Urban energy assessment by means of simulation techniques

Silvia Soutullo, Jose Antonio Ferrer, Maria del Rosario Heras,
Energy Efficiency of Buildings R&D Unit 7 Renewable Division, CIEMAT, Madrid, Spain

silvia.soutullo@ciemat.es
ja.ferrer@ciemat.es
mrosario.heras@ciemat.es

Abstract. Current trends in energy consumption and greenhouse emissions make energy problems in cities take special importance. This situation has led to evaluate different urban configurations that combine the reduction of the energy demands with the optimization of the energy generation systems including renewable sources. The use of dynamic simulation programs allows the quantification of the energy impacts produce by the building stock and the energy generation systems that make up an urban area. Simulation environments have been defined to evaluate and optimize the energy performance of urban areas. This paper presents a modular methodology based on phases to develop a global urban model. This methodology has considered many variables that characterize an urban area.

Keywords: Dynamic modelling, Urban areas, Modular methodology

Introduction

Currently, cities are responsible for many environmental, social and economic problems that affect humanity due to their high-energy consumption. With the aim of minimizing the urban energy trends, the European Union is promoting several programs, platforms and directives in urban areas (Directive 2010/31/EU) to develop clean, safe and efficient sources of energy in cities (Connolly et al., 2014). Effective implementation of the European energy proposals supposes great efforts to improve the building renovation, maximize the efficiency of grids and infrastructures, promote the use of high-efficiency cogeneration and district heating and cooling or maximize the renewable share into the energy market.

The Spanish energy import dependency (73%) is much higher than the mean of the European Union (54%), with a renewable production of 13% (Eurostat Statistics, 2017; COM (2015)/080/EU). This situation has led to design more sustainable cities with more efficient buildings and optimized energy systems that integrate renewable sources. But it is necessary to quantify the energy impact produced by the building stock and energy generation systems into the urban areas. With this objective, simulation programs are presented as excellent tools to analyze the energy performance of urban areas. These programs consider all the energy balances produced by external and internal fluctuations, solving the coupled and time-dependent equations (Crawley et al., 2008) and setting the limits of the model as well as the boundary conditions. The use of dynamic simulation programs allows modifying input variables, parameters and boundary conditions at small time steps. But these programs require an exhaustive definition of the inlet information and a greater computing capacity to solve the mathematical equations that characterize the urban system.

The use of these simulation tools with experimental data recorder in urban areas, enable the validation and calibration of the theoretical models used (Enríquez et al., 2017, Díaz et al., 2015, Sánchez et al., 2012).

In this line, the Energy Efficiency in Buildings research unit of CIEMAT has carried out a theoretical methodology to evaluate the energy performance of urban areas over specific periods of time. This methodology has been developed coupling modular simulation environments to analyze, in a realistic and rigorous manner, the dynamic performance of whole system.

Methodology

The simulation process has been understood as a closed loop between local renewable resources, building stock, urban planners, energy generation plants, distribution systems, mandatory regulations and energy patterns. The overall objective is the development of global simulation models to analyze the energy performance of urban areas over specific periods of time. With this philosophy, an iterative methodology based on phases has been carried out:

- Initial considerations.
- Building simulation models.
- Energy generation and distribution models.
- Simulation environments.
- Energetic assessments and optimization process.

Dynamic simulation process

The energy quantification of urban systems has been done linking different simulation models. These models are described by a set of coupled mathematical equations with time dependence. Dynamic simulation tools, based on numerical methods, have been used to solve these equations in short time steps, considering the boundary conditions given by the surrounding environment.

