On the role of urban modelling tools to support the urban energy transition

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Abstract
Over 50% of the world’s population lives in urban areas, responsible for 70% of global CO2 emissions. To design strategies for urban greenhouse gas emission reductions, simulation models are essential to compare scenarios for zero-emission building stock transformation and how to match energy supply and demand in a renewable energy future. This study, part of the IEA Annex 83 Subtask B, presents methodologies and tools for modelling energy systems worldwide. Using case studies in different climates, various energy system modelling tools and frameworks are presented in terms of their capabilities and use cases. The study discusses each case study’s objectives, problem formulation, assumptions, and results.

Highlights
• Energy system modelling frameworks are compared
• An automated workflow for urban energy system modelling is proposed
• GIS-based tools are discussed for early planning stages

Introduction
With the emergence of high computing power machines, the work on computer-aided energy system modelling started in the 1970s and the 1980s (Lopion et al. 2018). Since then, numerous energy system modelling frameworks (ESMFs) and energy system models have been developed that are different in various characteristics. The increasing number of available modelling tools and frameworks has raised the question, “Which model is better in different applications?” for the users. Therefore, several studies have been devoted to categorizing the energy system models to facilitate the choice between different user options. Prina et al. (2020) and Lopion et al. (2018) have provided a brief history of the classification of energy system models and proposed their classification schemes. Hall and Buckley (2016) focused on the challenges arising from the variety of models, proposed a new schema for the classification of ESMFs and urged the researchers trying to develop a new ESMF to follow their scheme to provide an accurate representation of the model and a better understanding of the results. Among the criteria used to differentiate the ESMFs, the analytical approach and the underlying methodology are the most common.

The analytical approach refers to the method of the system being broken into smaller parts and how these parts interact (Fattahi, Sijm, and Faaij 2020). Based on their analytical approach, the ESMFs could be divided into top-down, bottom-up, and hybrid models. Economists and public administrations mainly use the top-down or macroeconomic approach. In this approach, the energy system is considered a part of the whole economy, and its interaction with other macroeconomic sectors is studied (Prina et al., 2020). On the other hand, in the bottom-up approach, the system is built component by component from the bottom to the top, which enables the modellers to create a model with a high level of technical details (Klemm and Vennebjerg 2021). This method is also known as the techno-economic approach (Subramanian, Gundersen, and Adams 2018) and is mostly used by engineers to conduct feasibility studies to find the most efficient or cheapest system (Lopion et al. 2018). Finally, hybrid models were developed to compensate for the shortcomings of both top-down and bottom-up approaches and bridge the gap between them. This work could be done by transferring data and parameters from one model to the other to take the macroeconomic impacts of the top-down approach and the technical details of the bottom-up approach into account.

The underlying methodology expresses the methods taken to reach the general purpose of the model. Generally, the underlying methodology of an ESMF could be categorized into the simulation (forecasting), optimization, and hybrid methods. Due to the high cost of creating a physical replica of a system or doing experiments on the system, simulation models are developed to assess the outputs of a specific system configuration based on given input values. Numerous optimization models, including linear, non-linear, dynamic and heuristic methods, have been developed to find the optimal value of the desired objective function(s) over the defined time horizon. The result of an optimization model could be used for finding the optimal investment strategies by municipalities or the optimal operation strategy of a system based on the given constraints. Optimization models are less complex than simulation models but could be used for long-term strategy-making (Lund et al. 2017). While simulation and optimization models, especially simulation models, use the bottom-up approach, the equilibrium models adopt a top-down approach. These models consider the
whole or a part of the economy and assess the impacts of adopting certain energy-related strategies on the selected part (Ringkjøb, Haugan, and Solbøkke 2018).

Various review papers have been published conducting a multi-criteria analysis (MCA) on the existing modelling frameworks and tools. A branch of these MCA analyses is one that only reviews the properties and structural features of ESMFs (Prina et al. 2020)(Klemm and Vennemann 2021)(Allegrini et al. 2015). Lyden et al. (2018) reviewed 13 tools capable of modelling renewable energy systems, demand-side management, and storage and proposed a selection process for choosing the appropriate tool for different applications. Tozzi Jr. and Jo (2017) also compared 14 other tools for simulating or optimizing renewable energy systems. Hall and Buckley (2016) analyzed the UK's 22 most common energy system models, while Ringkjøb et al. (2018) reviewed 75 modelling frameworks and tools used in electricity systems.

