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A model to design and optimize multi-energy systems in buildings at the design concept stage

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Abstract

Increasing interest is currently being addressed to multi-energy systems in buildings. These systems integrate different energy sources, at least one of which is renewable, in order to cover the thermal and electrical loads of a building. Since the design and operation of such systems is very complicated for many reasons (e.g. the intermittent nature of the renewable sources, the highly interlinked system lay-outs), it is of the foremost importance to provide tools to help select the best system configuration and energy sources mix.

A modelling approach to multi-energy systems in buildings, based on the *energy hub* concept is presented in this work. This approach allows the coupling between the energy demand and the energy supply in a building to be modelled in a synthetic way. The model was customised to be used at the concept stage of the building design, either as a system simulation tool or as a system selection tool. If the prices and the characteristics of the energy converters and of the energy-wares are known, it is possible, with a certain set of constraints, to determine the configuration that minimises the initial investment costs, the use of non renewable sources or the life-cycle costs. This approach makes it possible to avoid the simulation and ranking of a set of different system configurations, and also permits the study of the behaviour of such systems in an open configuration and not as individual systems. An application of the methodology to a case study is provided.

Keywords: multi-energy systems, design, design concept, simulation, optimisation

Nomenclature

A_C	sun catching area	m^2
c^K	specific cost of the hub component K	€/kW
c^ν	specific cost of the energy-ware ν	€/kWh

COP_K	coefficient of performance of the converter K	
d_{nm}	backward coupling matrix entry	
$\mathbf{D}$	backward coupling matrix of the hub ($n \times m$)	
$\mathbf{E}_{in}$	vector of the hub energy input ($n \times 1$)	
$\mathbf{E}_{out}$	vector of the hub energy output ($m \times 1$)	
$\mathcal{E}$	energy-ware/energy source set	
f	function	
$\mathrm{I}_{\mathrm{sol}}$	solar radiation	kWh/m^2
$\mathcal{K}$	hub converter set	
$\mathcal{L}$	building load set	
m	number of building loads	
n	number of energy-wares/energy sources	
P_C	cooling capacity of a converter	kW
P_H	heating capacity of a converter	kW
P^{α}_{in}	power of the energy-ware/energy source α at the input port of the hub	kW
$\mathbf{P}_{in}$	vector of the hub energy flow input (n-dimension)	
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^{a}_{out}	power of the building load a at the output port of the hub	kW
$\mathbf{P}_{out}$	vector of the hub energy flow output (m-dimension)	
T	period of time (generally one year)	y
y^K	life time of the hub component K	y
ε^{a}_{K1}	ratio between the load a covered by the converter $K1$ and the load a	
$\bar{\varepsilon}$	mean factor ε	
η_K	(conversion) efficiency of converter K	
τ	time	s
Subscripts		
C	chiller	
CB	condensing boiler	
d	design	
e	electricity	
HP	heat pump	
K	hub component/converter	
PV	photovoltaic	
s	seasonal/annual	
sas	season	
SC	solar collector	
WB	wood boiler	
Superscripts		
K	hub component/converter	
t	thermal energy	
c	cooling energy	

e	electricity
ec	economy based
en	energy based
ev	environment based
s	solar radiation
ν	energy carrier

1 Introduction

A system designed to allow the operator to choose between multiple energy sources is referred to as a multi-energy system (or hybrid energy system [1]). These systems are currently receiving increasing attention as they represent a valuable mean of exploiting renewable energy sources and options for facility owners.

There are various types of multi-energy systems, which use different combinations of thermal and electric equipment such as cogenerators, electric chillers, engine-driven chillers, gas or steam absorption chillers, fuel cells, traditional boilers, wood boilers, thermal solar collectors, photovoltaic collectors, thermal and photovoltaic collectors, etc…[2]. A multi-energy system is therefore fed by a combination of various energy sources, both renewable and non renewable, to cover the thermal and electric loads of a building with the maximum efficiency. The rationale behind the integration of multiple energy sources and/or energy converters is to overcome the limitations that may be inherent to each one [1].

Several examples of multi-energy source building systems can be found in literature, which combine cogeneration with solar energy (both thermal and PV) and wind energy [3], exploit geothermal and solar energy through solar assisted heat pumps [4], combine CHP with absorption chillers and desiccant cooling [5], exploit solar energy to produce both heating and cooling [6], [7] and [8], exploit wind energy through a fuel cell stack [9] or through hydrogen storages [10],[11],[12].

The design of multi-energy systems involves resolving some problems such as: the correct sizing and the efficiency of the different systems and the cost and availability of different energy-wares. This is done, in the pertinent available literature, primarily by detailed studies (and optimizations where applicable) of single building systems as in the previously cited references [3]-[5], [7], [9]-[12] and, as an example of studies on heat pumps, in the techno-economic comparison of ground-coupled and air-coupled heat pumps [13], [14] and [15]. These studies require the estimation of the building energy demand, the energy resources characteristics and the energy converters technology at a level of detail that usually is not available during the first design stages of a building construction project.

Another important design and operational problem concerns the mismatch between the energy demand (the load) and the energy supply (both renewable and conventional energy sources) and this problem is usually addressed through the integration of a storage and/or a back-up energy source and connection to the power network. Typical storage mediums are water (refrigerated or ice), the ground, PCM or hydrogen. Since there are many adoptable configurations, it is important to carry out an optimization study between the energy demand, the energy supply, the converters, the storage and the back-up sources characteristics when designing and operating a multi-energy system.