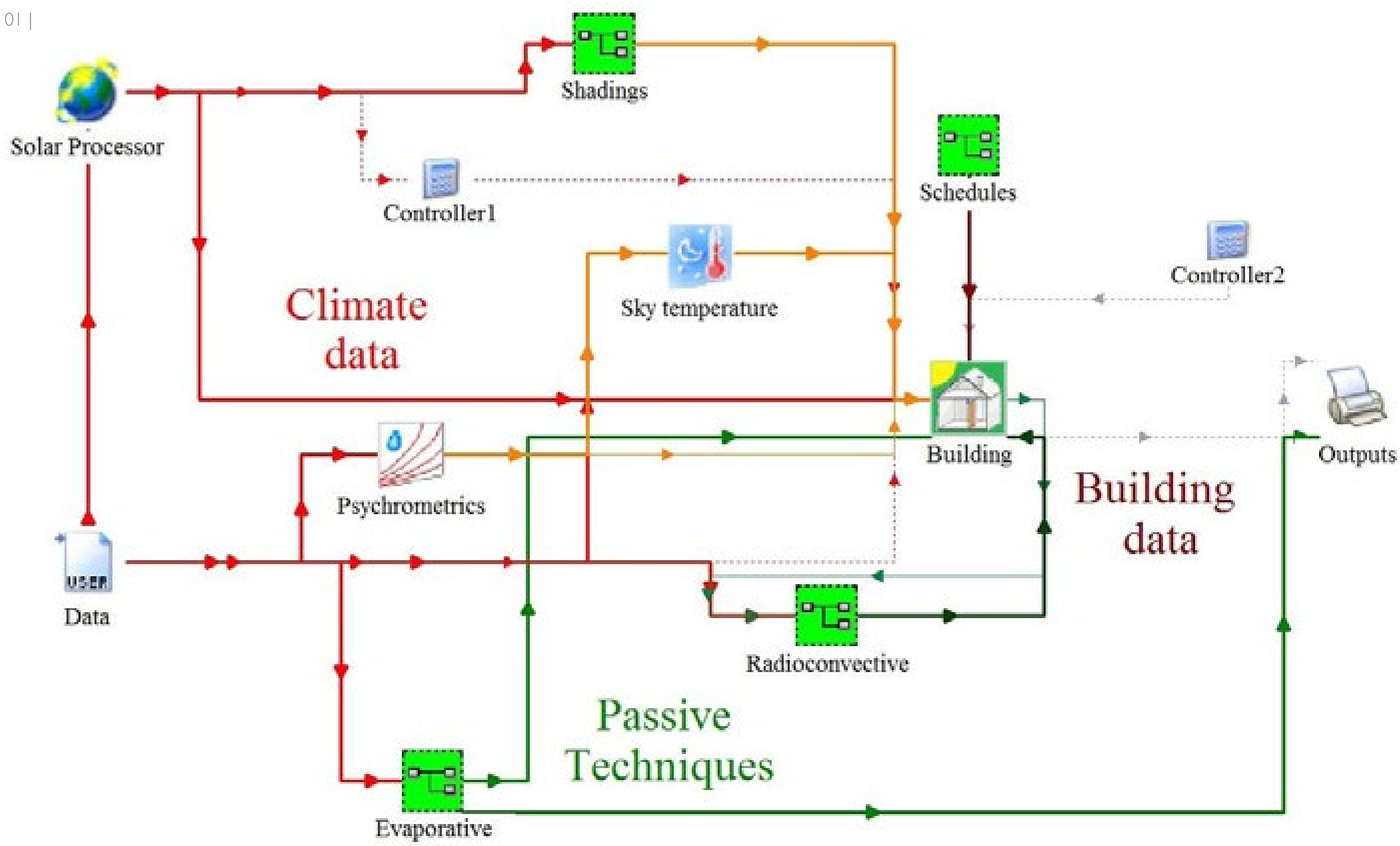
Initial considerations

Previous to the modelling process it is necessary to define the boundary conditions and the inlet information required to characterize the urban area. These considerations depend on the studied location but specific information always must be collected: climate, building stock, user's patterns, energy systems, energy storage and mandatory restrictions. This information should be provided by real data (building projects, energy audits, energy certificates or monitoring campaigns) but, in many cases, it is not possible, implying many assumptions.

One of the most critical points when assessing the energy performance of urban systems is the availability of representative climatic databases. These files should be created through the treatment of the principal meteorological variables registered by weather stations over long periods of time (Soutullo et al., 2017_1). Hourly and annual patterns of the meteorologi-

ISSN online: 2239-0243 | © 2018 Firenze University Press | http://www.fupress.com/techne
DOI: 10.13128/Techne-22746

01 |



01 | Structure of the building TRNSYS project

cal variables determine the renewable potentials and the best combination of passive and active techniques to be implemented (Givoni, 1994).

