Energy and Buildings 41 (2009) 1037–1050

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

An hourly modelling framework for the assessment of energy sources exploitation and energy converters selection and sizing in buildings

Enrico Fabrizio [a,*], Marco Filippi [b], Joseph Virgone [c,d]

[a] Dipartimento di Economia e Ingegneria Agraria, Forestale e Ambientale (DEIAFA), Università degli Studi di Torino, Via Leonardo da Vinci 44, 10095 Grugliasco (TO), Italy
[b] Dipartimento di Energetica (DENER), Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy
[c] Université Lyon 1, Villeurbanne, France
[d] Université de Lyon, Département Génie Civil et Bâtiment (DGCB), FRE 3237, ENTPE, rue Maurice Audin, 69518 Vaulx-en-Velin Cedex, France

ARTICLE INFO

Article history:
Received 24 January 2009
Accepted 16 May 2009

Keywords:
Multi-energy systems
Renewable energy sources
Design
Hourly simulation
Optimization
Building

ABSTRACT

The promotion of the exploitation of renewable sources in the built environment has led to the spread of multi-energy systems in buildings. These systems use more than one energy source in various energy converters to overcome the limitations that may be characteristic of each source. However, the design of the optimization of such systems is a complex task because the number of design variables is high and the boundary conditions (climate, operation strategies, etc.) are highly variable, so the system simulation has to be performed in the time domain. In this work an original hourly model to optimize multi-energy systems is presented and applied on a case study. It is an evaluation method to assess, in an integrated fashion, the performance of a building system as a whole and the viability of the exploitation of various energy sources. This tool is intended to take into account the variation of the conversion efficiency as a function of the design power, part load, boundary and climatic conditions. The relations that can model the energy converters of the case study (standard boiler, condensing boiler, various types of chillers and others) from the energy performance and from the financial points of view are also presented. This model represents a valuable alternative to currently available tools for hybrid systems simulation because of the optimization approach and of the detail in the thermal energy converters performance. Ultimately, the theoretical and applied knowledge of this contribution aims also at promoting a more conscious use of renewable and non-renewable energy in the built environment.

1. Introduction

It is well known that the increase in the energy efficiency of the building systems is one of the most promising strategies to reduce the energy use in the built environment without penalizing the indoor comfort and the satisfaction of the final uses. This can be done not only by using highly efficient energy converters (or components) at both full and part loads, but also – in a broad sense – by the exploitation of natural resources and by matching the local energy supply with the building energy demand.

There has been a great development of small-scale renewable energy systems, and this caused a gradually developing integration of various energy sources into systems that can be called hybrid systems [1] or multi-energy systems. The second term is used to stress the fact that these systems are fed by a mix of sources and use more than one energy converter to cover one load, contrarily to conventional systems that, for each load, are fed by one energy source that is used in one energy converter.

In fact, one of the main reasons of the spread of multi-energy systems refers in fact to the use of various renewable sources, that are characterized by an intermittency that causes a mismatch between the energy demand and the energy supply that affects the system reliability and can be overcome by an integration of various converters working at the same time. This is why hybrid systems, originally used in remote applications [2,3], are recently used also in the building sector, as can be seen from the theoretical and experimental studies [4–10]. The definition of the lay-out and the sizing of the energy converters and components of this type of system is however quite a complex task, since it involves the assessment of highly variable quantities as the building energy demand and the energy sources, especially renewable sources, and the characterization of the energy converters.

The design of a multi-energy system, both in terms of components sizing and definition of operation strategies, can be specified as the determination of the energy demand and supply profiles and in the optimization between the energy demand, the

* Corresponding author. Tel.: +39 011 6705525; fax: +39 011 6705516.
E-mail address: enrico.fabrizio@unito.it (E. Fabrizio).