This integration problem can be solved by determining all the relationships between the different quantities that affect the system performance and then by finding the values of the optimal design parameters once an objective function has been established, as performed by Ooka and Komamura [16] using an optimization scheme based on genetic algorithms and the software tool HOGA [17], or by simulating a great number of different cases and subsequently ranking them as a function of a combination of performance parameters. This second option is frequently adopted in the case of building systems simulation and selection, not only in studies (as for example [18]) but also in software tools like the distributed optimization model HOMER [19] that simulates various design scenarios and ranks them as a function of the life cycle cost. Other studies take into account not only costs and emissions related to the operation of the building system but also the material consumption of a building system in terms of ecological burdens: this is the case of Alanne and Saari [20] that addressed the issue of fuel cell based cogeneration for buildings by means of the MIPS (Material Input Per Service) unit method.

All the previous studies are based on specific system configurations and on a detailed modelling of the energy converters characteristics, energy demand and energy supply, so that they are not easily implemented at the design concept stage. This is the reason why this work provides a new way to model and optimize multi-energy systems.

2 Purpose of the work

Multi-energy systems usually adopt non convectional energy converters, new aggregations of components and unusual system layouts, and they are also particularly sensitive to boundary conditions of any type – energy, economic, environmental. For these reasons, it is necessary to have the availability, from the design concept stage (also called pre-design, schematic design or conceptual design) of an energy-economy-environmental feasibility analysis procedure of these systems.

This concept also agrees with recent integrated design process theories, which are based on the whole building concept, where “all the design variables that affect one another are considered together and resolved in an optimal fashion” [21]. The presented modelling procedure provides a powerful tool to implement the sustainable design sequence based on:

- the minimization of the building loads;
- the increasing of system efficiency;
- the use of regenerative systems;
- the use of renewable sources as system driving inputs.

On one hand, it is well known that the potential benefits of the design inputs taken at the design concept stage are much higher than the benefits of design choices taken at the design development and construction document phase. As stated by Lewis in [21], the cost of implementing concepts to improve the energy performance of a building is also lower at the earliest stages.

On the other hand, the multi-energy systems modelling and evaluation methods that are currently available, based on detailed simulation models, can only be applied with a great number of input data, boundary conditions and user profiles (which are really important in building energy assessment [22]) that are usually not known in the design concept stage. These modelling methods are therefore useful during advanced design stages to evaluate a finite set of alternatives, in accordance with a top-down approach, that may be called a *design-evaluation approach*.

An answer to the lack of quantitative evaluation methods that are suitable for the first phases of the design, when it is not convenient to carry out detailed simulations, and when it is very important to evaluate a large number of different design alternatives [23], was given in the field of building design through the elaboration of architectural conception design aid tools that are able to optimize, at the design concept stage, the building shape, window size, orientation, building height, etc…[24]. There is still however a need for simplified procedures to model and optimize the energy system of the building.

Being aware of the fact that the degree of the design effort is higher during the programme pre-design and schematic design phases [21], it is of a great importance to concentrate research activities on the elaboration of a methodology that is able to model and optimize the coupling between energy demand and energy supply in a building at the design concept stage, taking into account all the constraints that arise in real-life building design.

3 The energy hub concept

The energy hub [25] (or hybrid energy hub) was introduced by a research team at the Power Systems and High Voltage Laboratories at ETH Zurich in the framework of a project named *Vision of Future Energy Networks*. This project – summarised in [26] and available on the net at [27] – aims at defining the structure of energy networks in the long term. Two major key aspects mark the project [28]: the network is supposed to adapt to the needs of consumers and producers and not only those concerning electricity, but also other energy needs (heating, cooling, chemical power, etc…) are taken into account.

The energy hub is an abstract model of the interface between power producers, consumers and transportation infrastructure (energy interconnectors). Many examples of energy hubs can be found, e.g. power stations, industrial plants, urban districts, island power systems and also buildings.

The concept of the energy hub has been specified as a set of matrix formulations that relate the power flow at the input port and to that at the output port of a hub. This can be found in the report [29] written by Geidl, where the port-to-port power flow coupling and the hub continuity equation were determined and explained for some cases.

This modelling approach was used by Geidl and Andersson to perform a topological (or structural) optimization of a single energy hub [30] and to perform an operational optimization of a system of interconnected hubs [31], [32]. Koeppel and Andersson assessed the reliability of supply with the same modelling approach [33].

The energy hub concept and the simplified energy flow theory developed by Andersson, Frölich, Geidl [34], Koeppel [35] *et al.* set a general theoretical framework to help understand the behaviour of complex, highly interlinked combinations of various energy supply systems. As stated by the Authors in [28], this theory also covers the lack of literature concerning the general integration of different modelling methods in one theory for hybrid energy systems, since hybrid energy systems have been addressed as individual systems over the past 20 years.

