Building Stock Energy Models and ICT Solutions for Urban Energy Systems

# Chapter 22
# Building Stock Energy Models and ICT Solutions for Urban Energy Systems

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## ABSTRACT

*The existing building stock presents a high potential of energy savings and $CO^2$ emissions reductions. To this purpose, literature provides novel city-scale building-oriented studies, aimed at developing suitable tools for stakeholders, city planners, and decision-makers. To achieve an effective urban energy planning, urban energy systems (UES) models are developed; they employ a multi-domain approach, embracing the complex interactions in urban areas, such as energy flows, environmental indicators, social and economic factors. To perform an advanced modelling and to simulate the complexity of the UES, ICT (information and communications technology) represents nowadays the right answer to the needs of integration of data, tools, and actors in different domains. The chapter investigates the current studies in the field of building stock energy modeling and the application of advanced technologies to develop UES models. As an exemplification, the technological approach followed in the SEMANCO project to support urban scale energy modelling is presented.*

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## INTRODUCTION

The world population is currently about 7.8 billion and it is expected to increase to 10 billion in 2050. The current share of urban and rural population at world level is 56% and 44%, respectively, but it is foreseen a growing of the population share living in urban areas to 68% in 30 years. In Europe, despite 3.7% decrease of total population is expected in 2050 compared to 2020, the urban population share will move from 75% in 2020 to 84% in 2050 (Ritchie & Roser, 2018). The increase of urbanization determines a corresponding intensification of human activity and the related energy consumption; thus, it is necessary to carry out effective urban energy planning that takes into account sustainable development plans and quantifies the effect of related policies.

The building stock represents a significant share in energy use and greenhouse gas emissions; in 2017, it accounted for 42% of final energy consumption and 17% of $CO_2$ emissions from fuel combustion in Europe (European Commission [EC], 2019). Therefore, it offers a great potential for energy efficiency and integrated sustainable energy solutions. The key-role of buildings in the energy balance of cities has boosted novel city-scale building-oriented studies, aimed at developing suitable tools for stakeholders, city planners and decision-makers. These tools will enable to understand urban energy systems and to formulate energy plans, suggest sustainable initiatives and decide on constructive policies (Torabi Moghadam et al., 2017).

To develop urban energy planning tools, models of Urban Energy Systems (UES) should be conceived through an integrated multi-domain approach, which embraces complex interactions in urban areas, such as energy flows, environmental indicators, social and economic factors. The increase of model data and complexity requires more advanced technologies. In this field, Information and Communications Technology (ICT) represents the right answer to the need of integration of data, tools and actors, spanning across different domains and scales of analysis (i.e. building, neighborhood, city, and region). ICT is a very wide term; sometimes "digitization" and "datafication" are used to refer to the issues derived from data retrieval, modelling and analysis in urban contexts. This technology grants automatic access to data dispersed in different sources, interoperability of data and tools for energy simulation, optimization and decision support through multi-criteria analysis, and visualization in a 3D environment. To these objectives, ontology and semantics form the basis to develop UES models using ICT (Pauwels et al., 2017). Future UES models will take advantage from the nascent era of digitalization, through the inclusion of the Internet of Things (IoT) and Artificial Intelligence (AI) agents (e.g. data analytics, machine learning) (Boje et al., 2020), as to boost the development of Smart Cities.

In this context, the present chapter aims to investigate recent studies on integrated urban energy models, starting from building stock models and related tools, highlighting their strengths and limits, up to multi-domain energy models. In the field of UES, the chapter specifically focuses on projects and initiatives addressed to the creation of effective urban energy planning tools. As an exemplary case, the experience of SEMANCO (*Semantic Tools for Carbon Reduction in Urban Planning*), a European project part of the EC 7th Framework Programme, as well as the peculiarities of the UES tool developed in the project (Corrado et al., 2015) are presented. SEMANCO aimed to create an effective decision support system to reduce carbon emissions. Its approach was based on the interrelation of different actors – policy makers, planners, engineers, consultants, and inhabitants – to correlate a diversity of problems, spanning across distinct domains and geographic scales.

The chapter has been structured as follows:

- Background analysis on the approaches for energy and environmental modelling of building stocks.
- Presentation of urban building energy models (UBEMs), as recognized in literature as the most used techniques for building stock energy analysis, and urban scale energy models (USEMs), that integrate multi-domain energy assessment at city scale.
- Specification of Urban Energy Systems (UES) for the development of urban energy planning tools, and characterization and application of ICT systems for the integration and interoperability of data and tools.
- Description of the technological approach followed to create an effective tool for carbon reduction in urban planning, through the experience and the outcomes of the SEMANCO project. Presentation of the SEMANCO platform and of EECITIES (Energy Efficient Cities), an energy analysis service provider developed in the project.
- Conclusions and suggestions for future research in the context of Smart Cities development.

## Background

Integrated urban energy modelling is a complex approach that concerns the energy flows coming into, passing throughout, and going out of cities. To understand the drivers and patterns of energy flows, the element of the urban metabolism should be analyzed. In literature, urban metabolism has been discussed in social, natural, historical and political sciences. Urban metabolism is either recognized as an urban metaphor to describe the transformation of nature by society, or discussed through an ecological approach where the city is considered as an ecosystem. Urban metabolism also concerns the transformation that energy and materials undertake, and the effects of this transformations on the city. This last aspect matches with the engineering approach of urban metabolism defined by Carreón & Worrell (2018) as "a process that involves the exchange of energy and materials within a specific environment". According to Carreón and Worrell (2018), the drivers of energy flows are recognized as factors that directly or indirectly cause a change in the services provided by the energy systems, and can be related to environment (e.g. climate, energy sources), technology, economics, society, demography and politics. Devising an integrated urban energy modelling means developing an Urban Energy System (UES), i.e. "a formal system that represents the combined processes of acquiring and using energy to satisfy the energy service demands of a given urban area" (Keirstead et al., 2012). In this context, urban metabolism is a paradigm that overlaps with urban energy system.

Among the elements of urban metabolism, the influential role of buildings is well recognized. In literature, several studies concern building stock models, including both buildings, or demand-side, and districts, or supply-side, energy models, as well as their interactions. Within the demand-side energy models, the urban building energy models (UBEMs) are the most widely applied and well recognized by the research community (Johari et al., 2020). Despite UBEMs are largely included in the UES models, the latter are still scarcely investigated and not widespread.

## Building Stock Energy Models

According to the scientific literature, the building stock energy models are usually classified in function of two different methodological approaches: the top-down and the bottom-up models (Johari et al., 2020; Abbasabadi & Ashayeri, 2019; Kavgic et al., 2010; Swan & Ugursal, 2009).

The applicability of one technique compared to the other depends on the final aim to be pursued, on the correlation with different variables and on the diverse levels of detail of the input parameters. Specifically, the important differences between these two approaches concern: the different degrees of aggregation of data, the different computational capacity required by the computer, and the different purposes for which they are conceived and used.

The top-down model is mainly used to predict a future scenario, based on situations from the past time series. The bottom-up, instead, is used to define the current circumstances and ultimately to investigate future possibilities, such as improving energy performance of certain buildings. In general, the top-down model determines a broad-spectrum view of the system without venturing too far into detail. On the contrary, the bottom-up model specifies each component, and as a result provides a deeper knowledge of the phenomenon to be studied. In the following subsections, top-down and bottom-up building stock energy models are presented in terms of main features and applications, strengths and limits, as pointed out in literature.