0378-7788/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.enbuild.2009.05.005

Nomenclature

A	sun-catching area (m^2)
A_{sp}	specific area of a PV module (m^2/kW$_p$)
c^K	specific cost of the hub component K (€/kW)
c^ν	specific cost of the energy-ware ν (€/kWh)
C^K	cost of the hub component K (€)
COP_K	coefficient of performance of the converter K
COP_{hub}	coefficient of performance of the energy hub
d_{nm}	backward coupling matrix entry
$\mathbf{D}$	backward coupling matrix of the hub ($n \times m$)
e^ν	emission factor for the energy carrier ν
ε_{in}	vector of hub energy input ($n \times 1$)
ε_{in}	vector of hub energy output ($m \times 1$)
ε	energy-wares/energy sources set
f	function
H	hub
I_{sol}	solar radiation (W)
$\mathcal{K}$	hub converters set
$\mathcal{L}$	building loads set
m	number of building loads
n	number of energy-wares/energy sources
P_{in}^α	power of the energy-ware/energy source α at the input port of the hub (kW)
$\mathbf{P}_{in}$	vector of hub energy flow input ($n \times 1$)
P_K	power of the hub converter K (kW)
$P_{K,in}$	input power of the hub converter K (kW)
$P_{K,out}$	output power of the hub converter K (kW)
P_{out}^a	power of the building load a at the output port of the hub (kW)
$\mathbf{P}_{out}$	vector of hub energy flow output ($m \times 1$)
P_{sto}^ν	energy flow entering or leaving a storage (kW)
p^ν	non-renewable primary energy emission factor
p_T^ν	total primary energy emission factor
PLF	part load factor
PLR	part load ratio
REF	renewable energy fraction
t_{co}	entering condenser fluid temperature (°C)
t_{ev}	leaving chilled water temperature (°C)
T	period of time (generally one year) (year (y))
T	absolute temperature (K)
y^K	life time of a component (year (y))

Greek letters

α	scaling exponent
ε_{K1}^a	ratio between the load a covered by the converter $K1$ and the load a
η_K	(conversion) efficiency of the converter K
τ	time (s)

Subscripts and superscripts

d	design
K	hub component/converter
ν	energy carrier

energy sources, the energy converters, the storages and the back-up components. In the literature this problem is addressed with reference to specific system configurations (e.g. geothermal heat pump coupled with solar collectors, trigenerators, etc.) as it is – for example – in the works [11–19], but not by means of an integrated tool that may make it possible to compare a great number of different design scenarios. Such a tool is the scope of the research work that is presented hereinafter.

2. Scope of the work

An hourly model to simulate and optimize multi-energy systems in buildings is presented in this work. It is based on the customization of the hybrid energy hub concept and was developed to be used at late design stages.

The application of the energy hub concept allows the complex problem of the matching between energy demand and energy supply to be modelled in a simple form and all the energy carriers (chemical, solar, thermal, cooling, electric energy) to be considered altogether. This holistic approach can account for all the interactions between various energy flows, through the building envelope and the energy converters, that sometimes can be in conflict with each other.

This dynamic analysis tool is intended to take into account:

- the differentiation of the building loads inputted to the model as a function of the thermal level of the heating and cooling energy;
- the variation of the conversion efficiency of each hub component as a function of the design power, that is to say the maximum power that the converter must meet at design conditions (e.g. gas boilers show greater efficiency when the nominal power increases);
- the variation of the conversion efficiency of each hub component as a function of the part load of the converter (e.g. at part load conditions, the converter efficiency generally decreases);
- the variation of the conversion efficiency of each hub component as a function of climatic conditions and other boundary conditions (e.g.: the variation of the condensing fluid temperature – air, groundwater, pond water – affects the coefficient of performance of chillers);
- the intermittent nature of renewable sources and the variation of utility network tariffs of non-renewable sources.

All these properties require that the simulation of the system is performed in the time domain. The general modelling framework, the model specifications to be adopted for an hourly simulation method, the energy performance and financial assessment of the converters are addressed from a methodological point of view and applied to a case study.

The outcomes of a market research on the installation costs of some energy converters are also summarized.

3. Energy hubs for the building system modelling

The energy system of a building is modelled following the approach of the so-called "*energy hub*" developed by Geidl, Andersson and other researchers [20–24] of the Zurich ETH within a project on multi-energy carriers systems of the future [25].

The energy hub concept was applied by Fabrizio [26] to the modelling and optimization of the building energy systems in a series of previous publications that addressed the modelling and optimization of an energy system at the design concept stage [27] and the definition of criteria and parameters to select a building energy system [28].

In the following paragraph, the main features of this modelling framework are addressed. A complete discussion of these issues can be found on ref. [26].

Following a black-box approach, only energy input and energy output of the system or a component are taken into account.