholders Analysis, in order to later integrate the Multi-Criteria Decision Analysis (Torabi Moghadam et al., 2016a).

From the literature emerged that between the mentioned statistical approaches, the regression methods have been coupled with GIS more than the other methods. These methods are appropriate for short-term planning based on large data requirement and to create energy retrofit scenarios.

3.2.1.3 Hybrid models

Hybrid models combine different methods in order to merge their strengths. These models have performed well in case of the small sample, but according to Chalal et al. (2016) "*it could be possible to utilize them in urban energy planning when certain parameters, especially the thermal ones, are unattainable*". These methods have been widely integrated with GIS in the literature. Particularly, Tornber and Thuvander (2005) developed a model toward a sustainable management of the building stock. In this study, a top- down approach is combined with a bottom-up approach to compensate the lack of data and complete each other.

A methodology called EnerGIS has been proposed by Girardin et al. (2010) to support qualitative long-term scenario analysis involving building renovation. EnerGIS is based on the pinch analysis and statistical analysis. Ascione et al. (2013) suggested a new method for the calculation of the space heating demand for buildings with aim at characterizing both winter and summer energy performances. Their target was to promote efficient refurbishment solutions for existing buildings and effective design for new ones.

Mutani and Pairona (2014) proposed a hybrid approach (i.e. regression and archetype) to calculate the energy consumption of residential building stock by starting from census information and real energy consumption data.

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

3.2.2 Urban Comprehensive Energy System Modelling

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

Bottom-up comprehensive energy systems models are typically adopted for long-term runs (Herbst et al., 2012). The application of a comprehensive energy system models at urban and regional levels has been introduced from 2000 in Steidle et al. (2000). Compared to large scale applications, urban comprehensive energy system models require a higher focus on end-uses at a disaggregated level. In this study, models and tools are classified according to Connolly et al. (2010) and Timmerman et al. (2014) in Scenario, Simulation and Hybrid**.** It should be stated that, besides this classification, any individual model can have characteristics belonging to different model types making the categorization ambiguous (Hourcade et al., 2006).

3.2.2.1 Scenario models and tools

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

Urban models based on linear programming approach exist and can be coupled with GIS tools. A GIS application of LP method has been implemented by Brownsword et al. (2005) to simulate spatial changes in energy demand profiles. Jennings et al. (2013) implemented an energy system model to support urban stakeholders in their choice among several building technologies. One of the main conclusions is to assess the long-term allocation of investments among several alternatives measures in both demand side and supply side. Other urban models based on LP have been developed by Farzaneh et al. (2016) to address the urban electric deficiency and by Huang and Yu (2014) for the optimization of the urban heating energy system.

Furthermore, there are many existing tools based on LP optimization that can be applied in urban areas. In particular, authors highlight the Integrated MARKAL-EFOM System (TIMES) developed by the Energy Technology System Analysis Program. TIMES is a multi-scale economic model generator suitable for medium (20-50 years) or long-term (up to 100 years) analysis (Loulou et al., 2005). It allows creating user defined time-slices (Lewis, 2008; Vaillancourt et al., 2007). TIMES may require complementary interfaces for the simplification the input/output data management (VEDA or ANSWER). A recent spatial analysis based on TIMES can be referred to the InSMART project (InSmart, 2015).

Another important scenario tool based on LP-optimization techniques is the Open Source Energy Modelling System (OSEMOSYS) where the structure of time-periods is not multi-year, but a single year structure (Timmerman et al., 2014), with particular attention on the capability of modelling Smart Grids (Howells et al., 2011; Welsch et al. 2012). To the best of the authors, any urban application of OSEMOSYS exists in current literature, but the structure of the model allows to be scaled for urban and regional analyses.

3.2.2.2 Simulation models and tools

Simulation tools "simulate the operation of a given energy system to supply a given set of energy demands" and "are operated in hourly time-steps over a one-year time-period".

As reviewed by Mendes et al. (2011), starting from the concepts of micro-grids and distributed generation some models have been developed. The Hybrid Optimization Model for Electric Renewables (HOMER) is an open source energy system simulation model, which searches for the best mix of technologies able to minimize the total life cycle cost. Some applications of HOMER can be found in Bahramara et al. (2016) and in the (NREL, 2016). It can be integrated with the Village Power Optimization of Renewable (ViPOR) to design the distribution grid of a local area. ViPOR requires a GIS import of spatial data, but can only be used for electric analysis, neglecting the thermal aspect. Another model focused on distributed generation is the Distributed Energy Resources Customer Adoption Model (DER-CAM). It is based on Mixed-Integer Linear Programming optimization techniques (Siddiqui et al., 2001). It aims at finding the most suitable combination of technological solution, their relevant size and operational profiles. A link with GIS tools to catch layout constraints and site new tech has been proposed by (Edwards et al., 2002). With similar purpose and approach, the Economic Evaluation of Micro-grids (EAM) has been developed by (Asano and Bando, 2006).

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

3.2.2.3 Hybrid tool

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

Comprehensive energy system analyses aren't widely used for UR_IEP yet, however, they can be used to perform spatial urban building energy analyses.

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

Table 2. Comprehensive energy system tools and models characteristics

3.3 Phase III-Prioritization and decisional process

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

As it can be observed in Section 3, energy and environmental analyses have traditionally considered a single measurement criterion, as costs benefit maximization, to make their decisions (Greening and Bernow, 2004). However the conflicting and multidimensionality concept of long-term urban sustainable development matters cannot be relied on just a single criterion. Moreover, UR-IEP should be sustained by collaborative and inclusive processes since cities are dynamic living organisms that are continuously evolving (Lombardi and Ferretti, 2015). In this regard, it is necessary the use of the appropriate tools and methods to address complex interactions of energy planning problems.