The second issue to consider is the definition of the building characteristics considering the building stock, building envelopes, operational conditions, air movements and mandatory regulations. These factors have been used to create a complex selection matrix that feeds the simulation models (Soutullo et al., 2017_2).

Finally, it is necessary to define the main characteristics of the energy systems (generation plants and energy distributed systems) to create an optimal configuration that supplies the urban energy demands (Buonomano et al., 2012). Building loads, climatic conditions, efficiency curves, regulatory and space restrictions have been used to feed the energy models.

Building models Dynamic simulation tools have been used to analyze the hygro-thermal and mechanical behavior of buildings (Fig. 1). All the aspects considered by the selection matrix have been taken into account to create a simulation matrix that represents new and existing buildings.

New models have been developed to quantify the energy performance of some specific techniques that are not considered in the basic building models (Jiménez and Madsen, 2008). Techniques such as solar chimneys (Martí and Heras, 2007), wind towers (Soutullo et al., 2012), ventilated façades (Giancola et al., 2012), glazed galleries (Suárez et al., 2011) or radiant panels (Ferrer et al., 2015) have been implemented into the global model. The coupling between new models and basic building models improves the accuracy and quality of the final results.

Air renovations from outside through windows, doors, air ducts...can lead to increase the thermal loads in buildings, so it is very important to minimize air infiltrations (Enríquez et al., 2010) and optimize natural and mechanical ventilation (Enríquez et al., 2015).

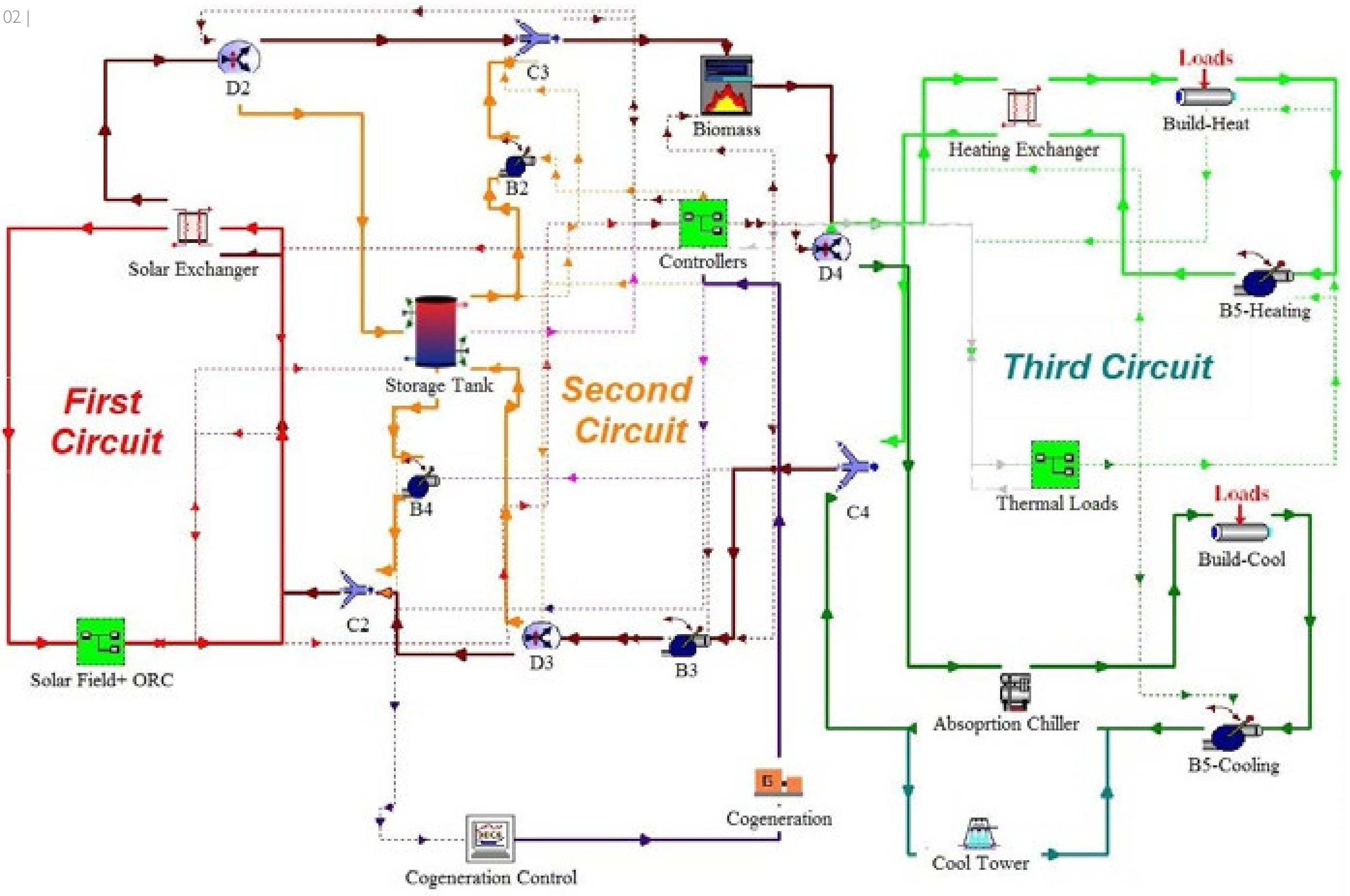
Finally, the user behavior has a great influence on the energy performance of the building. Factors such as occupancy (Díaz et al., 2017), internal gains or set point temperatures are important issues to obtain an accuracy building model. The use of real data to evaluate the building performance minimizes the error obtained in the results.