## Top-down Models

The top-down model in general concerns the resolution of complex systems, in which the final objective is to divide the output into a finite number of parts, in order to more easily identify the existing interconnections between them. It consists in associating a predefined number of black boxes to the problem, in order to mathematically demonstrate the possibility of obtaining that result without necessarily having to depend on the knowledge of the physical laws that govern the phenomenon itself. Through the analysis of the final solution, it is possible to identify the missing resources so as to complete the codification of the problem.

The top-down models, typically based on historical data series, are developed to investigate the macro-relationships between the energy, technological, and economic sectors. Usually, the initial parameters from which building consumption is calculated are a function of economic variables (gross domestic product, unemployment, inflation, per capita income), energy price, and/or climate data. Since it must work with aggregated data, the top-down model does not contain a direct and explicit representation of the technologies adopted.

The econometric model is an example of a top-down approach, which is developed to determine the influence of economic variables on the effects of energy policies adopted by following a statistical calculation. The difficulties in applying this methodology depend on the energy-economic interrelation of the parameters considered. The main purpose in the adoption of this model, implicitly based on the microeconomic theory, is the prediction of the energy demand of a building stock in a statistical way, generally adopting linear regression equations according to per capita income.

In literature, it is often possible to come across the distinction between econometric and macro-econometric models, whose diversity is mainly based on different applied economic theories: microeconomics in the first case, and macroeconomics in the second. In the macro-econometric model, the aggregated data are based on national income and not on per capita income. Many examples of econometric top-down models can be found in literature, like the work of Bianco et al. (2009), in which an energy model able to predict the urban energy use has been developed through regression analyses that correlate gross domestic product and population to yearly electricity use in Italy. Another example of a top-down approach is the one proposed by Haas & Schipper (1998), who developed several econometric models, thus correlating energy variables to economic ones, for countries belonging to the OECD (Organisation for

Economic Co-operation and Development). Specifically, the authors performed an analysis to estimate the energy demand of a residential building stock by correlating it to the price of energy, to the related consumption expenditure, and to the value of degree days in the reference country.

Having to do with multi-collinearity, one disadvantage of the top-down building stock energy model lies in the impossibility of evaluating the influence of a precise and defined technological measure, but the overall trend would be established in any case.

Strengths and limits of the top-down energy models are summarized in Table 1.

*Table 1. Strengths and limits of top-down building stock energy models*

| Strengths | Limits |
|---|---|
| • Simplicity linked to reliance on aggregated historical data<br>• Capability to extract relationships between factors that indirectly determine urban energy use<br>• Ability to predict long-term energy consumption<br>• Independence from detailed technological description | • Dependency on historical trends data<br>• Generalization of the existing conditions<br>• Absence of determination of individual end-uses<br>• Unsuitability to examine changes in technology |

## Bottom-up Models

A bottom-up model, unlike the top-down one, builds an ordered and sequential action strategy to achieve the final result, providing a detailed explanation of each subsystem and of how it is connected to the others. The bottom-up building stock energy model is based on disaggregated and extensive data. These are acquired by the developer beforehand through analytical, statistical or empirical means, in order to be able to proceed with the subsequent calculation phases. Disaggregated data are applied to estimate the end-use energy of individual buildings or group of buildings, and then the aggregated energy demand is extrapolated at a wider territorial scale. This way, it is therefore possible to individually evaluate the behavior of potential energy refurbishment interventions aimed at improving the energy performance of predefined building stock in detail. Consequently, a major skill required to the developer is to know how to manage the complexity and uncertainty of the input parameters needed to complete the model.

In literature, bottom-up building stock energy models are commonly divided into three categories, namely *engineering* (or *physical*) *models*, *data-driven models*, and *hybrid models*.

The *engineering* (or *physical*) *models* are based on an analytical calculation; the methodological approach entails the solving of the energy balance equation of the system. To pursue this objective, a complete knowledge of the input parameters is necessary. It can be obtained from in-field measurements or from empirical references, i.e. based on the observer's experience. To this regard, it is necessary to know the climatic data of the site of interest, the geometrical properties of the buildings and of the urban environment (surfaces, volumes, heights, window-to-wall ratio), the thermo-physical characteristics of opaque and transparent envelope components, information on the user behavior and technical building systems data. The engineering model is the most used approach in literature to assess the energy use of a building stock; it is usually recognized as *urban building energy model* (UBEM). The following section of the chapter is specifically dedicated to present UBEMs and related lines of research.

Starting from a large sample of data, the *data-driven models* allow associating the building characteristics and other parameters, such as user features, to the energy use by means of statistical analysis or models based on artificial intelligence. The mathematical relationship identified is then used to estimate the energy use related to specific end-uses (Abbasabadi & Ashayeri, 2019). The data-driven statistical models involve regression techniques, such as linear or polynomial regression. These methods are widely applied in estimating the energy use due to very simple structure and fast processing time. Anyway, the regression model is not able to take into account complex patterns related to the real world. This limitation can be overcome by the data-driven models based on artificial intelligence, which commonly apply Machine Learning (ML) techniques. These allow identifying statistical patterns in data, fitting the model, and then finding the mathematical law to correlate the energy use to building parameters. The ML techniques include both un-supervised and supervised methods. The former relies on clustering approach, while the latter comprises neural network techniques. An example of a data-driven approach is the one proposed by Pasichnyi et al. (2019), which is based on the creation of a building stock model, referring to the urban reality of Stockholm, to investigate what interventions can be made to the existing building stock. Three improvements are proposed, and the best combination ensures a decrease of 18% in annual demand for the heating of the building stock involved.

A common issue of the building stock energy models is the lack of a complete picture of input data that can be discussed in terms of “data availability”, “data accessibility”, and “data accuracy” (Goy et al., 2020). The advantage of using a data-driven model compared to an engineering model consists in getting results that are more accurate. However, the accuracy of data-driven models can be easily compromised whereas the available dataset is not sufficiently representative or the data are aggregated. On the other hand, the engineering models do not suffer from the lack of historical data (e.g. available energy use data), differently from the data-driven ones, but are more sensitive to the estimation uncertainties of energy use due to the simplification of building characteristics and user behavior data.