Multi-Criteria Decision Analysis (MCDA) is an integrated form of a sustainability evaluation. It provides well-established decision support tools for energy development because of the multi-dimensionality of the sustainability goal (Wang et al., 2009a). However, MCDA approach cannot make the actual decisions by itself, but it should aid decision makers to make better decisions. A huge number of MCDA models and approaches are available in the literature (Herbert A Simon, 1977; Simon, 1960).

The general MCDA process in sustainable decision-making is shown in Figure 5 according to (Pohekar and Ramachandran, 2004; Sharifi and Rodriguez, 2002; Wang et al., 2009a). As it can be seen in Figure 5 , generally, the first phase in MCDA consists in formulating the problem and alternatives for sustainable energy decision-making problem, setting the evaluation sustainable criteria and normalizing both quantitative and qualitative criteria data. Afterward, criteria weights are defined to show their impact performance. It is then necessary to structure the model and the evaluation matrix (acceptable criteria and alternatives matrix). Finally, after selecting the appropriate method, it can assess and evaluate the alternatives in order to rank/sort/choice/describe them. To ensure the consistency of the obtained result, a sensitivity analysis should be performed.

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).

So far, there are a number of MCDA review methods in the literature regarding the sustainable energy planning. The most comprehensive review of Decision Analysis in energy and environment modelling was presented by Huang et al. (1995). The study conducted by Greening and Bernow (2004) has surveyed the application of MCDA methods. The importance of MCDA methods and energy-related environmental studies have been underlined also by Zhou et al. (2006). In this survey, more than 250 studies have been reviewed in order to classify the MCDA methods according to the application type and methods. Furthermore, the literature review conducted by Løken (2007) has emphasized that energy planning is a suitable field for the use of MCDA. Pohekar and Ramachandran (2004) have reviewed the application areas of MCDA in energy planning. They found out that the commonly applied MCDA methods are multi-objective optimization, AHP, PROMETHEE, ELECTRE, MAUT, fuzzy methods and decision support systems (DSS). DSS are interactive computer aided methods which can support the decision makers in the collaborative, participative, criteria/alternatives selection procedure (Pohekar and Ramachandran, 2004).

Although the MCDA aims at presenting the most suitable plan, it should fulfil the understanding of the multi-criteria complex situation by supporting the interactive planning, helping people to express their value judgments, and documenting the values and the alternatives of each recommendation (Mirakyan and De Guio, 2013). However, since the energy consumption at the built environment is influenced by many different features, urban energy planners, and decision makers need proper MCDA tools to identify potential areas where improvement is necessary (Chalal et al., 2016). This requires data visualization of the geographical locations of alternatives. McHarg was the first one who used maps to make decisions (McHarg, 1969). The use of maps in decision-making processes has been defined in 1991(Charlton and Ellis, 1991). GIS produces thematic maps and performs spatial operations, while Multi-criteria methods translate these maps into value maps (Arciniegas et al., 2011).

Due to this reason, in the last two decades, a lot of geospatial data processing have been done to gain information for decision making processes and many spatial decision problems gave rise to the GIS-based multi-criteria spatial decision support system (MC-SDSS) (Malczewski, 2006). Interestingly, these two tools take advantage of each other (Laaribi et al., 1996). According to Chakhar and Martel (2003) the components of the SDSS are :(i) acquire, manage and store the spatially-referenced data, (ii) perform the analysis of spatial problems, and (iii) provide to the decision maker and/or analysts an interactive, convivial and adequate environment to perform an effective visual decision-aid activity. The main advantage of MC-SDSS is the fact that the decision makers are able to express and exert their preferences with respect to evaluation criteria and/or alternatives, and consequently, get back feedback in order to increase the decision makers trust in the results. Moreover, they are powerful visualization tools through which maps become a '*visual index*' in order to offer solutions to the planners to optimize the conditions (Andrienko and Andrienko, 1999; Chakhar, S; Martel, 2003; Jankowski et al., 2001). Some of the existing SDSS/MC-SDSS tools related to sustainable energy planning are presented. Among SDSS, MEU (Urban Energy Management) (Rager et al., 2013) is a web-based platform, which integrates with CitySim (Robinson et al., 2009) to develop different energy demand and supply scenarios, including GIS-based visualization of the results. It permits to continuously monitor annual energy flows, consumptions and related actions (Puerto et al., 2015).

Another open source SDSS tool for scenario development and simulation for the city scale is UrbanSim (Waddell, 2007). It is an integrated platform to share data, design alternative plans, simulate the impacts of those plans over time, and visualize outcomes in 3D. This platform analyses the impacts of alternative scenarios, adopts UrbanCanvas for interactive design, UrbanSim Commons to share data on the cloud. This tool is not specifically produced for the building sector; however, it is used to evaluate alternative transportation and land use plans taking into account the building stock evolution.

Additional example is DIMMER (District Information Modelling and Management for Energy Reduction) Dashboard/Portal (Lombardi et al., 2014). It is an open platform for existing and real-time data processing and visualization to support decision making by energy managers and public authorities, monitoring district energy data. DIMMER integrates Building Information Model (BIM), System Information Model (SIM) and Geographic Information System (GIS).

InViTo (Interactive Visualisation Tool) (Pensa and Masala, 2014) is an interactive SDSS web interface to support users in the exploration of spatial data. The tool aims at providing a structured framework to aid users in accessing and interrogating a geo-referenced spatial thematic database. InViTo works with GIS database and relies on free and open web technologies such as Google Maps and Google Fusion Tables.

An ongoing project to support decision makers and other stakeholders towards 'Smart' City is INDICATE (MELIA et al., 2015). It aims at developing a SDSS interactive cloud-based tool, which will provide a dynamic assessment of the interactions between buildings, electricity grid, renewable technologies and Information Communication Technologies (ICT).

The integration of SDSS tools with MCDA (MC-SDSS) has been widely applied in the field of urban energy planning, especially in the siting of renewable energy technologies in land use. Few tools have been developed for energy analysis in the built environment but they can potentially be adapted for it. In this section, both are considered.