Energy system models Dynamic simulation programs have been selected to model the global performance of energy systems (Fig. 2). The main objective is to optimize different scenarios to supply the urban energy demands and maximize the renewable contribution. These models consider the generation and distribution of energy and the energy exchanges produced during the system operation.

Two configurations have been considered: building and district levels. The building level has been developed to supply the energy demand of a single building. These models are composed by power generation elements (heat, cold and electricity), storage elements and energy distribution elements to the end user (Soutullo et al., 2011_1). The district level has been developed through distributed polygeneration systems (Bujedo et al., 2017). These models are composed by different subsystems: biomass boilers, photovoltaic panels, solar collectors, wind turbines, cogeneration systems, absorption chillers, conventional systems and storage elements. All these subsystems are connected in different closed loops, which represent specific circuits of the whole system (Soutullo et al., 2016_1).

The correct system operation is regulated by pumps, valves and controllers. Real characteristics and performance curves for each subsystem, building energy profiles, space restrictions and mandatory regulations have been used as input values into the simulation models. Climatic data has been used to determine the renewable potential and boundary conditions. The use of real databases minimizes the final deviation from the real situation.

02 |



02 | Thermal poligeneration plant for a district area modelled in TRNSYS

Initially, renewable systems are used to supply the thermal and electrical loads of the building stock. There are many possibilities to incorporate these energy systems into the urban patters. The first possibility is the integration into the structure of the buildings. Solar thermal collectors or photovoltaic panels can be integrated into the walls, roofs or shading devices, reaching high levels of renewable fractions (Díaz et al., 2015, Soutullo et al., 2010). Wind small turbines can be integrated in the building structure too, but there are many structural and technical problems that should be solved. The analysis of the solar and wind potential as well as the restrictions of the available area determines whether it is necessary to use other renewable systems such as biomass boilers (García Fernandez et al., 2012). The second possibility consists of designing generation plants according to the space restrictions, distances of pipes, energy losses and mandatory regulations.
If is not possible to supply the energy consumption by renewable systems, conventional systems should be installed.
A local distribution has been included to minimize the losses produced by the distance between the generation plant and the consumption points.