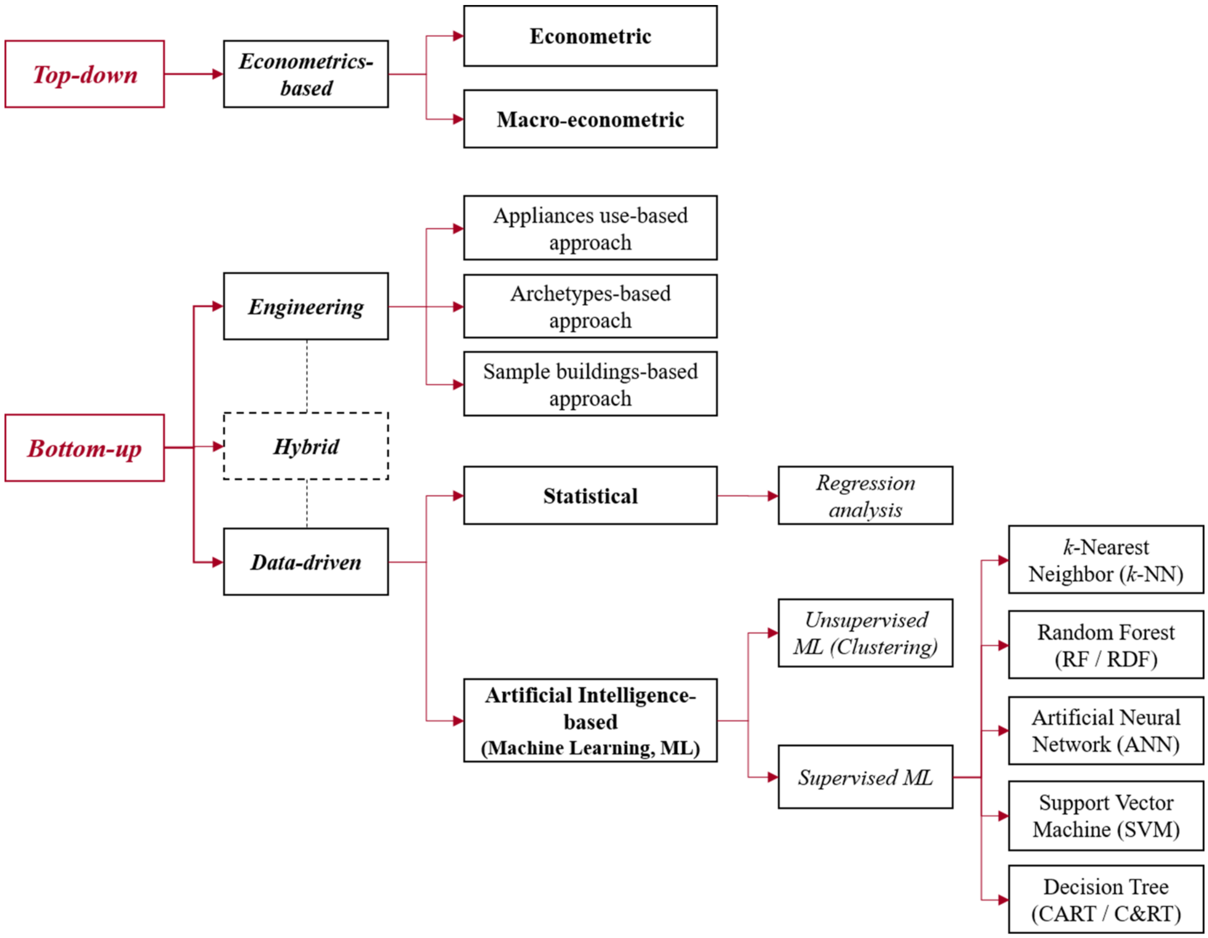
In agreement with the above approaches, an example is the research carried out by Nageler et al. (2018). The authors performed an energy simulation through the construction of two models. The first one involves the creation of a dynamic physical-based model. The second one, instead, defines a mathematical algorithm of the data-driven type. These digital objects have been created to estimate the thermal behavior of a residential area composed of 34 buildings, and show good agreement against measured data. In addition, the application fields of these approaches have been discussed.

*Table 2. Strengths and limits of the engineering and of the data-driven bottom-up energy models*

| Engineering models | | Data-driven models | |
|---|---|---|---|
| **Strengths** | **Limits** | **Strengths** | **Limits** |
| • Independence from historical data<br>• Easy assessment of efficiency measures<br>• High adaptability with BIM tools | • Computationally time consuming<br>• Loss of accuracy due to simplifications<br>• Need of detailed input data | • Efficiency of processing time<br>• Capability to include occupancy factors<br>• Accurate prediction of energy use | • Relying on historical data<br>• Limited adaptability in case of design variations<br>• Loss of accuracy in case of data unavailability |

The *hybrid models* are designed to overcome the limits of both engineering and the data-driven models, and to meet the need to complete the initial input data picture. Indeed, the stochastic distribution of certain parameters (e.g. those concerning occupant’s use) produces a certain degree of uncertainty in

*Figure 1. Classification of building stock energy models*




the creation of the engineering model. This issue can be overcome by deriving the necessary input data through statistical (data-driven) analysis of energy use historical data. This will then lead to the definition of a sophisticated bottom-up approach, whose aim is to determine the energy needs of a building stock, by extracting data from different information databases.

Strengths and limits of the engineering and of the data-driven bottom-up energy models are summarized in Table 2.

Figure 1 provides the classification schema of the building stock energy models.

## URBAN BUILDING ENERGY MODELS

### Classification and Features

*Urban building energy models* (UBEMs) are usually classified as bottom-up engineering models, despite different keys of interpretation attributable to the definition of UBEMs are provided in literature. For Sola et al. (2020) and Hong et al. (2020), the concept of UBEM is independent from the bottom-up approach adopted, engineering or data-driven. Reinhart & Cerezo Davila (2016) and Johari et al. (2020), on the other hand, refer the concept of UBEM to the engineering bottom-up model implemented to constitute an energy model, suitable for estimating the operational energy demand of a certain building stock. The energy demand, based on the energy services considered (space heating, space cooling, domestic hot water production, ventilation, artificial lighting, etc.), depends on the resolution of the mass and energy conservation equations.

In agreement with Swan & Ugursal (2009), which carried out a classification of the building stock energy models for the residential sector, the engineering models – and hence the UBEMs – can be further classified into three different modeling approaches:

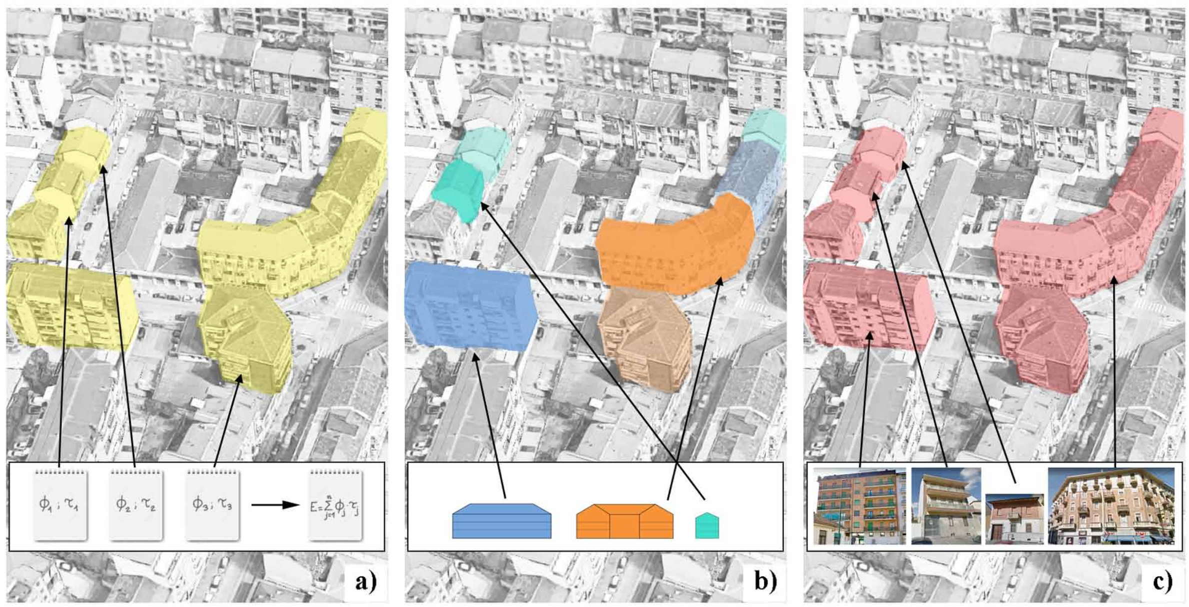
- the *appliances use-based approach*, that involves the estimation of energy demand through the study of the appliances used at regional or national level within housing units according to parameters, such as type, use, efficiency and consumption,
- the *archetype-based approach*, based on the definition of archetypes, i.e. buildings considered representative of subsets of the building stock in function of energy-related parameters (construction period, building size, use category, etc.), the subsequent assessment of the energy behavior of each archetype, and then the upscaling of the results to a wider territorial scale, and
- the *sample buildings-based approach*, based on the assessment of a wide variety of buildings with actual available data. If the buildings constitute a representative sample of the national or regional building stock, thanks to a large database of information, the energy demand of the stock can be derived through weighted factors.