For example, CommunityVIZ (Kwartler and Bernard, 2001) is an ArcGIS extension decision support system for community planning, which allows to provide different interactive visualization and understand their potential impacts (Lieske and Hamerlinck, 2013). It consists of two components: i. Scenario 360 for communication, analysis, and engagement; ii. Scenario 3D for three-dimensional visualization. It could be integrated into energy analysis and planning (Novak et al., 2012).

FASUDIR-IDST (Friendly and Affordable Sustainable Urban District Retrofitting-Development of Decision Support Tool) (Barbano et al., 2015) is an interactive decision support tool to analyse the effect of the building retrofitting strategies on the sustainability of the urban district. It features a 3D graphical user interface, in order to facilitate the interaction between the multiple stakeholders involved in the decision-making process.

Another example is AHP in ArcGIS. It is a very strong ArcGIS extension which determines a criteria weight considering the well-known Analytic Hierarchy Process (AHP) (Saaty, 1980).

Table 3 summarizes the most important characteristics of the explained tools of (Section 3.3) in order to facilitate the readers to choose the most appropriate one for their research and applications.

Table 3. SDSS and MC-SDSS tools characteristics

4 Results

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

4.1 Meta-analysis of previous literature

Over the 146 articles, 80 papers on the UR-IEP application have been identified. These papers have been classified based on three criteria for the purpose of presenting results effectively: the year of publication, the level of integration of UR-IEP phases and the types of combination of methodology. In Figure 6, the results of the meta-analysis are shown.

Figure 6. Meta-analysis of previous papers

- The level of integration. Phase I is always integrated with the other UR-IEP phases since it is the necessary basis of the entire planning procedure. Phase II is the most widespread phase, involving a total of 70 papers out of 80, accounting for 87,5% (27 papers integrate Phase I with Phase II, 36 papers belong to Phase II only and only 7 papers include all the Phases). Since

Phase III is the prioritization and decisional process, complementary to the other Phases, it is required to be integrated. The Figure shows that 17 papers (21,25%) are referred to Phase I, of which 10 papers integrate Phase I and III while 7 papers integrate all the Phases. The most important finding, relevant to be highlighted, is that the full integration of the different Phases is reported by only 8,75% of the papers (7 papers).

- Methods (shape of the bullets in Figure 6). According to the previous studies, the possible combinations of methodologies have been classified in: (i) Methodology isolationism: one method for one paradigm; (ii) Methodology enhancement: enhancing a methodology by exploiting other methodologies; (iii) Methodology combination: combining methodologies in a unique intervention; (iv) Multi-methodology: combining parts of different methodologies (Mirakyan and De Guio, 2013); (Mingers and Brocklesby, 1997). A total of 36 papers (45%), which are classified in Phase II by a circle shape (○), perform the methodology isolationism by proposing urban energy modelling approach without integration. 35 of reviewed papers (43,75%), shaped as a triangle (Δ), belong to Methodology enhancement classification since they enhanced the proposed approach by using GIS tools. Further, regarding to the Methodology combination shaped as a square (□), 6 papers (7,5%) have combined their approaches in a unique intervention. Finally, the remaining 3 papers (3,75%) shaped as (∗), have combined different parts of different methodologies in a Multi-methodology.

- Year of publication (colour of the bullets in Figure 6). The most important output from this analysis is that the UR-IEP is a very recent research topic. In fact, 78 papers (97,5%) have been published after 2000, red and blue bullets. Two other papers are older, but still relevant for the survey field.

In comparing the reviewed papers based on the three aforementioned criteria, this meta-analysis first recognises that in urban energy planning the number of papers that fully integrate the UR-IEP Phases are very few and very recent.

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

4.2 SWOT analysis

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

Figure 7. SWOT analysis related to the presented approaches.

Under the headings of Figure 7 the following considerations are derived:

- Phase II/Urban Building Energy Modelling: detailed information on the building stock and its retrofit potential can be derived, also relevant for design purposes. Among these models, the choice between archetype and regression methods mostly depends on data availability (i.e. structural data for archetype and real consumption data for regression) and the willingness to explore retrofit solutions (archetype) or to forecast energy consumption (regression).

- Phase II/Urban Comprehensive Energy System modelling: interdependencies between the building sector and the other sectors can be captured, but a lower level of data on the component descriptions is required. Simulation tools are mainly concentrated on the feasibility and operation of renewable energy applications, distributed generation and smart micro-grid with a high time resolution. However, scenario tools are mostly used for creating long-term investment strategies to fulfil government targets at the minimum system cost. In this case, the time resolution is lower in comparison to simulation tools.

- Phase III/Spatial Decision Support Systems: tool to build alternative actions, to express different and conflicting objectives, and to explore the different aspects that can influence final decisions. In addition, these tools can take into account both quantitative and qualitative aspects, considering all sustainability pillars. In this regard, a huge amount of data is required to compute all different aspects (i.e. social, environmental and economic). In some of these tools the MC methods are integrated into their application (MC-SDSS), and for the others, the MC analysis should be integrated exogenously (SDSS). This means that, once the scenarios are defined in the SDSS, the MC analysis will be performed separately.

From the SWOT analysis, urban energy planners can recognize how the weaknesses of the different approaches can be rectified by the strengths of others. Accordingly, the urban actors can realize which approach could be proper for their planning purposes. Therefore, the presented SWOT analysis may guide and support urban actors in the choices among the summarized individual approaches by highlighting the main characteristics. Furthermore, the SWOT analysis is extremely helpful to urban energy planners and decision makers since models become useful when the users are aware of the models' advantages and limitations in order to make effective decisions (Cheng and Steemers, 2011).

4.3 Major findings

After presenting the results of the systematic review, in the following section the major findings are summarized to give new insights for future research and extend existing research.

Taking into account the aforementioned considerations emerging from meta-analysis and SWOT analysis, Figure 8**Error! Reference source not found.** shows which approaches are suitable for creating the different scenarios explained in Section 2.1. Moreover, this figure illustrates the possible integration of different methods to help the urban actors in performing the whole UR-IEP procedure.