Energy assessments Global models of urban areas allow analyzing its energy performance considering constructive considerations, passive and active strategies, power generation systems, storage elements and distributed energy systems.
These global models have been used to evaluate the energy performance of different urban areas. Firstly building models have been introduced into the simulation tools to evaluate its energy needs. Secondly all the refurbishment measures proposed have been evaluated through simulation batteries, obtaining the energy fluctuations produced by the perturbations of the basic model (Soutullo et al., 2018). Finally the power generation systems are coupled to the building loads to supply the energy demands. The dimensions of these systems are optimized in terms of the objectives set at the beginning of the simulation process. The final results are the energy demands and the coverage achieved by the renewable systems (Bujedo et al., 2017, Soutullo et al., 2016_1).
To quantify the energy performance to variations of the selected variables, sensitivity analyzes have been done (Lomas and Eppel, 1992). Parametric runs have been executed varying only one of these values while the rest remain constant. The final objectives set the outputs of the simulations, which are defined as cost functions of the parametric runs.
An optimization process has been done to improve the efficiency of the urban system. This process has been carried out by batteries of simulations to quantify the model response to fluctuations of the selected variables. This phase extents until the optimal solution is obtained. This solution combines all the initial requirements of the project at a reasonable cost and with the minimum greenhouse gases emissions. Depending on the computational capacity, the variables available and the level of difficulty expected, uni-objective or multi-objective assessments have been done.
The improvements of the building performance and the renewable potential have been quantified in different Spanish cities applying this modular methodology. The PRENDE project (www.tucasaesmas.com) quantified the influence of constructive parameters of the residential building stock of Madrid. This project considered the climatic conditions and the economic cost of the refurbishment measures proposed through a citizen-oriented platform (Soutullo et al., 2018). The PSE-ARFRISOL project (www.arfrisol.es) modeled and monitored 5 buildings in Spain constructed with bioclimatic criterions and renewable energies. The DEPOLIGEN project quantified theoretically the renewable potential achieved by a poligeneration plant placed in different Spanish cities. These plants were designed with the combination of renewable energies, electrical and thermal storages and cogeneration systems (Soutullo et al., 2016_1).
Experimental data are needed to validate and calibrate the simulation models of urban areas (Enríquez et al. 2017, Soutullo et al., 2011_2). This procedure allows minimizing the differences between the theoretical and real energy profiles, and enables to predict the future behavior of urban areas with more accuracy.
Finally, it is important to design efficient cities with high level of comfort sensations, which includes air quality (Sánchez et al. 2015), illumination, noise and thermal comfort (Giancola et al., 2014). Thermal comfort has been quantified through hourly profiles of the thermal sensation in the studied areas. Two different scenarios have been studied: outdoors and indoors. Dynamic models have been developed to analyze outdoor comfort levels to increase the sustainability of the zone (Soutullo et al., 2011_3) and minimize the pollutants emissions (Santiago et al., 2017). Indoor comfort assessments have been carried out through experimental campaigns to quantify the energy savings achieved by the implementation of efficient measures in buildings (Soutullo et al., 2016_2).

Conclusions A modular methodology to evaluate the energy performance of urban areas has been developed. This procedure has considered different aspects of districts such as climate, building stock, architectonical designs, envelopes, thermal and electrical generation systems, storage elements and distributed systems. Renewable energies have been used to supply the energy demands individually in the building or through a polygeneration network for a district.

Real information about buildings and energy systems are used as inputs of a complex matrix that characterize the global performance of the urban area. This matrix is modeled in a flexible simulation environment to evaluate energy balances and patterns, comfort sensations, energy quantification to external variations and energy optimization of the system. The use of real data reduces the final deviation from the real situation.

ACKNOWLEDGMENTS OF VALUE

Juan Antonio de Isabel García
CEO GEOTER - GEOTHERMAL ENERGY S.L., Madrid, España
juan.isabel@geoter.es

The development of theoretical tools to characterize the energy performance of an urban area represents an important issue to optimize its energy consumption and minimize its pollutants emissions. The modular methodology created by CIEMAT supposes another step in the energy quantification of cities. The application of this methodology facilitates the global optimization of the urban systems with different configurations, so I think that this research work it is of great interest.

REFERENCES

European Parliament (2010), *Directive 2010/31/EU of 19 May 2010 on the energy performance of buildings*, Official Journal of the European Union, Brussels, BE.