A schematic representation of the three UBEM approaches is shown in Figure 2.

The first approach, which is less used, can be applied only for specific cases, for instance, if the electrical needs of a building should be estimated. In this case, it is necessary to know the type of appliances, the power absorbed and their use profile. This methodological approach falls within the bottom-up methodology, as it starts from a series of disaggregated data. Anyway, the most applied approaches are the last two, whose difference is substantially based on the different number of buildings concerned in the model. Whereas the number of archetypes is limited, despite they can be constructed using a large dataset of real buildings, in the third case, real data of hundreds or thousands of buildings have to be collected. In agreement with the methodologies presented, an example is provided by Cerezo et al. (2017) that proposed four archetype-base modeling methods to compare the simulated Energy Use Intensity (EUI) applied on 336 residential buildings located in a district of Kuwait City. Two of these methods are based on the deterministic approach, one on the probabilistic approach and the fourth introduces a new Bayesian calibration, which is significantly closer to the measured data.

The UBEM is a useful tool for urban planners, designers, or public administrations who are willing to analyze the energy performance of a city's environment, and to support and encourage programs aimed at improving the energy performance of the reference building stock. The main difficulty that the developer of an UBEM must be able to govern concerns the high degree of uncertainty in determining some of the energy data, especially when they refer to an existing building stock. Some information, available from statistical or empirical documents, can be obtained from municipal, regional and national databases, standard and legislative references, and scientifically recognized publications (Piro et al., 2020). However, the degree of detail of the input parameters depends on the purpose and on the calculation engine

*Figure 2. Types of urban building energy models (UBEMs): a) appliances-use based approach, b) archetypes-based approach, c) sample buildings-based approach*




used. The energy performance assessment in an UBEM can be based either on steady-state monthly calculation methods, or on dynamic models with hourly or sub-hourly time steps. Furthermore, once the model has been generated, it is necessary to proceed with the calibration steps. Therefore, in addition to the input data sets, a considerable number of terms of comparison (e.g. real energy consumption data) are also required to establish a good quality.

According to Reinhart & Cerezo Davila (2016), the accuracy of a building stock energy model increases from individual building to urban level to regional level. On average, the deviation between estimated annual energy use and measured annual energy consumption amounts to 7-21% for heating loads in case of UBEMs involving multiple buildings. An example of an accurate UBEM is the one developed by Hedegaard et al. (2019), defined to estimate the energy consumption of a Danish neighborhood, consisting of 159 single-family houses, served by a district heating system. The described model aims to decrease the daily overloads required from the network by predicting a consumption pattern comparable to the real situation.

In the scientific context, a significant amount of tools for UBEMs development has been created, the majority of them within academic contexts. They usually employ BIM (Building Information Model) to store, process and visualize data. In such tools, the UBEM is usually composed of a three-dimensional geometric model, climatic and topographic information from the site of interest, opaque and transparent thermo-physical characteristics of the envelope components, data on the building use, and data about the technical building systems.

To represent the geometric reality of the city context, the Open Geospatial Consortium (OGC) has conceived a standard model, called CityGML (Gröger et al., 2012), with different Level of Details (LoD). The geometric and informative precision of an UBEM is a function of the purpose of the analysis to be pursued. For example, a three-dimensional representation of masses with planar surfaces, represented by a LoD1 (according to the standard provided by the OGC), may be sufficient to calculate the requirements of a building stock. LoD2, on the other hand, also allows the representation of oblique surfaces, so that sunlight studies can be carried out with a better degree of precision. Finally, LoD3 and LoD4 complete and improve the quality of the previous geometrical model, including external window frames, and potentially internal building structures. Therefore, it is established that the level of detail of a simulation at a building and at a district scales would be different from one carried out on an urban or regional context.

### From UBEM to USEM - Urban Scale Energy Model

The urban building energy models, which only deal with building energy demand during operational phase, are often accompanied by other models, to take into account also supply and distribution energy in cities (Allegrini et al., 2015). The urban environment can be considered like a box, in which a series of energy conversion processes take place, which includes several areas, such as buildings, industry, transport, and city infrastructure in general. The approach to understand this urban thermodynamic system must be holistic and integrated, by including the exchange of different energy flows from different perimeters. In agreement with studies found in literature, this concept can be included in that of the *urban scale energy model* (USEM), as specified by Sola et al. (2020).

The USEM is a virtual model that involves a spatio-temporal resolution of energy flows in cities; it describes a certain energy system and proposes possible strategies to improve its urban energy performance. The virtual modeling of the USEM allows the evaluation of system losses, load peaks, unconsumed energy shares, and the relationship between consumer and supplier. In agreement with Basu et al. (2019), the USEM is not only distinguished by its physical elements, but also by the people who are part of the distribution process (agents, suppliers, consumers), as well as non-material entities (consumer feedback, incentives, energy policies, etc.).

About the incorporation of different urban energy components, models for building operational energy, models for transportation energy, and models for building embodied energy commonly coexist and usually operate independently from one to another. Instead, integrated energy models are scarcely developed, as also stated by Abbasabadi & Ashayeri (2019).

In the domain of USEMs, taking into account the different assessment models, both of the energy flows in cities (i.e. generation, distribution, and final energy demand) and of the energy consuming domains in cities (i.e. buildings, transport, industry), a detailed classification of the main existing tools can be drawn, as provided in Table 3.

## URBAN ENERGY SYSTEMS

### Overview

An energy efficient urban planning should be conceived by taking into account that urban elements, as energy consumers (e.g. buildings, transport) and energy suppliers, operate simultaneously at different levels and dimensions. This implies that models and related tools for the energy assessment of specific elements of cities should be integrated each other, as to mirror the complexity of the urban system with a hierarchical approach. To this purpose, the concept of *Urban Energy System* (UES) has been introduced to define "the combined process of acquiring and using energy to satisfy the demands of a given

*Table 3. Classification of the main existing tools for urban energy use assessment*

| Tool name | Reference | Model category [(a)] | Modelling approach [(b)] | Calculation time step[(c)] | Modelling object | | |
|---|---|---|---|---|---|---|---|
| | | | | | Energy demand | | Energy supply and networks |
| | | | | | Buildings | Transport | |
| UMI | Reinhart et al. (2013) | UBEM | EN | H | • | | |
| CityBES | Chen et al. (2017) | UBEM | EN | SH | • | | |
| SimStadt | Nouvel et al. (2015) | UBEM | EN | M | • | | |
| TEASER | Remmen et al. (2018) | UBEM | EN | H | • | | |
| CHREM | Swan et al. (2009) | UBEM* | EN, DD | SH | • | | |
| BEM-TEB | Bueno et al. (2012) | UBEM | EN | H | • | | |
| CitySim | Robinson et al. (2009) | USEM | EN | H | • | • | • |
| UrbanOpt | Polly et al. (2016) | USEM | EN | SH | • | | • |
| MESCOS | Molitor et al. (2014) | USEM | EN | H | • | | • |
| HUES | Bollinger & Evins (2015) | USEM | EN | SH | • | | • |
| CEA | Fonseca et al. (2016) | USEM | EN, DD | H | • | • | • |
| SynCity | Keirstead et al. (2010) | USEM | EN | D | • | • | • |

[(a)] UBEM = urban building energy model, UBEM* = engineering model with additional statistical analysis, USEM = urban scale energy model
[(b)] EN = engineering, DD = data-driven
[(c)] M = monthly, D = daily, H = hourly, SH = sub-hourly

urban area" (Keirstead & Shah, 2013). In addition, since the urban energy system is a dynamic model, it should be constructed as to be able to both understand the current state of the system and simulate its evolution (Shah, 2013). The evolution of the UES will help stakeholders to get answers on the future urban energy efficiency and, subsequently, to take decisions.