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.

As shown in Figure 8, Phase I must be integrated with all other phases in a spatial framework due to the necessity of handling a large volume of data (i.e. the building energy demands and the relative retrofit potential) to improve significantly the quality of planning and decision-making processes.

In Phase II, it is possible to interlink more than one method when it is deemed necessary. For instance, the output of the Archetype models could be used as the input of comprehensive energy system models (e.g. energy requirement of a building typology and retrofit solutions).

Phase III should be integrated with all the methodologies of Phase I and II to support a collaborative process, to better visualize the structure of group decision problems, and organize communication among participants. Therefore, in order to obtain an effective UR-IEP, decision making for sustainability should be broadened to include the participation of stakeholders. In this context, collaborative SDSS and MC/SDSS based on spatial knowledge and on expert systems are more appropriate to tackle the problem.

Existing tools are very effective in modelling energy consumption but not very effective in structuring urban planning problems.

The authors point out some of the most relevant findings of the review and some insights for future research developments. The major findings cover three points:

1. Urban energy planning has to take into consideration an integrated approach: considering that energy planning is complex and multi-disciplinary, from the in-depth analysis of the state of the art, the main challenge for future research is to integrate the existing different methodologies in

an agreed structure in order to enhance the quality and robustness of the planning results. In fact, although the research field of energy planning has become progressively important at urban and regional scales, performing the entire energy planning process by integrating different approaches is still not a common practice. The discussion so far underlines that the advantage of integrating different approaches is due to their complementarity in fulfilling different tasks of the process. Indeed, the preparation of the GIS supportive database allows to manage and visualize the territorial and socio-economic spatial peculiarities (Phase I); energy modelling tools allow to quantitatively analyse the current and future sustainable built environment evolution (Phase II); while MC-SDSS allows to involve the different actors in the decision process and to analyse and choose between the different strategies obtained from the energy modelling parts (Phase III).

2. An integrated urban and regional energy planning is an opportunity through which it is possible to contribute towards a greater sustainability. The whole process is essential to guarantee a future sustainable urban transformation by: investing responsibly in alternative consumption patterns and greener strategies; speeding the decision-making process through participation and intuitive visualization; strengthening the collaboration and relationship between research and private and public local authorities; leading to various new commercial consequences for the environment, economy and society at the national level down to the city level; offering the opportunities of engaging stakeholders in the planning process by establishing a shared framework between them.

3. The integrated procedure of urban energy planning faces several barriers. One limitation is related to the necessity of changing traditional thinking that may lead users to be discouraged since it requires integrating a wide range and diversity of disciplines. Moreover, a high level of

expertise is required to combine the different methods and to simultaneously handle the different sustainability aspects. A second barrier is related to the evaluation process difficulties that may be time consuming and certainty costly. This fact emerges from the need of high-level data (quantity and quality) and expertise for the assessment processes. Furthermore, the availability and reliability of large standardized databases and public data sources is limited at the local level. This issue is very challenging since the data is not always open-source and updated. Furthermore, the data collection process requires new instruments (e.g. smart meters) and new physical resources to analyse them. Finally, there is a necessity to synthesize the planning procedure in order to be understandable to decision-makers. This fact is crucial since it provides new opportunities for collaboration between non-experts and experts.

5 Conclusion and future developments

This study has drawn on an understanding of UR-IEP towards a more sustainable development of the built environment. In this paper, a systematic review of the available spatial approaches for performing UR-IEP has been proposed. The conclusion attempts to answer the proposed research question in the Introduction section. The systematic review showed that many spatial energy modelling approaches have been recently developed. Nevertheless, a unique UR-IEP framework is not available or agreed on among the several experts and scientific disciplines dealing with sustainable energy planning. From the proposed meta-analysis it can be highlighted how the great majority of current approaches do not integrate all the phases of UR-IEP. Consequently, not all planning aspects are taken into account in conventional practices for guiding policies along sustainable development paths.

Hence, the authors suggest reinforcing the collaboration between different research disciplines dealing with socio-economic, institutional and technical aspects with attention to spatial issues. In order to understand how to structure the UR-IEP, it is important to analyse how it is possible to implement the interaction among the different stakeholders, how to select different approaches and how to choose them considering the decision context peculiarities and the type of planning project. From this perspective, the proposed SWOT analysis is useful for all urban actors including, in particular, the new practitioner, researchers and decision makers, in understanding the most important characteristics of the available approaches for the different planning phases.

Although the approaches have not yet been integrated in order to cover and accomplish all of UR-IEP, it is important to push future research and practice to take into account the integration process. Extensive research should be focused on overcoming the barriers identified in the discussion section for developing more integrated techniques of various planning approaches related to sustainable urban planning horizons. This will allow the possibility to explore urban energy transition strategies in the spatial planning field according to sustainable development.

The ultimate aim of this research is to highlight the potential of existing approaches to be combined in order to cover all the UR-IEP phases and to reduce the current uncertainty faced by decision-makers at the urban energy planning level. As a preliminary theoretical framework, the outcome helps urban actors to (re)develop energy planning projects, guiding them in the choice among a significant number of existing planning approaches. Finally, the theoretical framework represents a significant step forward in evaluating the built environment in the context of a sustainable urban development. It also has the potential of allowing an understanding and evaluation of the concept of sustainable UR-IEP over time.