4 A coupling algorithm to model multi-energy systems in buildings

The energy hub framework was adopted to determine a modelling procedure for a generic building energy system. The energy system is portioned into three entities: the energy supply, the energy demand and the energy conversion, storage and regulation. The energy supply is intended as the set of energy-wares that are supplied to the multi-energy system of the building to feed the energy converters. Each quantity (power P, energy E) that refers to the energy supply side of the system, is identified by the subscript *in*. Given $\mathscr{E}$ the set {α, β, γ ...} of *n* energy-wares, the powers supplied to the energy system by the *n* energy-wares are

$$P_{in}^{\alpha},\ P_{in}^{\beta},P_{in}^{\chi}\ \ldots\ P_{in}^{n} \tag{1}$$

where the superscripts (α, β ...) refer to the energy-wares (e.g. natural gas, wood, electricity …). The set of *n* energy-wares power can be expressed in an *n*-dimension vector as

$$\mathbf{P}_{in} = \left[P_{in}^{\alpha},\ P_{in}^{\beta},P_{in}^{\chi}\ \ldots\ P_{in}^{n}\right]^{T} \tag{2}$$

The energy demand is the set of building loads that have to be covered by the energy converters of the multi-energy system of the building. Each quantity that refers to the energy demand side of the system is identified by the subscript *out*. Given $\mathscr{L}$ the set {*a,b,c...*} of the *m* building load typologies, the *m* building loads covered by the system are

$$P_{out}^{a},\ P_{out}^{b},P_{out}^{c}\ \ldots\ P_{out}^{m} \tag{3}$$

where the superscripts (*a*, *b* …) refer to the load types (e.g. heating energy at 75° C, heating energy at 45° C, cooling energy at 7°C, electricity at a voltage of 230 V …). The set of *m* building loads can be expressed in an *m*-dimension vector as

$$\mathbf{P}_{out} = \left[P_{out}^{a},\ P_{out}^{b},P_{out}^{c}\ \ldots\ P_{out}^{m}\right]^{T} \tag{4}$$

Once the vectors of building loads $\mathbf{P}_{out}$ and energy-wares $\mathbf{P}_{in}$ are defined, the coupling between the energy demand and the energy supply of a building energy system can be written as

$$\mathbf{P}_{in} = \mathbf{D}\ \mathbf{P}_{out} \tag{5}$$

provided that a suitable ($n \times m$) coupling matrix **D** is defined. This formulation is adopted since the vector $\mathbf{P}_{out}$ is considered to be known. The matrix **D** is a *backward coupling matrix*, since it relates the inputs as a function of the outputs and is in counter-flow to the direction of the main physical energy flows, assuming that the building loads at the output port are known and that the unknowns of the formulations are the energy sources at the input port.

As far as matrix **D** is concerned three basic aspects must be taken into account when deriving each entry d_{ij}:

1) the connections between the fluxes of the hub;
2) the conversion losses of the hub energy converters;
3) the energy stored in some hub components.

The first aspect deals with the dispatch of loads into different fluxes (the hub lay-out); the second aspect deals with the energy converters: they can in fact not only change the form of energy which passes through them (aspect theoretically already taken into account at point 1) but also change the amount of energy that passes through them due to the energy losses of the components of the converter; the third aspect deals with the storages, which affect the energy flow between the input and the output when a time-domain simulation of the hub is performed but are not dealt with in this paper.

4.1 The connection between fluxes

In the case of only a connection between fluxes without conversion losses, the entries of matrix **D** can assume:

- the values 1 (connection between the two fluxes) or 0 (no connection), in the case where an energy-ware supplies one or more loads;
- any value between 0 and 1, in the case where a load is fed by more than one energy-ware.

A parameter ε, which represents the ratio between the power flow on a line and the total power flow at the output, is introduced to take into account this second case. For example

$$\varepsilon^{a}_{\alpha\to a} = \frac{P^{a}_{\alpha\to a}}{P^{a}_{out}} \tag{6}$$

Is the ratio between the building load *a* covered by the energy-ware α and the building load *a*. Since ε has the physical meaning of a factor, it must fall between 0 and 1. The sum of all the factors ε, for each building load, equals 1 (as stated later in Eq. 9c), which means that the sum of each column of entries of matrix **D** is equal to 1 in case of only a connection between fluxes.

4.2 The energy converters

With the aim of modelling the multi-energy systems, in such a way as to simplify the complexity of these systems, the energy converters are considered as single unit black-boxes fed by one or more energy inputs $P_{K,in}$ which provide one or more energy outputs $P_{K,out}$. The conversion efficiency of the generic converter *K* is the ratio between the energy output $P_{K,out}$ and the energy input $P_{K,in}$

$$\eta_{K} = \frac{P_{K,out}}{P_{K,in}} \tag{7}$$

and has to be inserted into the coupling matrix **D**. It should be pointed out that the modelling of the converters includes many level of complexity (from simplified models to the most accurate ones) which leads to various levels of complexity of the coupling algorithm.

Fig. 1

As an example, the resulting matrix equation that models the hub in Figure 1 is

$$\begin{bmatrix} P_{in}^{\alpha} \\ P_{in}^{\beta} \\ P_{in}^{\chi} \\ \ldots \\ P_{in}^{n} \end{bmatrix} = \begin{bmatrix} \frac{\varepsilon_{K1}^{a}}{\eta_{K1}} & \frac{1}{\eta_{K2}} & 0 & \ldots & 0 \\ 0 & 0 & \frac{1}{\eta_{K3}} & \ldots & 0 \\ \frac{\varepsilon_{K4}^{a}}{\eta_{K4}} & 0 & 0 & \ldots & 0 \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ 0 & 0 & 0 & \ldots & 0 \end{bmatrix} \begin{bmatrix} P_{out}^{a} \\ P_{out}^{b} \\ P_{out}^{c} \\ \ldots \\ P_{out}^{m} \end{bmatrix} \tag{8a}$$

with the constraints

$$0 \le \varepsilon_K^i \le 1 \quad \forall\, i \in \mathcal{L} = \{\text{a, b, c, ...}\},\ \forall\, K \in \mathcal{K} = \{K_1, K_2, K_3, \ldots K_n\} \tag{8b}$$

$$\sum_{K=K1}^{Kn} \varepsilon_K^i = 1 \quad \forall\, i \in \mathcal{L} = \{\text{a, b, c, ...}\} \tag{8c}$$

$$0 \le \eta_K \quad \forall\, K \in \mathcal{K} = \{K_1, K_2, K_3, \ldots K_n\} \tag{8d}$$

where $\mathcal{K}$ is the set of energy converters. Converters with multiple energy inputs can be modelled using the same approach. Attention should be paid to converters that have multiple energy outputs, since these outputs are usually not independent variables, but related through some equations. Since in this backward coupling formulations, the outputs are considered as known terms, and are therefore independent, different relations from Eq. 8 must be set. In the case of a converter with *m* multiple outputs, only one of the outputs of the converter is usually independent while the other ones are dependent, therefore *m*–1 relations between the outputs have to be added to the fundamental matrix equation to simulate the multi-energy system performance.