Compared to an UBEM or to an USEM, an UES is not limited to the urban energy model itself, which is still the object of analysis, but the UES rather concerns the process to conceive and develop the model in a dynamic and multidisciplinary view. Although the multidisciplinary approach between UES and USEM is shared, what differentiates them is the simultaneous consideration of energy issues characterizing the urban environment. The description of Urban Energy Systems can be assimilated to that of a metabolic system (Keirstead & Shah, 2013), developed to assess the social, economic, and environmental impacts. This concept consists of the analysis of all the transformation processes of material and energy, dependent on external inputs, which occur within a given urban context. Therefore, although in USEM the simultaneous consideration of different energy models is attempted as much as possible, in UES the holistic assessment becomes a necessary condition. From this point of view, both UBEM and USEM can be defined as subsystems of UES.

In order to assess the temporal and spatial dynamism of the urban energy flows, the models of urban energy systems should take into account that, in the development of the UES, multiple experts and knowledge domains are involved. It means that the development of an urban energy system has an impact not only on the improvement of the energy efficiency of a territory, but it also has economic, political, social, demographic and cultural implications. These implications, in turn, have effect of the urban energy flows, as in a circular process.

## ICT Solutions for Developing Urban Energy Systems

To develop models of urban energy systems, a very high amount of input data coming from different disciplines is required. As the urban energy systems are complex and dynamic entities, the related information is usually heterogeneous and dispersed in numerous databases. In addition, UES models should rely on integrated energy assessment tools interoperable with reliable input data.

Nowadays, large amount of data are being generated by digitalization, thanks to the wide spreading of Information and Communication Technology (ICT). The introduction of ICT solutions into the market has ensured higher energy efficiency in the use of a building, through an effective control of the management and measurement processes, and comfort adapted to the needs of the occupants. Taking advantage from new technologies (e.g. smart meters), the collection and processing of consumption data is considered an effective driver for the increase of the energy efficiency and the improvement of the environmental footprint of the existing building stock. It has been quantified that, if properly used, the adoption of ICT within an inhabited space ensures energy savings of near 20% (Hannus et al., 2010).

In agreement with Jáñez Morán et al. (2016), in the context of energy management of buildings and energy communities, ICT consists of three fundamental pillars: the measurement systems, the sharing structure through which the exchange of information takes place, and the Building Energy Management Systems (BEMS), which ensure the operator's control over his own thermal, electrical or lighting system. ICT revolves around a huge volume of information that has to be collected, processed, and visualized by a precise computer structure in real-time.

In this regard, the importance of Information and Communication Technology should be discussed also with regard to the development of urban energy systems. In the work of Marinakis et al. (2020), a big data platform for smart energy services that integrates types of data from different sources and domains has been created. One of the main structural components of this platform is a "data interoperability and semantification layer".

The application of semantic technologies is fundamental to access data and integrate them from different domains, besides assuring the interoperability between data and tools in the context of urban energy systems. Ontologies are used to create vocabularies, shared between experts from different knowledge domains, and establishing relationships between the different objects within urban energy systems. According to Gruber (1993), an ontology is "a description (like a formal specification of a program) of the concepts and relationships that can exist for an agent or a community of agents". Therefore, an UES supported by ontologies built by domain experts allows for an effective representation of a complex reality.

Some international initiatives and projects have developed methods and instruments to carry out sustainable urban energy planning through an effective energy assessment of cities and the optimization of energy use. Most of them take advantage of ICT systems and Decision Support Systems (DSS). Some examples of platforms and tools developed in this context are provided in the following list. The models proposed fall into the category of UES, since their objective is to provide an assessment of a predefined urban context according to social, environmental, and economic indicators. As a result of this analysis, it will be possible to identify inefficient urban systems in order to develop regeneration plans.

- TRACE (*Tool for Rapid Assessment of City Energy*) is a DDS tool that provides authorities with an assessment of the energy use in public sector, the identification of cost-effective and feasible energy efficiency measures, covering many knowledge domains, such as buildings, transport, water use, solid waste, public lighting and energy supply (World Bank, 2018).
- i-SCOPE (*Interoperable Smart City Services through an Open Platform for Urban Ecosystems*) is an open platform focusing on different domains and providing three main services for *Smart Cities*: improved personal mobility of aging and diversely able inhabitants, optimization of building energy consumption, and real-time environmental monitoring of urban noise (de Amicis et al., 2012).
- e-SCEAF (*Smart City Energy Assessment Framework*) is a web based DSS tool that has been developed to evaluate the energy performance of a city or an individual sector with the aim to optimize energy use, to reduce $CO_2$ emissions and to minimize energy costs. Through appropriate indicators, the tool is able to assess the performance over three main axes, that are: the "political field of action" (i.e. achievement of energy savings and environmental targets), the "Energy and Environmental Profile" (i.e. calculation of $CO_2$ emissions, energy consumption and renewable energy production), and the "Related Infrastructures and ICT" (i.e. analysis of ICT, automations, monitoring and forecasting systems in the buildings of the city) (Papastamatiou et al., 2017).
- DPL (*Sustainability Profile for Districts*, in German) is a tool aimed at assessing environmental, social and economic profiles of districts. It uses a limited number of indicators based on collected data from municipal registers. If data are not available, the model allows alternative methods to estimate the indicators. From these data, environmental, social and economic profiles for the district are calculated. In addition, if required by the local authorities, the tool allows new indicators to be included (Kortman et al., 2001; Jensen, 2009).

## DEVISING AN EFFECTIVE URBAN ENERGY PLANNING

### The Experience of the SEMANCO Project

In the context of the urban energy systems and advanced technologies for their modelling, the following section is aimed at presenting the experience carried out in SEMANCO (*Semantic Tools for Carbon Reduction in Urban Planning*), a project co-founded by the European Commission within the Seventh Framework Programme, under the theme "ICT systems for energy efficiency" (SEMANCO, 2015).

An integrated platform to model multiple energy systems using a variety of tools was developed in SEMANCO. The tools operate with semantically modelled data located in different data sources, and include instruments for visualizing, simulating and analyzing the multiple aspects that determine the energy and environmental performance of cities. The framework of data and tools allows different users (e.g. planners, policy makers, consultants) to take decisions about the improvement of the energy efficiency in cities, or part of them (e.g. even single buildings).

