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Energy demand profile generation with detailed time resolution at an urban district scale: A reference building approach and case study

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HIGHLIGHTS

- A bottom-up engineering model (DiDeProM) for thermal energy demand profiles generation is developed.
- DiDeProM relies on samples of representative buildings technique.
- Parametric analysis at building and district scale is carried out.
- A stochastic aggregation method to generate a district thermal energy demand profile is applied.
- Hourly time step for thermal storage technologies and demand side management studies can be obtained.

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ABSTRACT

The energy demand in urban areas has increased dramatically over the last few decades because of the intensive urbanization that has taken place. Because of this, the European Union has introduced directives pertaining to the energy performance of buildings and has identified demand side management as a significant tool for the optimization of the energy demand. Demand side management, together with thermal energy storage and renewable energy technologies, have mainly been studied so far at a building scale. In order to study and define potential demand side management strategies at an urban scale, an integrated urban scale assessment needs to be conducted.

DiDeProM, a model that can be used to generate detailed thermal energy demand profiles, at an urban district scale, has been developed in the current study. It is a bottom-up engineering model, based on samples of the representative building technique. A parametric analysis of the important variables of building energy performance at an urban scale has then been carried out. This has generated a database of normalized thermal energy demand profiles with an hourly time resolution. The final step of the process includes the generation of a detailed overall thermal energy demand profile at an urban district scale.

DiDeProM was applied to a block of buildings in Turin (Italy) as a case study. After the calibration of the simulation model on real monitored data, a parametric analysis on 300 scenarios for a reference building was conducted, generating a database of seasonal thermal heating energy demand profiles with hourly time steps. An average hourly heating profile was generated from this database according to a specific aggregation approach. The DiDeProM application indicated that the model works properly at the scale of a typical small block of buildings, and it is able to generate a total thermal energy demand profile, with detailed time resolution, at an urban district scale. These profiles will be used to create demand side management strategies that will integrate thermal energy storage and r‘enewable energy technologies at a district scale.

1. Introduction

Approximately half of the earth’s population lives in urban areas, and this percentage is going to increase due to a rise in population in developing countries, such as Brazil, and India [1]. The main consumer of energy in urban areas is the building sector. In the European Union (EU), the building sector is responsible for 40% of the total energy consumption [2].

The European Union has been developing various actions to reduce the on-going energy demand and consumption increase, as well as to comply with the goals of the Kyoto Protocol. One of

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Nomenclature

$A_{B_x,cond.}$	conditioned floor area of a building, m^2
$A_{\mathcal{R}_{\mathcal{B},n},cond.}$	conditioned floor area of $\mathcal{R}_{\mathcal{B},n}$, m^2
$\mathcal{B}_n$	building n
C_{n,S_k}	cluster of $\vec{p}_{S_{k,g,m}}$ in the database
d_{typ}	typical monthly day
$\mathcal{D}$	database of normalized profiles
$\mathcal{D}_n$	sub-database of normalized profiles for each $\mathcal{R}_{\mathcal{B},n}$
$\mathfrak{I}$	urban district
$\vec{p}_{(\mathcal{R}_{\mathcal{B},n},S_{k,g,m})}$	normalized generated profile with an hourly time step, $W\,m^{-2}$
$\vec{\mathcal{P}}_{(\mathcal{R}_{\mathcal{B},n},S_{k,g,m})}$	profile with an hourly time step related to $S_{k,g,m}$, W
$\vec{\mathcal{P}}_{\mathcal{B}_x}$	generated profile of a building, W
$\vec{\mathcal{P}}_{\mathfrak{I}}$	profile of the urban district, W
$\vec{\mathcal{P}}_{\mathfrak{I},avg}$	average profile of the urban district, W
$\mathcal{R}_{\mathcal{B},n}$	reference building
R_i	daily mean solar radiation, $W\,h\,m^{-2}$
$\vec{R}_m$	average monthly solar radiation, $W\,h\,m^{-2}$
$S_{s,k}$	shading scenario
$S_{v,g}$	infiltration scenario
$S_{l,m}$	internal load scenario
$S_{k,g,m}$	parametric analysis scenarios
$SN_{\Delta T_i}$	serial number of the temperature variation
$SN_{\Delta R_i}$	serial number of the solar radiation variation
T_i	daily mean temperature, °C
$\vec{T}_m$	average monthly temperature, °C
TBM	thermal building model
Greek letters	
θ	fixed model parameters of the *TBM*
ΔT_i	variation in temperature, °C
ΔR_i	variation in solar radiation, $W\,h\,m^{-2}$