Connolly, D., Lund, H., Mathiesen, B.V., Werner, S., Möller, B., Persson, U., Boermans, T., Trier, D., Østergaard, P.A. and Nielsen, S. (2014), "The Heat Roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system", *Energy Policy*, Vol. 65, pp. 475-489.

Eurostat Statistics Explained (2017), "Shedding light on energy in the EU. A guided tour of energy statistics. Edition 2017", Eurostat statistics, available at: http://ec.europa.eu/eurostat/cache/infographs/energy-2017/index.html (accessed: 2018-05-03).

European Commission Comunication (2015), *COM(2015) 80 final. A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy.*

Crawley, D.B., Hand, J.W., Kummert, M. and Griffith, B.T. (2008), "Contrasting the capabilities of building energy performance simulation programs", *Building and Environment*, Vol. 43, pp. 661-673.

Enríquez, R., Jiménez, M.J. and Heras, M.R. (2017), "Towards non-intrusive thermal load monitoring of buildigs: BES calibration", *Applied Energy*, Vol. 191, pp. 44-54.

Díaz Angulo, J.A., Pérez Díez, J.J., Ferrer Tevar, J.A. and Heras M.R. (2015), "Energetic experimental evaluation of the active systems of the RDB building 70 of the SSP-ARFRISOL", *Energy and Buildings*, Vol. 87, pp. 272-281.

Sanjuan, C., Sánchez, M.N., Enriquez, R. and Heras, M.R. (2012), "Experimental PIV techniques applied to the analysis of natural convection in open joint ventilated facades", *Energy Procedia*, Vol. 30, pp. 1216-1225.

Soutullo, S., Sánchez, M.N., Enríquez, R., Jiménez, M.J. and Heras, M.R. (2017_1), "Empirical estimation of the climatic representativeness in two different areas: desert and Mediterranean climates", *Energy Procedia*, Vol. 122, pp. 829-834.

Givoni, B. (1994), *Passive and low energy cooling of buildings*, John Wily & Sons, New York, USA.

Soutullo, S., Giancola, E., Franco, J.M., Botón, M., Ferrer, J.A. and Heras, M.R. (2017_2), "New simulation platform for the rehabilitation of residential buidlings in Madrid", *Energy Procedia*, Vol. 122, pp. 817-822.

Buonomano, A., Calise, F. and Palombo, A. (2012), "Buildings dynamic simulation: water loop heat pump systems anslysis for European climates", *Applied Energy*, Vol. 91, No. 1, pp. 222-234.

Jiménez, M.J. and Madsen, H. (2008), "Models for describing the thermal characteristics of building components", *Building and Environment*, Vol. 43, pp. 152-162.

Martí-Herrero, J. and Heras-Celemín, M.R. (2007), "Dynamic physical model for a solar chimney", *Solar Energy*, Vol. 81, N.5, pp. 614-622.

Soutullo, S., Sanjuan, C. and Heras, M.R. (2012), "Energy performance evaluation of an evaporative wind tower", *Solar Energy*, Vol. 86, No. 5, pp. 1396-1410.

Giancola, E., Sanjuan, C., Blanco, E. and Heras, M.R. (2012), "Experimental assessment and modelling of the performance of an open joint ventilated façade during actual operating conditions in Mediterranean climate", *Energy and Buildings*, Vol. 54, pp. 363-375.

Suárez, M.J., Gutiérrez, A.J., Pistono, J. and Blanco, E. (2011), "CFD analysis of heat collection in a glazed gallery", *Energy and Buildings*, Vol. 43, No. 1, pp. 108-116.

Ferrer Tevar, J.A., Castaño, S., Garrido Marijúan, A., Heras, M.R. and Pistono, J. (2015), "Modelling and experimental analysis of three radioconvective panels for night cooling", *Energy and Buildings*, Vol. 107, pp. 37- 48.

Enríquez, R., Rodríguez, I., Rodríguez, A., Seco, O., Jímenez, M.J. and Heras, M.R. (2010), "Estimación experimental puntual de las infiltraciones mediante atmósferas dopadas de CO_2 en el PSE-ARFRISOL", paper presented at Congress of Architecture and Solar Cooling, Roquetas del Mar, ES.