Despite the development of numerous ESMFs, there are still several gaps to be filled in this area. The main gap in this area is the lack of a completely automated framework for modelling energy systems. Currently, the majority of the whole process of energy system modelling is done manually, which is complex and time-consuming. An automated framework will facilitate the process of energy system modelling, especially for non-expert users like urban planners and real estate developers. Moreover, there are lots of data-related gaps, including a lack of data with the appropriate temporal resolution and a lack of transparency and accessibility, which leads to making uncertain assumptions. Furthermore, most frameworks focus solely on the technical aspects of energy systems and do not consider the socio-political and indirect costs associated with an energy system, especially those with new technologies.

In the current study, two different urban energy modelling tools that contribute to IEA Annex 83 Subtask B have been compared regarding their data models, modelling approaches, level of detail, scalability, temporal resolution, and spatial resolutions. In addition, the development of data models and catalogue structures to organize energy system components and configurations as a prerequisite for automating urban energy simulation tools will be presented.

Methodology

In this section, the underlying methodology of the two frameworks are explained. While the first tool, the automated optimal energy system sizing framework, is concerned with preliminary design stages to find the best technologies and available manufacturers in any area, the GIS-based building stock energy model deals with strategic decision-making in urban scale. These two tools could be linked to identify the areas suitable for district heating and cooling networks, find the best energy supply systems, and size the central plant optimally.

Automated optimal energy system sizing framework

The proposed framework is a part of the urban simulation platform under development at the Next-Generation Cities Institute of Concordia University, where urban areas are modelled holistically. This simulation platform intends to consider different parts of an urban area, including buildings, energy systems, waste management strategies, and transportation. The proposed energy system modelling framework comprises 7 modules connected to automatically find the optimally sized energy system. The main motivation behind developing this framework is to provide a platform for non-experts like real estate developers to know what energy system helps them achieve the decarbonization targets at the lowest costs and what manufacturers they should refer to purchase the needed components. In the output module, the configurations with lowest costs and emissions are shown where the user is able to compare the different components of costs and emissions as well as their total values.

The backbone of the proposed energy system modelling framework is its data model. The stored data about the components and their connection is passed to predefined simulation models containing rule-based control strategies. Another framework module is a decision-making algorithm implemented to reduce the problem's dimensionality by eliminating some components for different technical and geographical reasons. After the component selection, the stored data associated with the remaining components and possible configurations are passed on to the sizing module, where initial sizing is first done. Then, an iterative process between the simulation and optimization module will be started to find the energy system with optimally sized components with minimum cost and emissions. A heuristic algorithm is used in the optimization. The reason for selecting a heuristic method is to reduce computational time.

To automate the parameterization of simulation models of energy systems, a data model is required to manage the necessary data. This database contains all technical and economic information about energy system components available in the manufacturer's catalogues on energy components required for the simulation models. The database is created independently as a stand-alone application and writes the data in an xml file format. The catalogue includes various components, such as heat pumps and thermal storage, along with their attributes, such as size and efficiency. Object-oriented modelling with the Unified Modelling Language (UML) is used to create the energy system component catalogue. Eclipse Modelling Tools is used to develop the data model. The central part of the library's data model is shown as a cut-out of the Ecore model. The top class is the library, which includes subclasses describing individual components. The subclasses have individual attributes that describe the instances of the class. A parent abstract class is inserted if attributes are needed for more than one class. The attributes can be described with strings, doubles, or enumerations. Figure 1 shows a part of the energy components catalogue data model. In
the Concordia platform, the building energy demand is dynamically modelled using the geometry of each building and construction and usage attributes based on archetypes chosen for a given usage and building age. The hourly resolved demand profiles are used to size the system components of a given energy system configuration.

Despite including detailed models of energy system components and automating the energy system modelling process, this framework cannot model a district with municipality-level data. Therefore, a GIS-based tool is presented in the next section capable of modelling districts with high levels of detail, but the energy system model is simpler than the automated framework.

![Image](https://doi.org/10.26868/25222708.2023.1605)

**Figure 1 (a) Representative of the energy component catalogue data model (b) An example of energy system component classes**

**GIS-based building stock energy model**

A GIS-based building stock energy model has been developed by TECNALIA in Spain, as a tool for cities to calculate annual and hourly energy demand at each building for a district or a whole city.