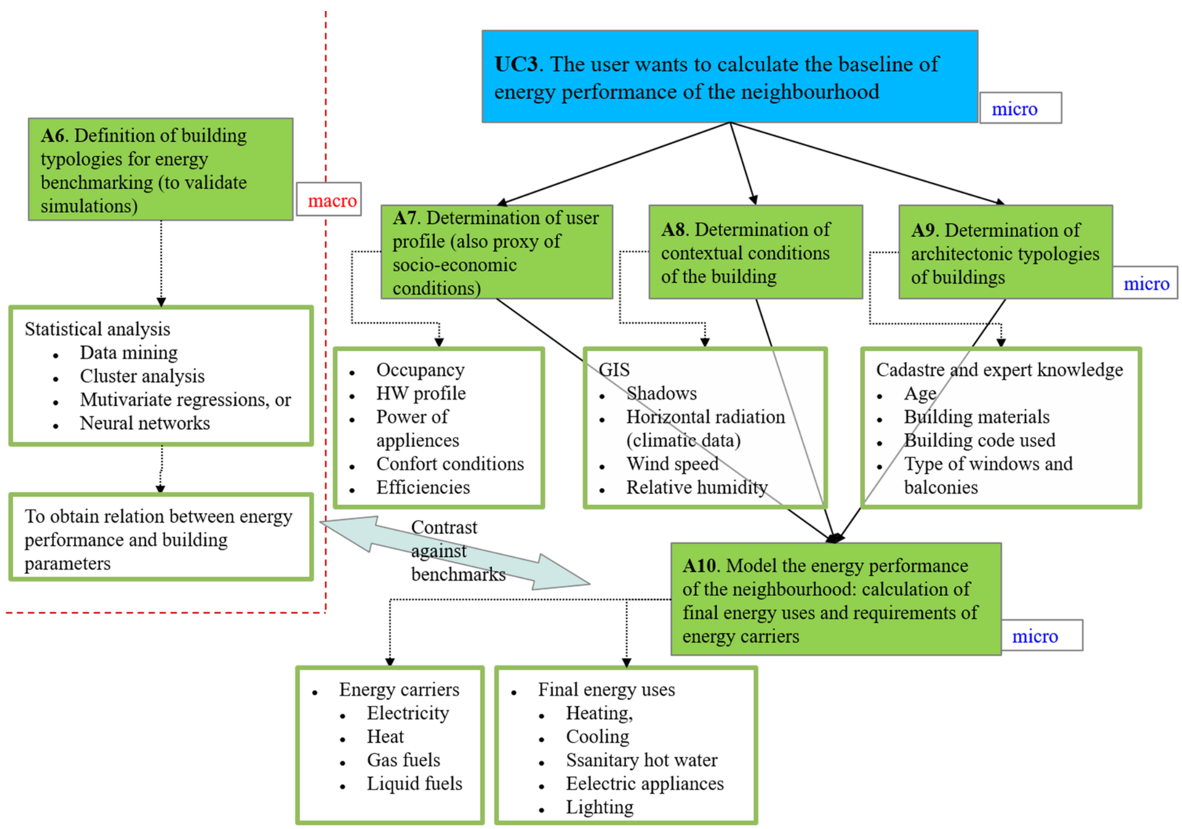
The main innovative aspect of SEMANCO consists in the close collaboration between experts in different knowledge domains aimed at creating the ontology and the platform. In such a way, the knowledge of each expert about a specific part of the overall system has been usefully taken into account; his/her knowledge is determined by the tools and method used in the discipline, by experience and by the information that he/she has at any given moment (Madrazo et al., 2014a).

To develop the models of the urban energy systems integrated in the platform, a *use-case* approach was assumed in SEMANCO. The use-case was defined as "a pre-conceptualization of a model which represents an urban energy system, as thought by experts within a particular context" (Madrazo et al., 2014a). To solve the problem described in the use-case, a series of actions, named *activities* in the project, were identified. An example of use-case, related activities and data needed to solve the problem, are shown in Figure 3. The use-case approach identifies a complex network in which the same activities can be shared by different use-cases. Each use-case and/or activity can be performed at different scales of analysis, such as micro-scale (i.e. building), meso-scale (i.e. neighborhood), macro scale (i.e. district/city).

The terminology used in the use-cases, in the activities and in the related data was set in accordance with standards and official references as to create the universally shared vocabulary (semantics) for the development of the SEMANCO ontology. The ontology created in SEMANCO constitutes the SEIF (Semantic Energy Information Framework) that forms the connection between the distributed data sources and the tools that use the data modelled semantically.

The development of the ontology in SEMANCO concerned the following six steps (Nemirovski et al., 2013):

*Figure 3. The use-case approach in SEMANCO to develop UES models: an example of use-case, related activities and data*



1. **Vocabulary capture:** the knowledge that domain experts have about the problems addressed in the use-cases is made explicit. The experts describe how actors, tools and data can solve a specific objective under a particular policy framework. In this step, the activities expressed in the different use-cases of SEMANCO were described by means of competency questions (Suárez-Figueroa et al., 2012), and then the data sources that contain the information required were identified (Madrazo et al., 2014a).
2. **Construction of the vocabulary:** the terminology provided through the use-cases was set up in form of *Energy Standard Tables*. According to Corrado et al. (2015), these tables constitute an informal vocabulary that precedes the construction of the formal vocabulary (i.e. the ontology), and represent an effective instrument to support collaboration between ontology engineers and experts from different domains. The *Energy Standard Tables* were implemented as a set of spread-sheets, where terms, descriptions, units of measure, and relationships between concepts are provided. These tables stand for a conceptualization of an UES, which is an inter-disciplinary domain, by providing the definition of the terms that experts consider relevant because related to the issue expressed in the use-case. The *Energy Standard Tables* encompass categories of energy data and energy-related data, such as energy cost data, climatic data, environmental data, building technical data, legislative constraints, geographical data, land and buildings registry data, urban planning data, socio-economic data, and demographic data. A total number of 25 *Energy Standard Tables* were created in the SEMANCO project, encompassing about 1000 concepts (Corrado & Ballarini, 2013). An example of *Energy Standard Table* for the *building* concept, included in the building technical data category, is shown in Figure 4.

3. **Mapping data sources to vocabulary:** the names of the data items, included in the data sources, which have been identified in the activities of the use-cases, are mapped on the vocabulary (i.e. concepts of the *Energy Standard Tables*). The mapping was carried out by the domain experts and by the data owners.
4. **Coding of the ontology:** the vocabulary set in the *Energy Standard Tables* was then translated in a formal ontology based on the DL-LiteA formalism. An ontology editor, in accordance with Wolters et al. (2013), performed the coding of the semantic energy model in SEMANCO. The SEMANCO ontology editor presents two possible simulation views of the developed ontology: (i) one view for the editing of the concepts taxonomy, (ii) another view for the editing of the graph of non-subsumption relations (Madrazo et al., 2014a).
5. **Integration of the data sources:** the outputs generated in steps 3 and 4 were used to transform the contents of the data sources into RDF (Resource Description Framework) resources. To do so, the mappings established in step 3 were coded as relations between a relational database and the ontology created in step 4. These mappings are usually implemented with declarative mapping languages that offer rich expressive features to bring the rigid relational schemas to real cases (Nemirovski et al., 2013).
6. **Evaluation:** the last step concerns the evaluation of the ontology created in the previous steps. Three elements were evaluated: (i) the ability of users to understand the ontology structure, (ii) the mapping compliance, and (iii) the computational efficiency, consisting in the capability of the ontology to support query with a short response time.