Enríquez, R., Bravo, D., Díaz, J.A. and Jímenez, M.J. (2015), "Mechanical ventilation performance assessment in several office buildlings by means of big data techniques", paper presented at 36th AIVC Congress, Madrid, ES.

Díaz Angulo, J.A. and Jiménez, M.J. (2017), "Experimental assessment of room occupancy patterns in an office building. Comparison of different approaches based on CO_2 concentrations and computer power consumption", *Applied Energy*, Vol. 199, pp. 121-141.

Soutullo, S., San Juan, C. and Heras, M.R. (2011_1), "Comparative study of internal storage and external storage absorption cooling systems", *Renewable Energy*, Vol. 36, No. 5, pp. 1645-1651.

Bujedo, L.A., Samaniego, J., Corredera, A., Frechoso, F., Sanz-Jimeno, R., Macía, A., Heras, M.R., Ferrer, J.A., Soutullo, S., Seco, O., Castellanos, A., Sánchez-García, J.A., Sánchez-Sánchez, J. and Gómez-Corona, L. (2017), "Modelling and simulation of a district heating with renewable polygeneration", paper presented at International Conference of Polygeneration, Cuernavaca.

Soutullo, S., Bujedo, L.A., Samaniego, J., Borge, D., Ferrer, J.A., Carazo, R. and Heras, M.R. (2016_1), "Energy performance assessment of a polygeneration plant in different weather conditions through simulation tools", Energy and Buildings, Vol. 124, pp. 7-18.

Soutullo, S., Enríquez, R., Sanjuan, C., Ferrer, J.A. and Heras, M.R. (2010), "Energy balances of four office buildings in different locations in Spain", paper presented at VI International Building Performance Simulation Association of Canada, Winnipeg, CAN.

García Fernandez, R., Pizarro García, C., Gutiérrez Lavín, A. and Bueno de las Heras, J.L. (2012), "Study of main combustion chracteristics for biomass fuels used in boilers", *Fuel Processing Technology*, Vol. 103, pp. 16-26.

Soutullo, S., Giancola, E. and Heras, M.R. (2018), "Dynamic energy assessment to analyze different refurbishment strategies of existing dwellings placed in Madrid", *Energy*, Vol. 152, pp. 1011-1023.

Lomas, K.J. and Eppel, H. (1992), "Sensitivity analysis techniques for building thermal simulation programs", *Energy and Buildings*, Vol. 19, No. 1, pp. 21-44.

Soutullo, S., Sánchez, M.N., Olmedo, R. and Heras, M.R. (2011_2), "Theoretical model to estimate the thermal performance of an evaporative wind tower placed in an open space", *Renewable Energy*, Vol. 36, No. 11, pp. 3023-3030.

Sánchez, M.N., Sánchez, B., Soutullo, S. and Santiago, J.L. (2015), "Modeling of urban greening effects on air quality in an undeveloped residential area", paper presented at International Conference on Urban Climatology, Toulouse, FR.

Giancola, E., Soutullo, S., Olmedo, R. and Heras, M.R. (2014), "Evaluating rehabilitation of the social housing envelope: Experimental assessment of thermal indoor improvements during actual operating conditions in dry hot climate, a case study", *Energy and Buildings*, Vol. 75, pp. 264-271.

Soutullo, S., Olmedo, R., Sánchez, M.N. and Heras, M.R. (2011_3), "Thermal conditioning for urban outdoor spaces through the use of evaporative wind towers", Building and Environment, Vol. 46, No. 12, pp. 2520-2528.

Santiago, J.L., Martilli, A., Martín, F., Borge, R., Quaassdorff, C. and De la Paz, D. (2017), "Modelling NOX concentrations through CFD-RANS in an urban hot-spot using high resolution traffic emissions and meteorology from a mesoscale model", *Atmospheric Environment*, Vol. 163, pp. 155-165.

Soutullo, S., Sánchez, M.N., Enríquez, R., Jiménez, M.J. and Heras, M.R. (2016_2), "Comparative thermal study between conventional and bioclimatic office buildings", *Building and Environment*, Vol. 105, pp. 95-103.