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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

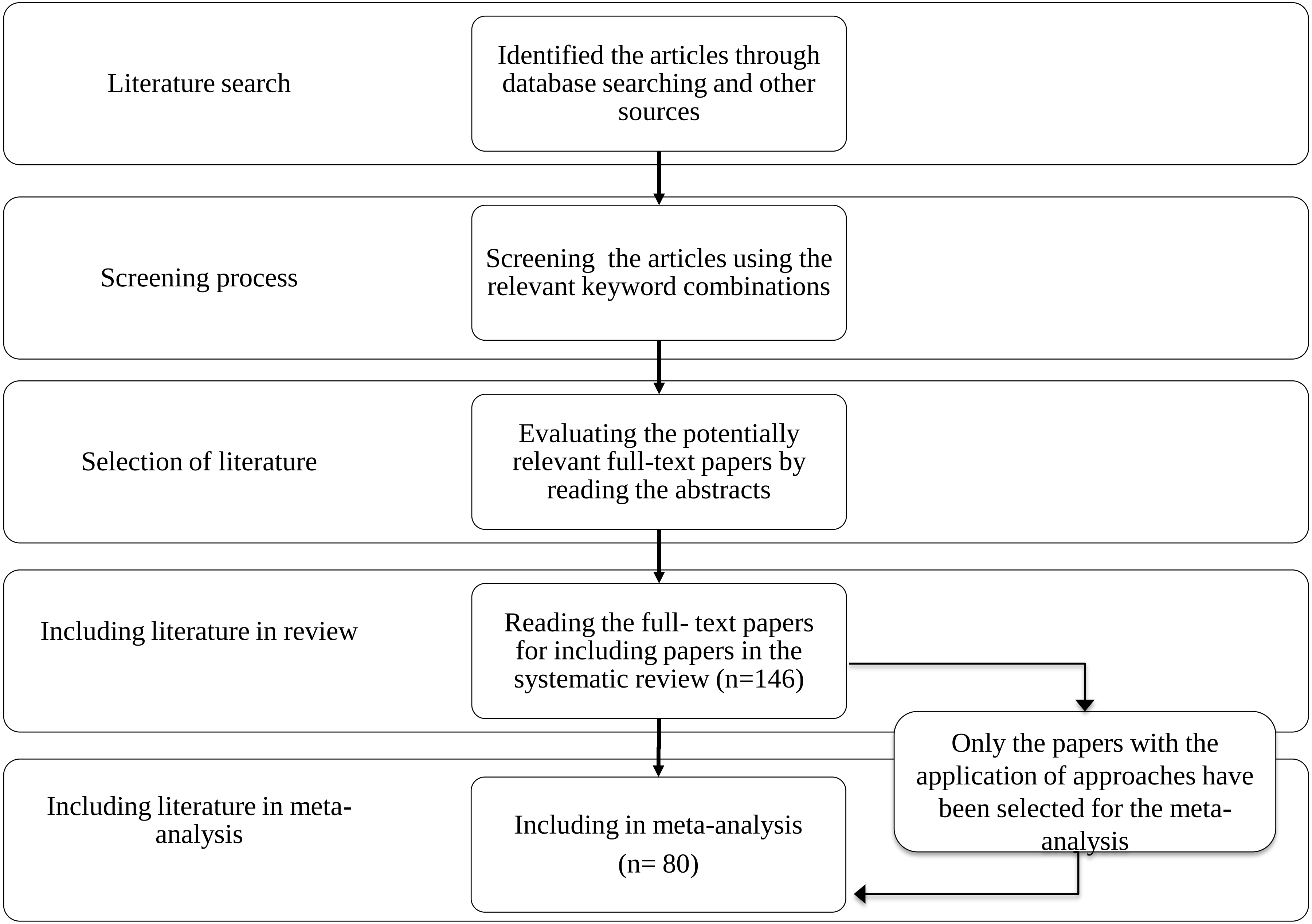

Figure 1. Flowchart of the systematic review outlining the study selection process

Figure2

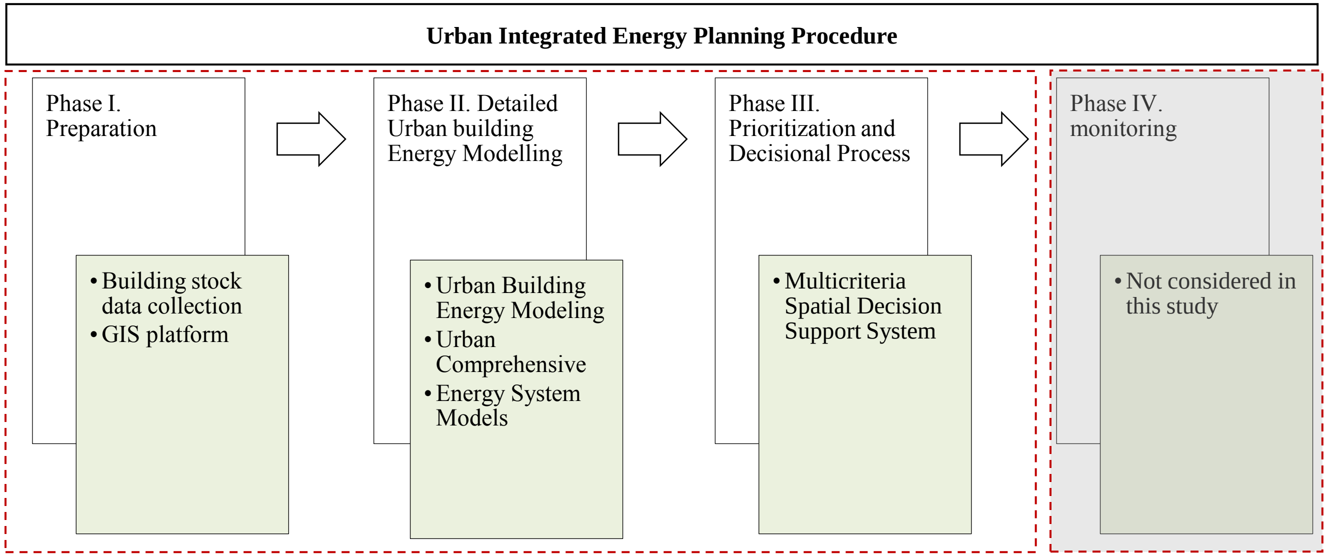

Figure 2. UR-IEP Steps, adapted from (Mirakyan et al. 2009).