*Figure 4. Example of Energy Standard Table for structuring the terminology related to the building concept. Extract from the SEMANCO project (Corrado & Ballarini, 2013)*

| Name/Acronym | Corresponding Name in D3.1 | Description | Reference | Type of data | Unit | Reference to other sheets |
|---|---|---|---|---|---|---|
| Building | - | construction as a whole, including its envelope and all technical building systems, for which energy is used to condition the indoor climate, to provide domestic hot water and illumination and other services related to the use of the building | EN 15603 | - | - | - |
| *has* Building_Name | - | name (ID) of the building | - | string | - | - |
| *has* Age | *building age* | construction period of the building | - | string | - | - |
| *is* Year_Of_Construction | - | year of construction of the building | - | string | - | - |
| *is* Age_Class | *building age class* [new] | period of years to be defined according to typical construction or building properties (materials, construction principles, building shape, ...) | TABULA | string | - | - |
| *has* From_Year | - | first year of the age class | TABULA | string | - | - |
| *has* To_Year | - | last year of the age class | TABULA | string | - | - |
| *has* Allocation | - | specification of the region the age class is defined for | TABULA | string | - | - |
| *has* Identifier | - | - | SUMO | A,B,C,D | - | - |
| *has* Building_Typology | *building typology* | building typology | - | string | - | - |
| *is* Flat | - | apartment in a building | - | string | - | - |
| *is* Detached_Building | - | small building, without attached buildings | TABULA | string | - | - |
| *is* Semi-Detached_Building | - | small building, with an attached building | TABULA | string | - | - |
| *is* Terraced_Building | - | small building, with two attached buildings | TABULA | string | - | - |
| *is* Row_Building | - | big building, with prevalent horizontal extension | TABULA | string | - | - |
| *is* Tower_Building | - | big building, with prevalent vertical extension | TABULA | string | - | - |
| *is* Courtyard_Building | - | big building having "L" or "U" shape | TABULA | string | - | - |
| *has* Internal_Courtyard_Orientation | - | | | | | |
| *has* Conservation_State | *conservation state* | conservation state of the building | - | string | - | - |
| *is* New_Building | - | building to be designed | - | string | - | - |
| *is* Existing_Building | - | existing building | - | string | - | - |
| *is* Refurbished_Building | - | building to be refurbished | - | string | - | - |
| *has* Building_Use | *building use* | use of the building | - | string | - | "b_use" |
| *has* Building_Geometry | - | geometry of the building | - | - | - | - |
| *has* Building_Floor_Area | *building floor area* [new] | sum of the areas of the building storeys | - | real | $m^2$ | - |

The methodology and the technological structure of SEMANCO were developed and tested in the project by means of three case studies, Manresa (Spain), Newcastle (UK) and North Harbour (Denmark).

## The SEMANCO Integrated Platform and EECITIES

The SEMANCO integrated platform is the front-end for users; it grants the access to tools and data, and provides services to model urban energy systems. The combination of experts' knowledge, captured through the use-cases, and the data linked to external data sources, accessible through the SEIF, constitute the basis to create models of UES. For a particular urban area – a city, a district, or a neighborhood – multiple urban energy models can be created combining data and tools in various ways. Within a given urban model, users can use the tools to assess the energy performance of the urban area, and to carry out plans to improve it. The open structure of the platform enables an urban energy model to be enhanced when new tools and data – either from existing data sources or from the data generated by the different applications – become available.

Different layers are provided for in the SEMANCO platform, such as:

- *urban energy system* that refers to a particular urban area delimited by the available data and by objectives to be achieved applying specific tools,

- *urban energy model* that is the conceptualization of the UES,
- *plans* that are defined to improve the energy performance of the urban area (see, for instance, Figure 5). The baseline, which represent the current condition of the analyzed area in terms of energy performance, can be estimated by using the energy assessment tools and the available data,
- *projects* that can be proposed as alternatives to improve the energy efficiency considering different measures. The improvements obtained by applying the proposed measures are then compared with the baseline in order to identify the optimal solution.

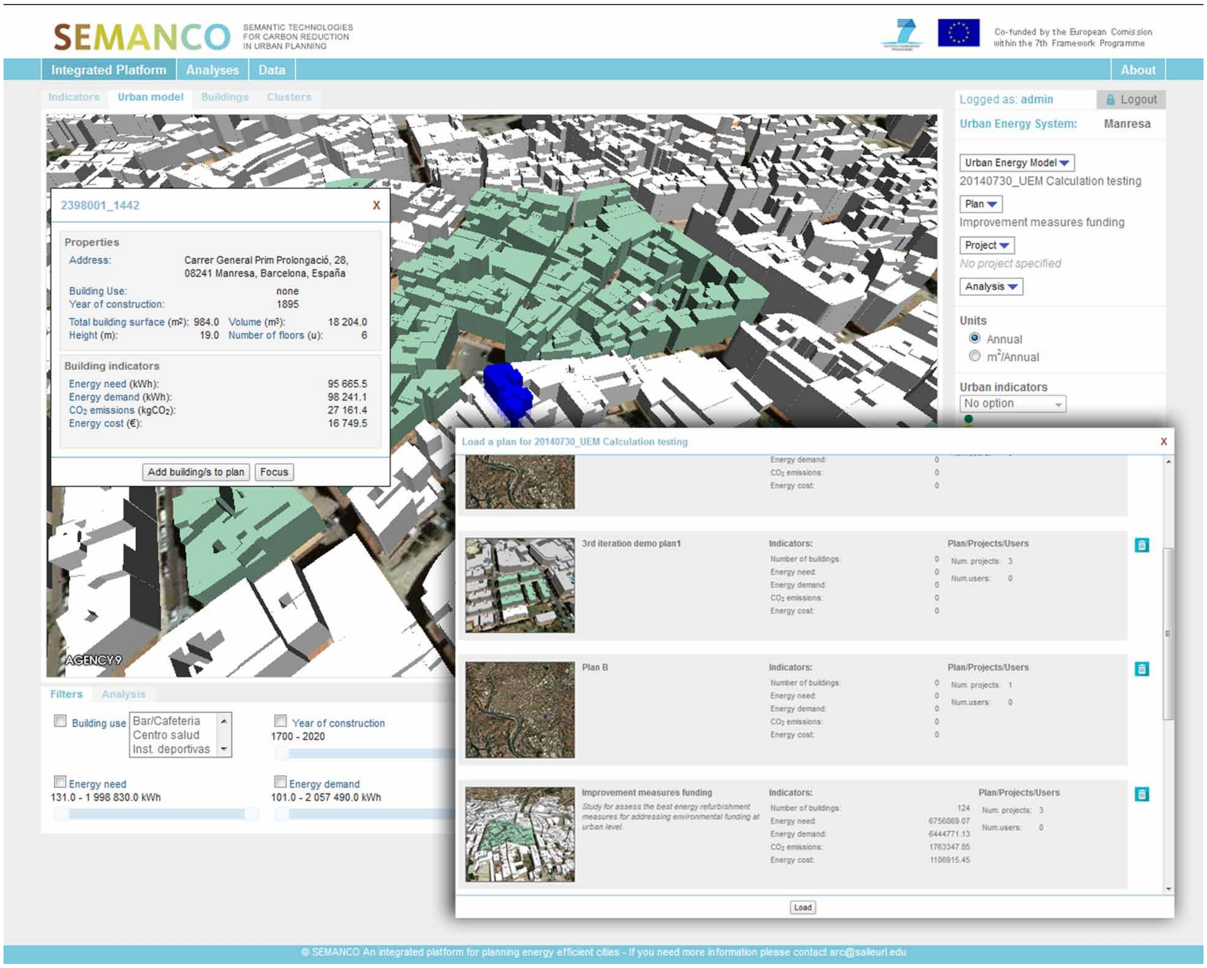
For example, a *plan* can be proposed to refurbish the old town of Manresa (one of the case studies implemented in the SEMANCO platform). This can be achieved in different ways, each one represented by a different *project*: for instance, the energy refurbishment of the external vertical walls, the thermal insulation of roof, or the replacement of technical building systems (e.g. heat generator). The results of implementing these measures are determined using the same tools already applied to calculate the baseline. Then, a multi-criteria decision-making tool is used to rank the performance of the different *projects* (Madrazo et al., 2014b).