As input data required to develop the model, basic inputs are needed, such as cartography maps or cadaster data. This information is used to define characteristics building by building, identifying building type, usage and construction age, and inferring physical envelope characteristics from the building construction or refurbishment period, information generally available in cadaster data.

In order to yield more reliable results, this data at the building level should be recently updated, and obtained from open data or provided by the municipality. Once building envelope characteristics and building type and use are defined from this data, the model follows a physics-based approach to perform calculations based on the heating degree hour method. Heating degree-hour (HDH) and cooling degree-hour (CDH) data are used to calculate heat gains and losses through the envelope, considering heating and cooling schedules for the different building uses. Internal gains, ventilation and solar gains are also accounted for in the hourly balance for each building, in order to calculate hourly heating and cooling demands.

Domestic hot water and electricity use (appliances, lighting, etc.) are pre-defined for the different building types based on internal databases of real and simulated data.

As a result of this analysis, hourly demands for different uses (heating, cooling, hot water, etc.) are available for each building within the district or the city, which is a good basis for further analysis of energy supply systems and studying potential strategies for decarbonisation.

To study the energy supply in more detail, the model can be completed with additional information on the building energy systems, which might be available, for example, from Building Energy Certificates. When this information on the energy systems is available, and assuming default efficiencies for the different types of systems, the energy use for different fuel sources can be calculated for each building within the city. In this case, the results can be compared and calibrated with real data from distribution companies (gas, electricity), if data is shared. It has to be noted that the accuracy and reliability of the GIS building stock energy model depends on the availability, level of detail, and veracity of the input data. (Muñoz et al. 2020).

These energy demands and energy use calculations provided by the model can be of great value for energy planning at the district and city level. For example, the tool can combine this data with other GIS-based information (e.g., thermal exchange resources, existing urban infrastructure, land use, heritage & conservation, etc.) and use a multi-criteria evaluation to identify potential areas in the city where heating and cooling distribution networks are more feasible, and support energy planning for heating and cooling in the city.
Results and discussions

This section presents and analyses the results of applying the frameworks to two case studies. The first case study is a mixed-use heritage building in Montreal where the automatic framework is used to size an energy system for the building to decarbonize the energy system of the building.

The second case study is a geo-referenced analysis of the city of Bilbao, where the GIS building stock energy model has been used as a basis to develop a heating and cooling plan.

The Dompark Complex consists of three big buildings in the southwest borough of Montreal, Quebec, with access to the Lachine canal. Due to the proximity to a water canal, the available ground near the building, and the low cost of electricity in Quebec, heat pumps using surface water, ground, and air as the heat source were chosen by the decision algorithm to provide the heating to the building. The industrial heritage buildings distribute heat using a steam system and might continue to require high-temperature heating due to high ceiling heights. Therefore, the objective is to design an energy system that uses the mentioned low-temperature heat sources and delivers high-temperature heating to the complex while comparing heat sources based on the efficiency and economy of the systems. Due to the large heated surface area of the building, the algorithm recognized that a fossil fuel auxiliary heater is needed to avoid excessive stress on the grid. Several energy system configurations stored in the data model include a heat pump and a boiler as the auxiliary heater. After an initial simulation, the following was selected as the energy system configuration due to the lowest operational cost and emissions.

\[ \text{COP} = a_1 \times T_a^2 + a_2 \times T_a + a_3 \times T_{sup} + a_4 \times T_{sup}^2 + a_5 \times T_{sup} + a_6 \]  

In this equation, \( T_a \) is the ambient air temperature, \( T_{sup} \) is the HP supply temperature, and \( a_1 \) to \( a_6 \) denote the fit function coefficients.

The framework provides technical output like the seasonal COP of heat pumps and operational costs and emissions as the economic and environmental outputs. The seasonal COP of heat pumps with surface water, ground, and air as heat sources are 3.34, 3.42, and 2.92, respectively.

