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Modeling the heating and cooling energy demand of urban buildings at city scale

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ABSTRACT

Many computational approaches exist to estimate heating and cooling energy demand of buildings at city scale, but few existing models can explicitly consider every buildings of an urban area, and even less can address hourly -or less- energy demand. However, both aspects are critical for urban energy supply designers. Therefore, this paper gives an overview of city energy simulation models from the point of view of short energy dynamics, and reviews the related modeling techniques, which generally involve detailed approaches. Analysis highlights computational costs of such simulations as key issue to overcome towards reliable microsimulation of the power demand of urban areas. Relevant physical and mathematical simplifications as well as efficient numerical and computational techniques based on uncertainties analysis and error quantification should thus be implemented.

1. Introduction

1.1. General context

The study of urban energy consumption is becoming more and more important because of three main facts:

(1) Urban population is increasing: in 1950, 30% of the world population lived in cities, and 54% in 2014, and this ratio will reach 66% in 2050, that being around 6.5 billion of persons, i.e. 2.6 billion persons more than nowadays [1]. Therefore, urban development is a crucial issue, in particular from an energy point of view as urban energy consumption per capita is also increasing (+32% in the last 40 years [2]).
(2) The energy paradigm changes: the need of dramatically reducing greenhouse gas emissions as well as fossil energy issues favor the use of renewable energies, which are often decentralized and intermittent. Related polices currently ongoing in many countries worldwide [3] change the previous centralized energy management scheme, which requires a better understanding and forecasting of power demand and power production, in particular in cities, where the network in dense.
(3) Urban heat stress during hot seasons due to the urban heat island (UHI) effect may further intensify effects of probable more frequent heat waves in the context of climate change [4]. This can lead to dramatic public health problems as well as energy issues due to the multiplication of active cooling devices, which would also contribute to increase urban air temperatures [5].

Therefore, urban energy consumption have been a critical research problem for the last 30 years (Keirstead et al. [6] referenced 219 papers concerning only urban energy models), and will certainly still remains a major issue for the following years.

1.2. Scope

This paper focuses on the building sector, which is responsible of the main part of the global energy consumption (40% of total final energy in the European Union [7]), and in particular on space conditioning (heating and cooling), which currently represents about 75% of the energy consumed by European residential buildings in 2014 [8]. The building sector is identified to have a “great potential” to improve energy efficiency [7] and to reduce greenhouse gas emission, thanks to refurbishment, including insulation and replacement of low-efficient energy technologies.

Moreover, renewable energy may relevantly be produced and used in buildings (e.g. solar panel and combined heat and power). But such a change implies to focus on power demand because of district network

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balance management problems (storage, sharing, etc.), and no more only on long term consumption.

Hence, this paper addresses building energy modeling at city scale, as integrated tools are needed for urban energy suppliers to manage energy networks and for city decision-makers to plan strategies in a context of urban growth and energy transition (point (2) of Section 1.1).

1.3. Modeling issues

The energy *demand* represents the energy used by energy systems, considering their efficiency and their behavior, to provide the energy *needs*. The *energy consumption* refers to the assessment (the sum) of the energy demand over a period, assuming that the energy demanded was supplied, whereas the *power demand* represents the instantaneous energy demand. Hourly energy demand is commonly used in building energy simulations (BESs) as the minimal temporal resolution required to estimate the power demand.

Simulating urban building power demand is more complex at the city scale than at building scale, mainly because of three reasons:

- A huge amount of information about built structures (geometry, physical properties of components, etc.) is needed because of the large size of the domain studied, whereas they are often unknown and difficult to obtain accurately [6,9]. Their determination needs expensive and time-consuming surveys and measurements;
- The behavior of the occupants (direct actions and use of systems) has a major impact on building energy demand [10–13] while at the district scale or lager, the temporal variability of occupants' behaviors makes the maximal total power demand different from the sum of the individual maximal power demands. This *diversity* requires specific models themselves based on extensive surveys [14];
- Because of the urban environment, buildings cannot be assumed standing-alone as it is usually supposed in building energy models (BEMs). Effects of the urban environment on building energy needs have to be accounted for [15–22], while external loads, such as meteorological loads, cannot be estimated generically as they are particular for each building.