5 Applications of the coupling algorithm

There are basically four sets of parameters in the most general formulation (Eq. 8a) of the multi-energy system coupling algorithm:

- parameters related to the energy demand side of the hub (building loads P_{in});
- parameters related to the dispatch of loads in the hub (factors ε);
- parameters related to the performance of the energy converters (efficiencies η);
- parameters related to the energy supply side of the hub (energy-wares P_{out}).

The determination of the first set of parameters involves the assessment of the building energy demand, which is considered to be known. The parameters belonging to the other sets may be either known or unknown quantities. Depending on the number and type of the unknown parameters, the energy hub formulation can be used to perform three types of analyses:

1) a design optimization of the multi-energy system;

2) an operational optimization of the multi-energy system;
3) a simulation of the multi-energy system.

The differences between the three types of analyses and the relations with the hub forms (generic hub, tailored hub) are also summarized in Figure 2. Only the optimization will be addressed in the following paragraphs.

Fig. 2

5.1 *Design optimization of the multi-energy system*

In this case, the building multi-energy system must be designed. This means:

- specifying the set of energy-wares that have to be consumed at the input port of the system;
- specifying the set of energy converters that have to be used in the system;
- specifying the values of the design power of the energy converters;
- specifying the values of the energy consumed for each energy-ware.

The hub optimization consists of finding the set of values of factors ε, the decision variables, that best minimize an objective function *f* which is selected on the basis of one or more decision criteria

$$\{\varepsilon^{a}_{K1}, \varepsilon^{a}_{K2}, \varepsilon^{a}_{K3}, \ldots\ \varepsilon^{b}_{K1}, \varepsilon^{b}_{K2}, \varepsilon^{b}_{K3}, \ldots\ \varepsilon^{c}_{K1}, \varepsilon^{c}_{K2}, \varepsilon^{c}_{K3}, \ldots\ \varepsilon^{m}_{K1}, \varepsilon^{m}_{K2}, \varepsilon^{m}_{K3}, \ldots\} : \min f \tag{9}$$

The unknowns of the optimization problem in Eq. (9) are not all ε factors since, as can be seen from Eq. (8c), the sum of factors ε for each building load must be equal to 1, thus resulting in one less unknown for each building load.

The optimization decision variables, factors ε, have the physical meaning of the distribution of energy fluxes between the energy converters of the hub: the hub layout is thus determined. Moreover, the knowledge of the values of these factors allows all the other unknowns of the problem (design power of the converters and the power of the energy-wares at the input port of the hub) to be determined under certain assumptions.

5.1.1 *The position of the problem*

The design optimization application process is outlined as follows

Objective function $f\,(\mathbf{P}_{in}, \mathbf{P}_{K})$
Data ⟶ Hub equation $\mathbf{P}_{in} = \mathbf{D}\,\mathbf{P}_{out}$ ⟶ Unknowns
Constraints on factors ε^{i}_{K}, other constraints

- values of $\mathbf{P}_{out}$
- parameters of $\mathscr{K}$ (e.g. cost in € /kW installed)
- parameters of $\mathscr{E}$ (e.g. cost in €/kWh consumed, emission factors, …)
- matrix $\mathbf{D} = f\,(\varepsilon, \eta)$ with parameters η known

- values of factors ε^{i}_{K}
- design power $\mathbf{P}_{K,out}$
- power $\mathbf{P}_{in}$

The unknowns are determined from the data through the minimization of one objective function subjected to the hub equation (8a) and to the constraints on factors ε (8b) and (8c). Other constraints may be necessary for the energy converters that have multiple outputs.

5.1.2 The resolution process

A scheme of the resolution process of the design optimization is given in Figure 3. The model inputs include the physical output of the hub $\mathbf{P}_{out}$, that is, the building loads, and the parameters and equations (efficiencies, part-load curves, etc…) that account for the performance of the energy converters at different working conditions. These last entries depend on the level of complexity of the adopted model and will be discussed later. The model calculates the values of the power of the energy converters $\mathbf{P}_K = \{P_{K1}, P_{K2}, P_{K3},\dots P_{Kn}\}$ and the values of the energy-ware power $\mathbf{P}_{in}$ at the input port of the hub. These output values of the model (the physical inputs of the hub) are the subject of an objective function used to perform the optimization. The objective function is defined using one or more optimization criteria (e.g. minimal cost, maximum return of the investment, minimal emissions of pollutants, etc.) and parameters that can numerically express the optimization criterion in a certain objective function. A solver is used to iteratively search for the set of ε^i_K that minimize the objective function.

A solver based on the Generalized Reduced Gradient (GRG2) algorithm, developed by Lasdon and Waren [36] to optimize nonlinear problems, has been used in the case study application. The used GRG algorithm is a nonlinear extension of the simplex method for linear programming and according to its Authors it can be used to efficiently solve small to medium size problems. The finding of a local optimum is only guaranteed for problems with continuously differentiable functions and in the absence of numerical difficulties.