Figure3

Section 3.1. Phase I-Preparation

preliminary required actions to create a supportive base of data and information to perform the Phases II and III

Major characteristics	• Creation of a supportive spatial database collecting and elaborating the data • Identification of major criticalities and constraints • Definition of a common vision of the city planning involving stakeholders
Involved actors	• Experts • Researcher • Decision makers
N° of analysed paper	8 papers from 2007 – 2016
Major viewpoints	• Importance of GIS usage to store, manage, pre-process and visualize data • Importance of stakeholder's involvement

Section 3.2. Phase II-Detailed Urban Building Energy Modeling

building stock energy assessment approaches and their applications for predicting building stock energy demand, with a particular focus on methodologies that can be linked with GIS tools

Major characteristics	• Assessment of building stock energy consumption • Creation of sustainable scenarios
Involved actors	• Experts and analysts • Researcher
Major viewpoints	• Top-down approaches have not been considered suitable for urban analysis • Bottom-up approaches have been recognized appropriate for urban analysis

Section 3.2.1. Urban Building Energy Modelling

Major characteristics	• Building physics methods • Statistical methods
N° of analysed paper	41 papers from 1998 -2016
Major viewpoints	The archetype and regression models have been the most used modeling techniques due to their suitability for energy savings potential assessment

Section 3.2.2. Urban Comprehensive Energy System Models

Major characteristics	• Simulation tools • Scenario tools
N° of analysed paper	35 papers from 1977 – 2016
Major viewpoints	The comprehensive energy system models are suitable for urban energy planning for investments optimizations (scenario tools) or operation optimizations (simulation tools)

Section 3.3 Phase III-Prioritization and decisional process

analyses different scenarios through multiple criteria spatial decision support systems, with particular emphasis on visualization features

Major characteristics	• Participatitive and stakeholders oriented approach • Decisional processes • Visualization opportunities
Involved actors	• Experts and analysts • Researcher • Decision makers
N° of analysed paper	35 papers from 1960 to 2016
Major viewpoints	• Importance of the integration of GIS and multi-criteria • Importance of identifying the critical zones through visualization features

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.