Figure 3 show another example of the automatically generated outputs by the framework presenting the operational costs of all considered configurations. As shown in the figure, replacing the current system with any type of heat pump reduces operational costs and emissions significantly. A comparison of different sources for the heat pump reveals that water-to-water heat pumps have a higher potential to reduce costs and emissions.
The second case study applies the GIS tool to support the early stages of planning for a city's heat and cooling supply. Data for the city of Bilbao has been gathered, mainly from the city cadaster, which has provided enough information to develop a city wide model including details for each building, such as area, height and number of floors, year of construction and type of use. Based on this data, envelope characteristics have been inferred, and hourly energy balances calculated as described in the methodology. Results from the calculation of heat demand are shown in Figure 5. As building energy certificates were also available, energy systems for each building have been identified and energy use calculated hourly for the full year. Total values per year for gas usage have been calibrated from aggregated data from the gas distribution company.

This data has been combined with other GIS layers, which are also relevant for assessing the viability of different strategies in relation to heating and cooling of buildings, such as ("Library – Decarb City Pipes 2050"): • Potential heating or cooling energy sources available in the surrounding areas to the buildings, including waste heat and geothermal or hydrothermal sources for heat exchange, can improve the economic viability of district heating or cooling networks. • Available public space: Availability of public space for constructing necessary infrastructures. • The protected or historic building, where implementation of certain heating/cooling technologies might not be possible. • Public buildings where implementation of low carbon strategies has become a priority.

City plans for new developments or urban regeneration

The combination of all these layers has been carried through a multi-criteria decision-making process, where a weighting and aggregation of each of those layers is obtained to be able to support decision making. This process has allowed the definition of the areas in the city which might be adequate for certain heating or cooling technologies.

For example, figure 5 shows results from the analysis showing where in the city district heating and cooling networks could be more feasible.

This type of analysis, part of the heating and cooling plan for the city developed under the EU-funded DecarbCityPipes project ("Library – Decarb City Pipes 2050"), serves as a first step in the city decision making towards transition in the heating and cooling sector. For example, it could identify priority areas for the development of heating and cooling networks, supporting the process for a more detailed analysis and feasibility study.

Conclusion

A wide range of tools are available for urban modelling, with different scopes and objectives. These tools are still mainly used at the research and academic level. The lack of data and use complexity generally hinders practical use to aid decision-making for urban energy transition.

This study, part of the IEA Annex 83 Subtask B, has presented two different urban energy system modelling tools with different characteristics and applications, and they were applied to separate case studies in different climates to show their capabilities.

The first tool presented is an automated energy system modelling framework, a part of the urban simulation platform under development at the Next-Generation Cities Institute of Concordia University, where urban areas are modelled holistically. This framework aims to provide a foundation for non-expert users of energy systems.
system models, like urban planners and real estate developers, to find the best energy system configuration with optimally sized energy system components automatically. The framework includes a central data model where all technical, economic, and environmental data of components and configurations are stored in it. Additionally, the data related to the manufacturer of each component is stored in the data model, which will help the framework used to know whom they should refer to for purchasing the equipment.

The use of the automated framework to evaluate the use of heat pumps on a mixed-use heritage building in Montreal has been presented, showing how a techno-economic analysis can be done and support decision-making to move towards lower emission solutions.

The second tool presented is a GIS-based building stock model, which has been used in Bilbao to prepare the first "Heating and Cooling Plan" for the city. The model has been developed from basic public information, such as cadaster and building energy certificates, and then calibrated with real data from the gas distribution company.

The results of the building stock energy analysis have been combined with other geo-referenced information from the city concerning urban planning, resource and infrastructure, or building heritage and protection. This analysis has served to map the city and identify areas and districts where certain technologies, such as heating and cooling networks, might be feasible.

The two presented tools are examples of urban modelling, which can be used at different stages of the decision-making process in urban energy planning or project design. The GIS building stock energy model could guide general strategic decisions in energy planning, for example guiding a “zonification” of a city prioritizing districts for implementation of certain technologies such as district network. The optimal energy sizing methodology could be used at a different stage on the process, for example at preliminary design stage where specific technologies need to be assessed in more detail.

Overall, the case studied have demonstrated the potential of these tools to support urban energy transition. There is a further need for integrated development, facilitating urban planners, strategist and designers, particularly at local authority level, the access and use to these type of urban energy simulation tools.

Acknowledgments:
This research was undertaken, in part, thanks to funding from the Canada Excellence Research Chairs Program. The work related to Bilbao’s heating and cooling analysis has been developed under the DecarbCityPipes project, which has received funding from the European’s Union Horizon 2020 research and innovation programme, under grant agreement No 893509

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