The full specification of the algorithm and the programme list is reported in [36]. To save time, it is possible to specify whether the model is linear (as in the case of the presented application): in this case, the solver implements the simplex method with bounded variables. In case of a nonlinear problem, the solver uses the generalized reduced gradient method as it is implemented in the code of [36].

Fig. 3

A graphical user interface is available to select various options (finite difference approximation scheme, maximum number of iterations, convergence). For a complete discussion on the capabilities of this solver, see [37].

5.1.3 Forms of the hub

As can be seen from the schematic representation in Figure 2, two different forms of hub can be selected as a starting layout for the optimization:

- a *generic hub*, which takes into account all the possible conversions (and the relative components) that energy sources can undergo to cover the loads: this is the most general one multi-energy system;
- a *tailored hub*, which takes into account only the conversions (and the relative components) that are of practical application and of interest to the building owner in the specific analysis context.

5.2 Simulation of the multi-energy system

The energy hub coupling formulation (9) is also a valuable way of performing the energy simulation of a multi-energy system. For an existing system, it is possible to determine the energy use under its actual operating conditions. Given a set of factors ε, the model can be used to simulate the different hub layout/scenarios of converters so that they can be compared with the optimized scenarios. This application can also be used to select a system according to a commonly used approach in building energy system simulation tools. In this case, the selection procedure is quite different: unlike the two previous optimization procedures, this one is based on a finite set of scenarios that must be selected by the user.

6 The seasonal method

In this section, the coupling algorithm presented in section 4 is applied to satisfy the need for a simple decision tool, applicable in the design concept stage of the building, to optimize a multi-energy system.

6.1 Model specifications

Equation (9a) can be applied both to design powers (subscript d) and to annual or seasonal energy (subscript s). This gives

$$\mathbf{P}_{in,\mathrm{d}} = \mathbf{D}_{\mathrm{d}}\ \mathbf{P}_{out,\mathrm{d}} \tag{10}$$

and

$$\mathbf{E}_{in} = \mathbf{D}_{\mathrm{s}}\ \mathbf{E}_{out} \tag{11}$$

It is $\mathbf{E}_{in} = \left[E_{in}^{\alpha}, E_{in}^{\beta}, E_{in}^{\chi} \ldots E_{in}^{n}\right]^{T}$ and $\mathbf{E}_{out} = \left[E_{out}^{a}, E_{out}^{b}, E_{out}^{c} \ldots E_{out}^{m}\right]^{T}$ with

$$E_{in/out}^{\upsilon} = \int_{\tau=0}^{T} P_{in/out}^{\upsilon}\ d\tau \quad \forall \upsilon \in \mathscr{E} \cup \mathscr{L} \tag{12}$$

where E^{α}_{in} is the energy of energy-ware α consumed at the input port of the hub in the period of time T and E^{a}_{in} is the energy a required at the output port of the hub.

Matrices $\mathbf{D}_{\mathrm{d}}$ and $\mathbf{D}_{\mathrm{s}}$, whose subscripts refer to design and seasonal conditions, are determined according to sections 4.1 and 4.2. The only difference between the matrices concerns the values of efficiencies that have to be adopted:

- design efficiencies (usually full load efficiencies) of the converters are used in matrix $\mathbf{D}_{\mathrm{d}}$;
- mean seasonal/annual efficiencies of the converters are used in matrix $\mathbf{D}_{\mathrm{s}}$.

The same principle applies when more than one energy efficiency is needed in the case of converters with multiple outputs.

As far as factors ε are concerned, the same factors are considered in both matrices for design and mean seasonal conditions. Furthermore, more than one season may be analyzed in a year, e.g. the heating season and the cooling season, assigning one hub lay-out to each season and therefore one set of decision variables ε. A distinction between the heating season and the cooling season is usually necessary in buildings systems, because of the variability of the energy demand over the year.

This distinction may be ignored and a single set of decision variables ε may be set in the optimization procedure when no interconnections between cooling energy and heating energy are present in the hub.

If more than one season is considered, the design power/capacity of the hub energy converters are the maximum values obtained over the seasons

$$P_K = \max_{sas}\left(P_{K,sas1}, P_{K,sas2}, \ldots\ldots P_{K,sasn}\right) \;\forall\; K \in \mathcal{K} \tag{13}$$

This has to be specified since the design capacity of the energy converters is used in many objective functions to perform the optimization.

In the case of energy-wares or energy sources that are available at the input port of the hub with some limitations, specific constraints must be added to Eqs. (10) and (11). Energy-wares such as natural gas, electricity and district heating may be considered as always being available whereas other energy sources, like renewables, are assumed be available from the environment according to a certain regeneration rate. These limitations are usually taken into account at this stage together with other more detailed ones, by imposing a simple maximum value constraint on all the decision variables related to this particular energy source. This may be done by limiting the appropriate factors ε to within a range

$$0 < \varepsilon < \varepsilon_{\max} \tag{14}$$

where ε_{max} depends on the properties (area, orientation) of the solar collecting area of the building. It should be pointed out that, at a seasonal stage of development of the method, only the limitation on design capacity of the converters and integral values of energy can be enforced. No limitation can be enforced on the particular availability profile of an energy source.