More precisely regarding this last point, meteorological loads of urban buildings and subsequently their energy behavior depend on (see Fig. 1):

- Obstructions caused by surrounding constructions, which decrease the sky view factor, and consequently reduce solar gains (increase of the heating needs in winter and decrease of the cooling needs in summer) and the radiative cooling to the sky (reverse effect on the space conditioning needs) [15,16,23,18,17,19,21];
- Surrounding surfaces, which reflect solar radiations and emit and reflect longwave radiations, impact on the surface energy balance of urban buildings (e.g. a north-oriented surface may receive solar radiations from a south-facing opposite surface, therefore its thermal losses may be reduced) [17,19];
- Urban morphology, which modifies airflows around buildings, and, consequently, impacts convective heat exchanges [18,20,21] and the potential of natural ventilation of urban buildings, including infiltration [24];
- The general UHI effect, which means that air temperature within a city is often higher than in rural areas (decrease of the heating needs but increase of the cooling one [25,15,26–28,20]. According to Oke [29], the UHI results from the combination of the above mentioned phenomena, which generally increase urban surfaces temperatures, in addition to the high thermal absorbance of urban materials, the lack of vegetation (evaporative cooling), and the anthropogenic heat sources.

1.4. Objective

The aim of this paper is not to give an exhaustive review of studies addressing the simulation of building energy demand at the urban scale, but *to identify the approaches and the models developed in the literature in order to simulate building heating and cooling power demand, from the building scale to the urban scale, taking into account the urban environment and possible changes in building characteristics*. For this purpose, the paper is structured as follows: a first part (Section 2) presents the main approaches and methodologies used to estimate urban building energy consumption and particularly power demand at district or city scale; then a second part (Section 3) details the specific models used in these approaches in order to tackle modeling issues in the urban context; finally, the last part (Section 4) closes the paper and specifies outlooks.

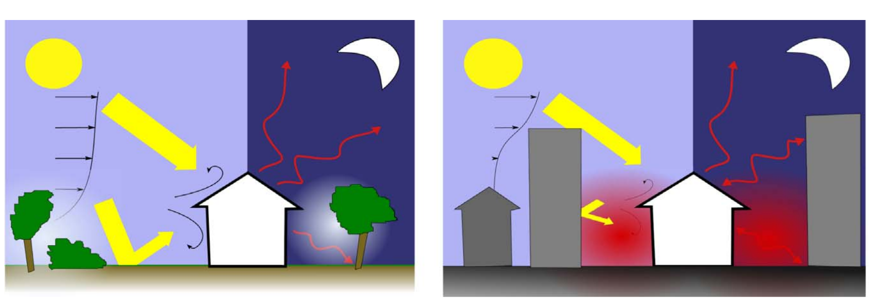
2. Overview of urban energy models

At the city scale, numerous phenomena of various scales interact, urban geometry is very complex and heterogeneous, and materials are diverse. Therefore, explicit simulation of urban energy demand requires huge amount of data, which are difficult to gather, and high computational capacities, which are currently not available for usual use [6,9]. Consequently, simplified approaches have been mostly developed.

2.1. Top-down and bottom-up approaches

Two approaches addressing urban energy issues were commonly defined: *top-down* and *bottom-up*. According to the review of Swan and Ugursal [30] about modeling techniques of energy consumption in the residential sector:

> “Top-down models utilize the estimate of total residential sector energy consumption and other pertinent variables to *attribute* the energy consumption to characteristics of the entire housing sector. In contrast, bottom-up models *calculate* the energy consumption of individual or groups of houses and then extrapolate these results to



(a) Stand-alone building (b) Urban building

Fig. 1. Modification of the energy balance of an urban building compared to a stand-alone one.