The platform provides different types of tools, embedded (i.e. part of the platform), interfaced (i.e. existing tools interacting with other tools and services in the platform), and external (i.e. accessed through the platform, operating separately and exporting output to be imported in the platform). The tools developed in SEMANCO for the energy analysis of the three case studies included SAP (*Standard Assessment Procedure,* used in the UK), UEP/UEO tool (*Urban Energy Planning/Optimization*, used in Denmark) and UsiT-*Improvements tool* (used in Spain). In addition, the platform allows performing multi-criteria decision analysis (MCDA), cluster analysis and data-mining analysis.

One of the main outcomes of SEMANCO is EECITIES (*Energy Efficient Cities*, http://www.eecities.com/), a provider of energy analysis services to support the planning of energy efficient cities (Madrazo et al., 2015). The services represent the exploitation of the technologies created in the project, while the service providers are the domain experts involved in SEMANCO. A specific web portal is dedicated to EECITIES (EECITIES, 2015). It has been structured into: technologies (i.e. a summary of the tools provided), services that experts can facilitate, applications (i.e. objectives to be achieved by using the platform) and learning, through access to tutorials and other information. The EECITIES members are experts involved in the development of the SEMANCO platform, as follows:

- ARC Engineering and Architecture La Salle, Barcelona, Spain (developer of the SEMANCO integrated platform, ontology design and data integration)
- University of Teesside, Middlesborough, United Kingdom (developer of the energy assessment and improvement tools SAPMAP)
- CIMNE BeeGroup, Barcelona, Spain (developer of the USiT tool, multicriteria evaluation)
- Politecnico di Torino, Department of Energy, Torino, Italy (energy data structuring)
- Hochschule Albstadt Sigmaringen, Germany (ontology design, energy data analytics)
- Agency 9, AB Lulea, Sweden (3d visualization, developer of the software 3dMaps)
- Ramboll, Copenhagen, Denmark (developer of the UEP evaluation tool)
- National Energy Action, Newcastle, UK (energy experts)
- Fòrum, Manresa, Spain (building energy experts)

*Figure 5. Example of a plan in the SEMANCO platform*
*(Source: EECITIES, 2015)*




## FUTURE RESEARCH DIRECTIONS

Future research in the field of efficient urban energy planning should be based on the lines of research provided in literature and the methodologies highlighted in the present chapter, and finalized at solving some still open issues. One of these is related to the presence of inaccuracies in the building stock energy models. Accurate urban energy performance modelling is still a challenge, due to the uncertainties of input data and the use of assumptions in the engineering models, on the one hand, and the use of aggregated data in the data-driven models, on the other hand. An effective mean to give robustness and reliability to building stock energy models would be the advancement in the use of hybrid models, got by coupling the strengths of engineering methods (UBEMs) with those of the data-drivel models. For instance, the widespread archetype approach can be enriched with probabilistic input data derived from machine learning techniques.

Another important aspect to be investigated is the dynamic integration of the different parts of an urban scale energy model (USEM), as to be conceived more and more as an urban energy system.

In the field of urban energy systems, the experience of the SEMANCO project allowed the creation of an effective tool to develop UES. Anyway, after the completion of SEMANCO, the EECITIES integrated platform did not work as expected. This was mainly due to the need to manually upgrade the input data, with the consequent loss of dynamism that is required from an UES. A continuous input data flow should be guaranteed in a digital twin. The issue of data accessibility, curation, continuity over time, is a cornerstone of integrated data platforms. These aspects originate from inherent difficulties, such as the data formats (i.e. limits related to data interchanges), the data ownership (i.e. limits related to data accessibility), and the data reliability (i.e. limits related to accuracy).

The enhancement of the integrated models of urban energy systems is a precondition for the energy planning of Smart Cities. This will be supported by advanced technologies that make use of ontologies, and encouraged by the nascent era of digitalization, in which big data will be available from IoT technologies. The new models should be conceived as to guarantee a strong and effective collaboration between experts in the fields of energy analysis and computer science.

## CONCLUSION

This chapter presents a wide overview of the current studies in the field of building stock energy modeling and on the application of advanced technologies to develop urban energy systems.

The main classifications of urban building energy models (UBEMs) and urban scale energy models (USEMs) are reviewed and related concepts are defined. The development of urban energy planning tools through the implementation of urban energy systems is also discussed.

As confirmed by several research projects and various platforms and tools implemented, the addressed topic appears as an outstanding issue in urban energy planning and in the design of future cities. The importance of advanced modelling and integration of data, tools and actors in different domains at city and district scale is stressed. In this context, there is the need for platforms that provide real-time information (e.g. sensors, appliances, etc.) and data analysis, on a continuous basis, to mirror the dynamism of an UES.

In addition, difficulties related to access and management of data should be overcome by means of standardized procedures for data collection and integration. Despite significant progress has been achieved in the field of computer science in terms of data exchange protocols, further research is needed to increase energy data availability and quality. A universally recognized ontology of energy data and related-energy data (e.g. building-physics properties, user behavior, climatic data, etc.) is still lacking; a step toward this direction has been done by the SEMANCO project. International technical standards represent an effective mean to provide a common structure for information exchange between urban energy models in the next future. In this way, a development of digital twins more oriented to urban energy systems can be attained.

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## KEY TERMS AND DEFINITIONS

**Bottom-Up Building Stock Energy Model:** Energy model of the building stock, in which disaggregated data are used to estimate the end-use energy of individual buildings or group of buildings, and then the aggregated energy demand is extrapolated at a wider territorial scale.

**Ontology:** An explicit specification of a conceptualization, in which a set of objects is described through relationships among them to form the universe of discourse.

**Top-Down Building Stock Energy Model:** Energy model of the building stock, in which aggregated data of energy consumption are correlated to economic or other parameters to derive relationships for the prediction of the energy demand at a smaller territorial scale.

**Urban Building Energy Model:** Type of bottom-up building stock energy model that derives the energy demand through an engineering or physical-based approach, i.e. applying building heat balance equations.

**Urban Energy System:** The combined process of acquiring and using energy to satisfy the demands of a given urban area that is modelled using integrated tools, as to mirror the dynamism and the complexity of cities with a hierarchical approach.

**Urban Metabolism:** Process that involves the exchange of energy flows and materials (e.g. water, food, waste) within an environment.

**Urban Scale Energy Model:** Energy model that involves a spatio-temporal resolution of energy flows in cities, allowing the evaluation of system losses, load peaks, unconsumed energy shares, and the relationship between consumer and supplier.

**Use-Case:** The pre-conceptualization of a model that represents an urban energy system, as thought by experts within a particular context.