No energy storage device can directly be taken into account in this method since the simulation is not performed in the time domain. The performance of an integrated energy storage can, however, be simulated by the use of an appropriate value of the mean seasonal efficiency. This is the case of the thermal solar systems that are always used with the integration of a water storage. In these cases, a preliminary parametric study of the integrated converter+storage performance system must be performed. As an example, appropriate values of the mean annual efficiencies of a solar system for a residential unit, determined from a sensitivity analysis carried out with dynamic simulation, are reported in [38], [39] and can be used in this method.

6.2 Input data

Consistently with the design stage at which this method has to be applied, the number of input data is very small. As regards the building energy demand, the only necessary data are:

- design value for each building load;
- annual/seasonal energy requirement for each building load.

These values refer to the energy that must be supplied by the energy system of the building, therefore they do not necessarily represent the building energy needs, but must take into account all energy losses that may occur (distribution and regulation energy losses for example) after the energy system.

Even though, from a theoretical point of view, many evaluations can be used, at this stage the energy demand is more likely determined through:

- simplified standard methods (e.g. the EN 12831 calculation procedure for the heating design load [40], ISO 13790 for the energy needs for heating and cooling [41]);
- literature values (e.g. BSRIA Rules of thumb for cooling loads and energy requirements [42]).

However, the number of input values for the energy demand equals $2 \cdot m \cdot s$ where m is the number of building loads and s is the number of seasons that have to be analyzed.

The same rationale can be used when assessing the performance of the energy converters: two values of conversion efficiencies must be provided for each converter, one at full load and the other at the mean seasonal/annual condition. This second value is the most difficult to determine *a priori*, and it must be based on some existing literature, results, or – at least – consultant experience.

6.3 Output data and results

The time integral in Eq. (12) is only reported to clearly define the quantity E, but it is not computed at any point in this calculation procedure since only a value of seasonal/annual energy is provided as an input. The values of the energy-ware powers entering the hub and energy consumed by the hub can be determined from Eqs. (10) and (11). The application of the steady-state method to the problem of the selection and design of the energy system of a building is presented in the following section.

7 Application to a case study

7.1 Case study description

A five-storey 1230 m² multi-family building consisting of 10 apartments was selected. The building is built in concrete; the walls are made of two brick layers with an internal glass wool layer. The roof is plane and not insulated. There are warehouses on the first floor, which interfaces with the ground. The building has been partitioned into three thermal zones to account for the presence of the stair-well and the warehouses which are both unconditioned. Only the internal zone of the apartments is conditioned.
The building is located in Turin. The building energy demand characterization is shown in Table 1. The space heating and cooling loads are reported in Figures 4 and 5 in terms of time series and cumulative frequency curves. The monthly heating (space and DHW), cooling and electricity demands are reported in Figure 6. Even if not strictly necessary form the point of view of the input data, the building energy demand was calculated for completeness of information by dynamic simulation through the software EnergyPlus [43] .

Figs. 4-6
Table 1

7.2 The energy hub description

The energy hub considered for this case study is reported in Figure 7. The energy-wares at the input port are wood (superscript *w*), natural gas (*g*), solar energy (*s*) and electricity from the grid (*e*). The combination of the selected components (tailored hub) provides the possibility of satisfying the thermal load (superscript t) – alternatively or in any combination – through:

- a wood boiler (WB);

- a condensing boiler (CB);
- a water-to-water reversible heat pump (HP);
- a thermal solar combisystem (SC).

The cooling load (superscript c) can be satisfied by:

- a central cooling system equipped with a central water-cooled chiller (C);
- an air-to-water reversible heat pump (HP);

The electricity load can be satisfied by:

- the national power grid (e);
- a photovoltaic system (PV).

The input powers can be expressed as a function of the output powers and of the efficiencies of the energy converters as

$$\begin{aligned}
P_{in}^{w} &= \frac{1}{\eta_{WB}}\varepsilon_{WB}^{t}P_{out}^{t} \\
P_{in}^{g} &= \frac{1}{\eta_{CB}}\varepsilon_{CB}^{t}P_{out}^{t} \\
P_{in}^{s} &= \frac{1}{\eta_{PV}}\varepsilon_{PV}^{e}P_{out}^{e} + \frac{1}{\eta_{SC}}\varepsilon_{SC}^{t}P_{out}^{t} \\
P_{in}^{e} &= \frac{1}{\mathrm{COP}_{HP}^{t}}\varepsilon_{HP}^{t}P_{out}^{t} + \frac{1}{\mathrm{COP}_{HP}^{c}}\varepsilon_{HP}^{c}P_{out}^{c} + \frac{1}{\mathrm{COP}_{C}^{c}}\varepsilon_{C}^{c}P_{out}^{c} + \varepsilon_{e}^{e}P_{out}^{e}
\end{aligned} \tag{15}$$

with the usual significance of the factors ε discussed in section 4.1. The term COP^{t}_{PC} refers to the heating operation of the heat pump, while the term COP^{c}_{HP} refers to the cooling operation of the heat pump in the reverse cycle. In the last row of Eq.(15), the thermal and cooling output of the heat pump can be summed together (the first two addendum on the right hand side of the equation) since if $\varepsilon^{t}_{HP} \neq 0$ then $\varepsilon^{c}_{HP} = 0$ and similarly if $\varepsilon^{c}_{HP} \neq 0$ then $\varepsilon^{t}_{HP} = 0$, as stated by the constraints in Eqs. (25) and (26).