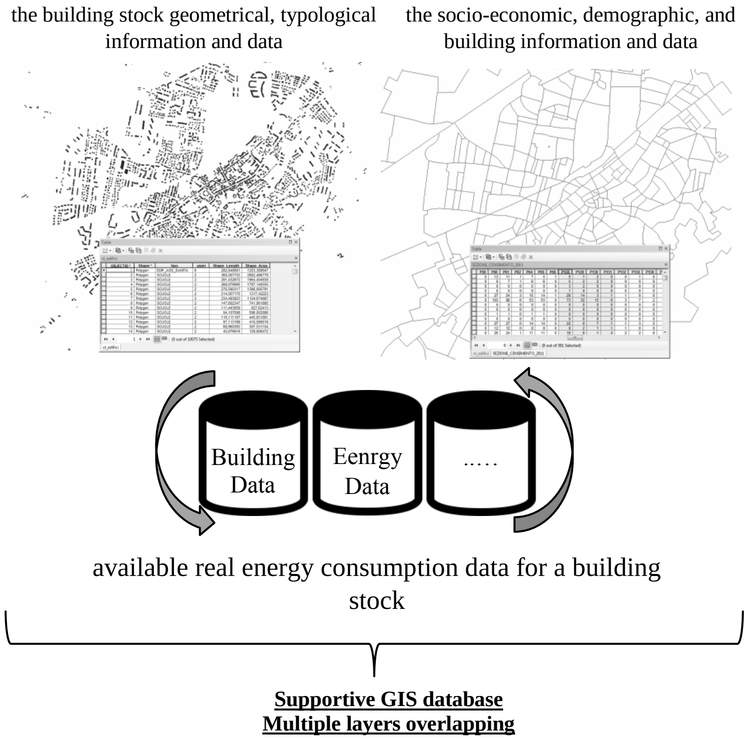

Figure5

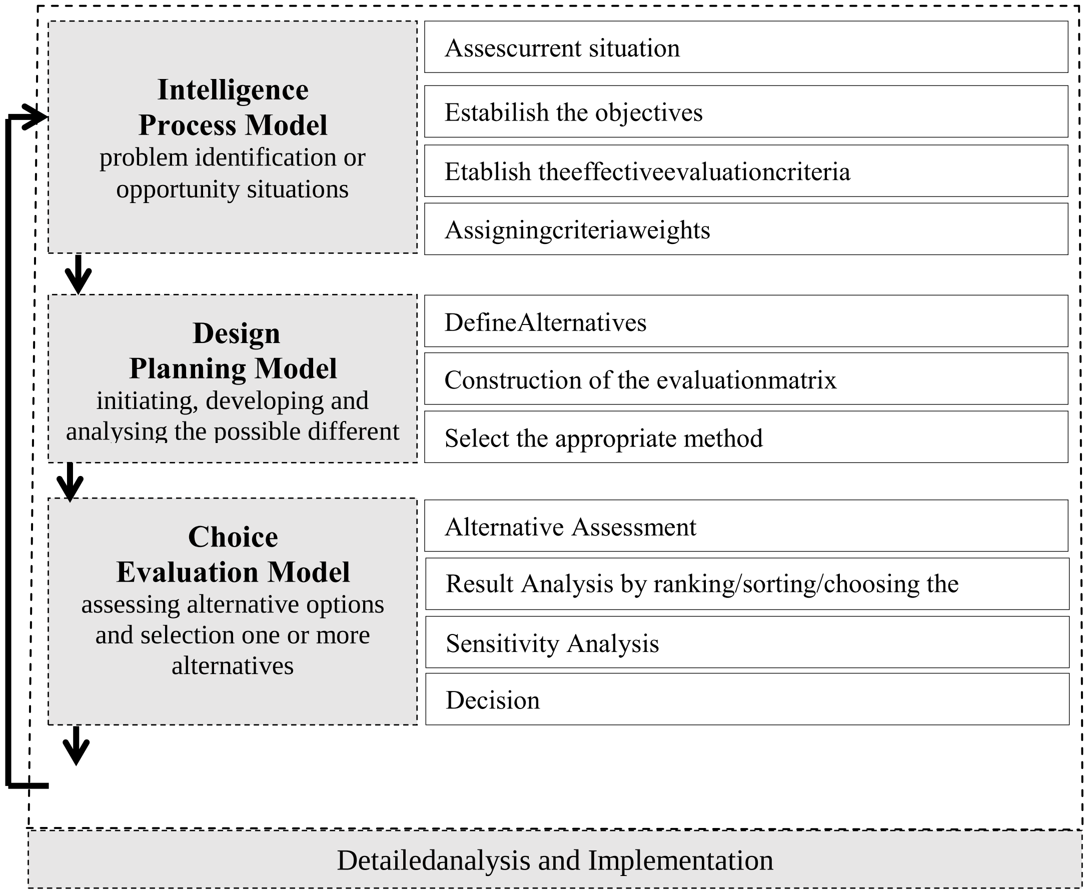

Figure 5. MCDA process in sustainable energy decision-making, elaborated from (Pohekar and Ramachandran, 2004; Sharifi and Rodriguez, 2002; H.A. Simon, 1977; Wang et al., 2009b).