these actions is the Directive on the Energy Performance of Buildings (EPBD), which came into force in 2002 (Directive 2002/91/EC) [3]. The goals of this Directive are to reduce energy consumption and reduce greenhouse gas emissions (GHGs) in the building sector, as well as to increase the share of the energy production by means of renewable energy technologies (RETs) by the year 2020. Therefore, the EU has developed actions, such as the creation of a common general framework for the assessment of the energy performance of buildings, the application of the minimum energy performance requirements to new buildings, the increase in the number of nearly zero-energy buildings (nZEB), the introduction of HVAC system inspections of buildings and energy certification of the buildings [3]. The tools that were used, or are at present under research and development for these purposes, include the building occupant and user awareness to energy efficiency concept, the refurbishment of existing buildings with low energy techniques, the construction of new low energy buildings, the optimization of energy systems with the integration of renewable energy and storage technologies, and the use of monitoring controls. However, in order to study the benefits of all of the aforementioned strategies, building models are necessary. The modelling and the prediction of the impact of efficient measures through simulations [4] are necessary because it is extremely difficult, or even impossible, to create an entire building or a building district in a laboratory with the purpose of conducting tests. The modelling and the development of tools to assess and improve the efficiency of individual buildings in urban areas has been underlined as a priority and an important challenge for the European Union's environmental policy in the 21st century.

The building models that have so far been developed for this purpose can be classified as physical, statistical or hybrid [5]. Physical models are very detailed, physics-based building models that investigate the energy performance of a building in terms of natural ventilation, heating, cooling etc. These models include the CFD approach, the zonal and the multi-zone or nodal approach. Statistical models are models that were developed using statistical approaches and methods. These models do not need the physical details of a building as input and do not need any physics or heat transfer equations of the buildings. Statistical models are based on a collection of large databases of measured quantities (e.g. energy consumption, econometric values and meteorological data), and include conditional demand analysis CDA, genetic algorithms, artificial neural network, etc. Hybrid models are models that couple statistical and physical models. These three types of models are currently well developed at an individual building scale, and are used extensively to assess energy retrofitting measures, to predict future energy consumption, to mitigate carbon emissions and to develop new technologies.

However, the interest of the EU over the last few years has not only focused on the building scale, but also on the urban scale, in order to create models for an integrated city-scale energy performance assessment [6–8]. This is because an investigation at a building scale does not represent a reliable approach to the behaviour of a building at an urban scale, where the interactions between the buildings in a neighbourhood or between urban districts represent a crucial parameter in the assessment of building energy behaviour.

One of the main aims of the CI-NERGY European Project [9], which studies and develops methodologies and tools that can be used for integrated energy management at an urban scale, is to develop a strategy for the integration of demand side management with thermal energy storage technologies at an urban district scale. In order to study the integration of thermal energy storage and demand side management techniques, it is necessary to generate thermal energy demand profiles, with a detailed time step, at an urban district scale. Within the same project, a characterization of domestic hot water end-uses for integrated urban thermal energy assessment and optimization was developed [10].

A methodology for the generation of an overall thermal energy demand profile, with a detailed time resolution at an urban district scale, has been developed in this paper. A review of building stock modelling approaches has been carried out in the next section. Top-down and bottom-up modelling approaches are presented in the review. The review has mainly been focused on bottom-up modelling approaches, and the different techniques that are used to create a bottom-up engineering model. After the review, a bottom-up physics-based building model is developed, presented and applied to a case study in order to generate an overall thermal energy demand profile, with an hourly time-step, at an urban district scale. A data post-processing has been developed and presented. This post-processing is in fact a methodology for the identification and selection of typical monthly days. The post-processing is a very important step in the overall methodology as it is used to obtain a synthetic representation of detailed thermal energy demand profiles for demand side management and active thermal energy storage integration at an urban district scale [11,12].