The matrix equation reads

$$\mathbf{P}_{\mathrm{in}} = \mathbf{D}\,\mathbf{P}_{\mathrm{out}} \tag{16}$$

$$\begin{bmatrix} P_{in}^{w} \\ P_{in}^{g} \\ P_{in}^{s} \\ P_{in}^{e} \end{bmatrix} = \begin{bmatrix} \frac{1}{\eta_{WB}}\varepsilon_{WB}^{t} & 0 & 0 \\ \frac{1}{\eta_{CB}}\varepsilon_{CB}^{t} & 0 & 0 \\ \frac{1}{\eta_{SC}}\varepsilon_{SC}^{t} & 0 & \frac{1}{\eta_{PV}}\varepsilon_{PV}^{e} \\ \frac{1}{\mathrm{COP}_{HP}^{t}}\varepsilon_{PC}^{t} & \frac{1}{\mathrm{COP}_{C}^{c}}\varepsilon_{C}^{c} + \frac{1}{\mathrm{COP}_{HP}^{c}}\varepsilon_{PC}^{c} & \varepsilon_{e}^{e} \end{bmatrix} = \begin{bmatrix} P_{out}^{t} \\ P_{out}^{c} \\ P_{out}^{e} \end{bmatrix} \tag{17}$$

As far as the decision variables are concerned, only 5 out of the 8 ε factors are independent, since, for each load, at the output port for Eq. (8c) we have:

$$\sum_{i} \varepsilon_i^{t,c,e} = 1 \tag{18}$$

The design efficiencies and the mean seasonal efficiencies of the energy converters are assumed equal to the values reported in Table 2.

In order to select an appropriate value of the performance parameters for the *C* and *HP* converters, certified data on the coefficient of performance (COP, in heating mode), energy efficiency ratio (EER, in cooling mode) and European seasonal energy efficiency ratio (ESEER, in cooling mode) were collected for various water-cooled liquid packaged chillers and are reported in Figures 8 and 9. These data were determined according to the Eurovent certification procedure and are available at the certification web site [44]. The converters whose data are reported in Figure 8 are dedicated to air-conditioning applications, while the others (Figure 9) are dedicated to radiant heating/cooling applications because of the high temperature of the chilled water, produced at 18 °C and not at 7 °C, with a resulting increase in the machine efficiency. The air-conditioning machine values are used for the case study.

Figs. 7-9
Table 2

7.3 *The objective functions*

Three objective functions were identified:

1) an economic function based on the energy consumed during the heating and cooling seasons and on the installed powers, which reads

$$f_1 = \left(\sum_{\beta} c^{\upsilon} \left(E^{\upsilon}_{\text{in, heat}} + E^{\upsilon}_{\text{in, cool}} \right) + \sum_{K} \frac{c^{\mathrm{K}} \left(\max\left(P_{K,heat}, P_{K,cool} \right) \right)}{y^{K}} \right) \tag{19}$$

where the subscripts “heat” and “cool” refer to the heating and to the cooling seasons, respectively. Fixed specific investment costs of energy converters c^{K} were adopted and are reported in Table 3. The costs for energy wares c^{ν} are equal to 0.025 €/kWh for the wood, 0.06 €/kWh for the natural gas, 0 €/kWh for the solar energy and 0.15 €/kWh for the electricity from the grid;

2) an energy objective function based on the consumed energy defined as

$$f^{\,en} = f\left(\mathbf{P}_{\text{in}}\right) = \sum_{\upsilon=\alpha}^{n} \left(p^{\upsilon} E^{\upsilon}_{\text{in}} \right) \quad [\text{kWh}_{\text{t}}/\text{y}] \tag{20}$$

whose weighting factors *p* are the non-renewable primary energy factors according to European standard EN 15603 *Energy performance of buildings – Overall energy use, CO_2 emissions and* *definition of energy ratings* [45];

3) an environmental objective function such as

$$f^{ev} = f(\mathbf{P}_{\text{in}}) = \sum_{\upsilon=\alpha}^{n} \left(e^{\upsilon}_{\text{CO}_2} \cdot E^{\upsilon}_{\text{in}} \right) \; \left[\text{kg}_{\text{CO}_2}/\text{y} \right] \tag{21}$$

where the factor *e* considers only the carbon dioxide emissions.

Table 3

7.4 *Constraints on the renewable sources and on the heat pump*

In order to properly take into account the solar energy in Eqs. (10) and (11) and avoid an overestimation of the energy input at both design and seasonal mean conditions, it is necessary to introduce further constraints such as (14).

Solar energy converters

Solar energy is in fact proportional to the sun catching area A_{C}, which – in the absence of more detailed information – may be assumed equal to half of the roof area. This quantity, multiplied by the total horizontal solar radiation I_{sol}, can be assumed as an indicator of the upper limit of the solar energy. A decision can be made on the considered analysis period (one year, one season, one month).

For this case study, and for a period of one year, we have

$$E^{s}_{\text{in,max}} = A_{\text{C}} \cdot I_{\text{sol}} = 123 \cdot 1320 = 162.360 \text{ MWh} \tag{22}$$

and the upper value of the solar energy input for the heating season is

$$E^{s}_{\text{in,max}} = A_{\text{C}} \cdot I_{\text{sol}} = 123 \cdot 512 = 63.0 \text{ MWh} \tag{23}$$

This is the upper value of the energy input to the solar collectors and the PV modules, which gives the following inequality constraint on the factors ε of the SC and PV components

$$E^{S}_{in,\max} \geq \frac{P^{t}_{out}\,\overline{\varepsilon}^{\text{t}}_{\text{SC}}}{\overline{\eta}^{\text{t}}_{\text{SC}}} + \frac{P^{e}_{out}\,\overline{\varepsilon}^{\text{e}}_{\text{PV}}}{\overline{\eta}^{\text{e}}_{\text{PV}}} \tag{24}$$

where conversion efficiencies and factors ε are assumed as mean seasonal values.