Figure6

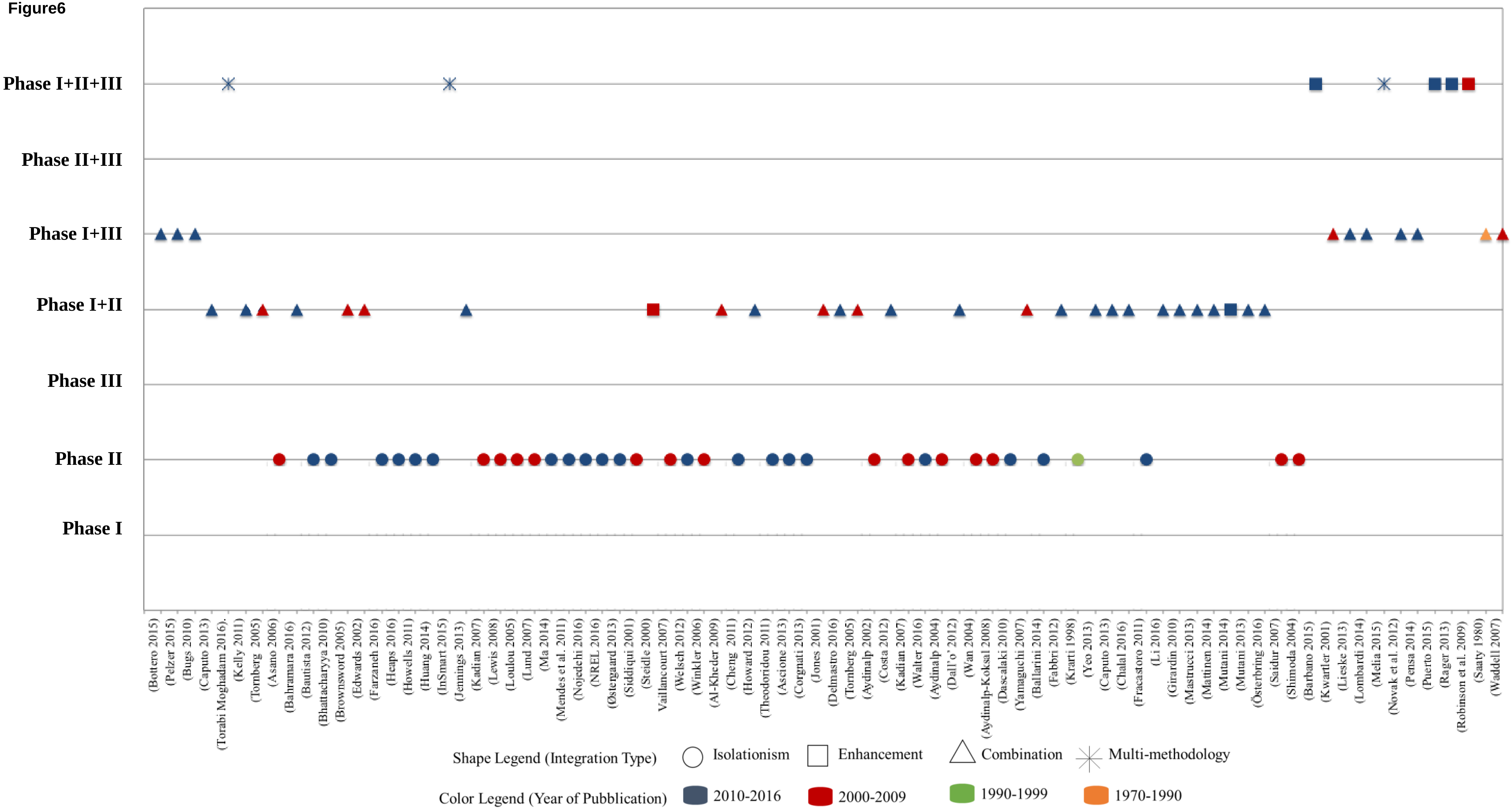

Figure 6. Meta-analysis of previous papers

Figure7

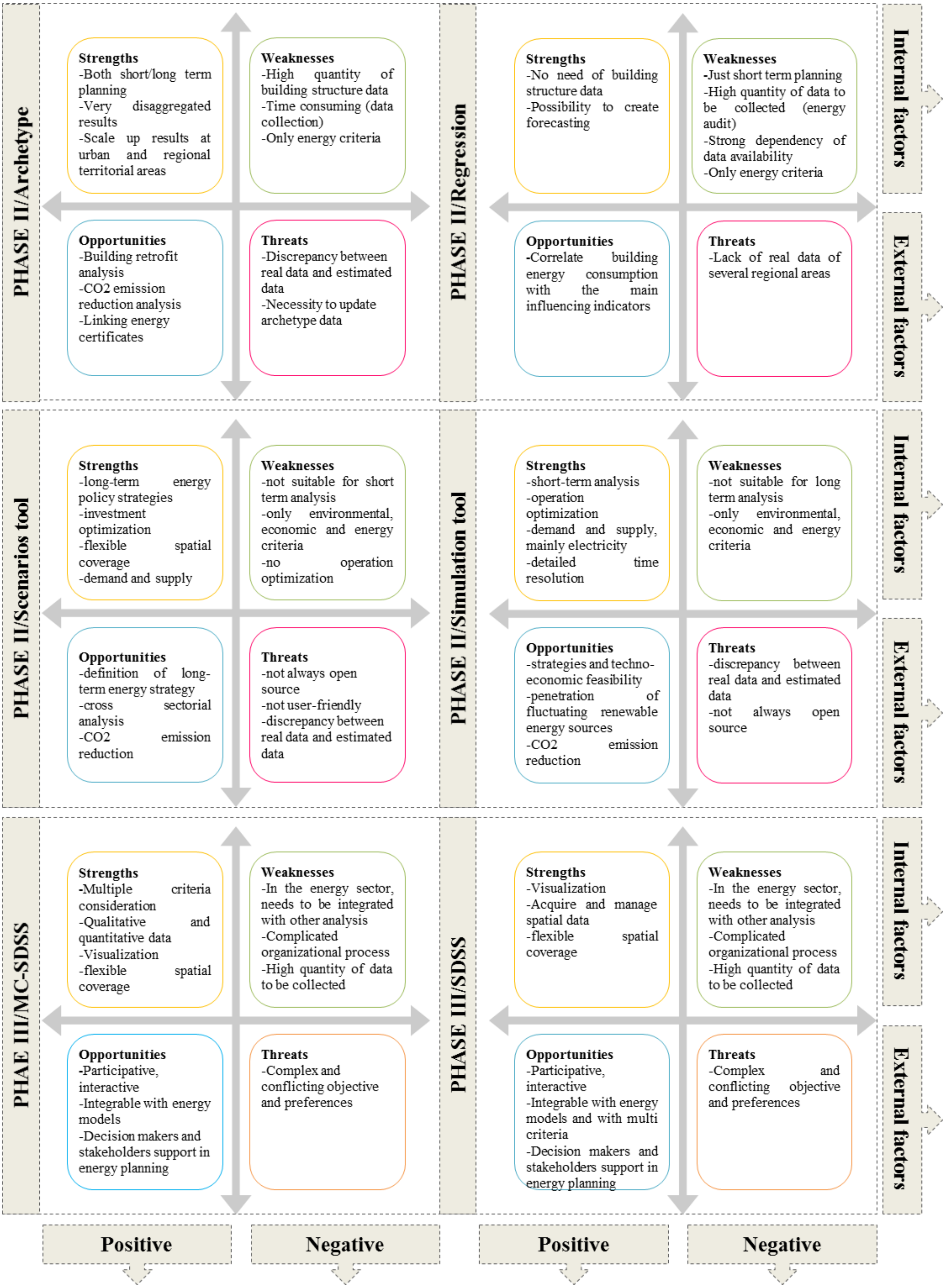

Figure 7. SWOT analysis related to the presented approaches

Figure8

Scenarios Type	Integration Possibility			
SUITABILITY FOR CREATING FUTURE SCENARIOS	**Approaches**	**Phase I**	**Phase II**	**Phase III**
PREDICTIVE , EXPLORATIVE, NORMATIVE	PREPARATION			
PREDICTIVE	REGRESSION			
PREDICTIVE , EXPLORATIVE, NORMATIVE	ARCHETYPE			
PREDICTIVE , EXPLORATIVE	SIMULATION			
EXPLORATIVE, NORMATIVE	SCENARIOS			
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
PREDICTIVE_ What will happen? (Probable futures)					
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	-
EXPLORATIVE_ What can happen? (Possible futures)					
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
NORMATIVE_ How can a certain target be reached? (Preferable futures)					
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 & Stead 2004).

Table2

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).

Table3

Table 3. SDSS and MC-SDSS tools characteristics

	SDSS					MC-SDSS		
Name of the tool	DIMMER Dashboard	InViTo	INDICATE	MEU	UrbanSim	CommunityViz	FASUDIR-IDST	ArcGIS with AHP
Developer	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
Open Source	Yes	Yes	No	Yes	Yes	No	No	No
Objective	District energy saving	Guide users in building their spatial knowledge by dynamic maps	Support stakeholders in the transition towards smart cities	Urbanenrgy managment	Community Planning Tool	Visualize, analyze and communicate about planning decisions	Define different retrofitting scenarios with regards to sustainable KPI	Spatial Anlysis
Visualization	2D-3D	2D	2D-3D	2D-3D		2D-3D	2D-3D	2D-3D
Approach	Participative Collaboration	Open collaborative web tools	Participative Collaboration	direct collaborative framework	simulation, visualiza tion, and shared open data	Collaborative decision-making	Collaborative stakeholders	data integration and collaborative
Method	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
Spatial Coverage	Building and District	Cities and regions	City and neighbourhood	Urban district	community/urban	Cities and regions (large and small)	District and neighborhood	user-dependent
Type of tool	WebGIS Dashboard	Web platform	Platform	ArcGIS based web platform	Software based on Python data	ArcGIS Extension	Web based software	ArcGIS extension
Time resolution	Real-time	_	_	Hourly	Short/long term	Time-scope	Long-term	User-dependent
Link	http://www.dimmerproject.eu/	http://invito.urbanbox.it/	http://www.indicate-smartcities.eu/	http://meu.epfl.ch/	http://www.urbansim.com/urbansim/	http://placeways.com/communityviz/	http://fasudir.eu/	http://www.spatial.redlands.edu/sds/ontology/?n=SDSSTool:ArcGIS-AHP