Heat pump

Another constraint is necessary on the operation of the heat pump which, being reversible, can also operate for cooling purposes, but not at the same time for heating and cooling. This can be stated as:

$$\text{if } \varepsilon^{\text{t}}_{\text{HP,cool}} > 0, \text{ then } \varepsilon^{\text{c}}_{\text{HP,cool}} = 0 \tag{25}$$

$$\text{if } \varepsilon^{\text{c}}_{\text{HP,cool}} > 0, \text{ then } \varepsilon^{\text{t}}_{\text{HP,cool}} = 0 \tag{26}$$

Since there is no cooling energy demand in the winter season, it is not necessary to impose an analogous constraint on the heat pump operation in the winter season.

7.5 System design: results and discussion

The values of the factors ε that minimize each of the three adopted objective functions are reported in Table 4. The initial guess is a system where all the loads are uniformly distributed over the various energy converters.

Tables 4 and 5

Minimum cost criterion

The design configuration of the components that can be derived from the minimum cost criterion is reported in Figure 10 and is based on the following components:

- a thermal solar collector system that provides 21% of the heating demand in the heating season and 56% of the heating demand in the cooling season; the size of the collectors is limited by the upper value of the solar energy input in the heating season;
- a 41 kW heat pump that covers part (63%) of the heating load in the heating season and that, in reverse cycle, covers all the cooling load in the cooling season;
- a 10.5 kW wood boiler that covers the remaining heating load (16%) in the heating season and 44% of the heating load in the cooling season;
- connection to the power grid to cover the entire electricity demand in both seasons.

Fig. 10

In this way, the reversible heat pump is designed to cover the cooling load during the cooling season and most of the heating load in winter. The remaining heat load is covered by a small capacity wood boiler which in the winter, covers only a small part of the load, but which, in the summer, is the only integration source for the solar collectors.

Even though there are three components to cover the heating load in winter, this configuration has a minor cost than the one that sizes the heat pump to cover the entire thermal load in winter and provides the cooling energy from a chiller. The use of a condensing boiler instead of a wood boiler leads to a greater annual cost (12.75 €/y), due to the high cost of gas compared to wood, which cancels out the greater investment cost of the component.

It should be noted that, compared to the initial guess system, this one reduces the annual investment and purchased energy ware costs, but increases primary energy consumption and carbon dioxide emissions.

Minimum primary energy criterion

A second design configuration can be derived from the minimum primary energy criterion and is reported in Figure 11. This is based on the following components:

- a 65 kW wood boiler which provides all the heating energy both in the heating and cooling seasons;
- a 35 kW chiller – and not the heat pump in reverse cycle – which provides the cooling

energy;

- a 26 kW_p PV system which covers 89% of the electricity demand in the cooling season and 41% of the electricity demand in the heating season;
- connection to the electricity grid to meet the remaining electricity needs.

The constraints in Eq. (14), on the solar energy input, limit the use of the PV panels to cover only a part of the electricity demand.

The reason why the use of PV is preferred in this scenario to the use of solar collectors is that, even though the conversion efficiency of the PV modules is lower than that of solar collectors, PV modules provide an energy output (the electricity) whose cost and primary energy emissions are greater than those of the thermal energy provided by the solar collectors.

All this results in a great decrease (– 56%) in the primary energy consumption and in an increase of 45% in the annual cost.

Minimum emissions criterion

Finally, a system selection based on the environmental objective function gives the same result as a system selection based on the energy objective function, as expected. Fig. 11

8 Conclusions

An original modelling approach, based on the concept of the hybrid energy hub, has been developed and applied to a case study. To the Authors' knowledge no building systems modelling techniques exists that can consider variable design power of the energy converters and variable dispatch factors of the loads between the energy converters. In the model presented in this work, the power of the energy converters can assume any value as a result of the factors that represent the distribution of energy fluxes between the hub converters which can assume any value between 0 and 1. Some tools, such as the EnergyPlus system simulation manager, allow the capacity of an energy converter to be autosized, but this is done on the basis of a design day simulation, and not on the year-round energy, environmental and economic performance of the converters of the system.

One of the main features of the presented procedure is that it is convenient when there is a high number of converters and therefore the number of aggregations of converters worth being simulated dramatically increases.

The seasonal application that has been presented is quite simple and allows multi-energy system analyses to be performed in the presence of only design power and annual or seasonal energy demand data. Such a model meets the requirements of simplicity that characterize the design concept phase, even though a factor of uncertainty exists due to the choice of the efficiency values. The mean seasonal efficiencies greatly affect the results, and appropriate values of these properties are difficult to determine *a priori* and must be based on the experience of a consultant.

A first consideration can be made on the basis of the application: the solution is particularly sensitive to the boundary conditions and calculation assumptions, especially the costs, in the case of economic optimizations, and primary energy factors, in the case of energy optimizations. A second consideration, which is even more important than the first one, is that the outcomes of different optimization criteria vary considerably: in other words, the selection criteria are frequently in conflict. Different objective functions in fact lead to different results, especially economy versus energy or environmental objective functions: the selection of an energy objective function instead of an economy objective function can result in a completely different system lay-out and converter types (and not only sizes).

Further research studies are being carried out with the purpose of overcoming these drawbacks.

A first study is directed towards the assessment of the performance parameters of the energy converters that are most frequently used in buildings, in terms of design capacities, design efficiencies and seasonal efficiencies, in order to create a large database of performance parameter data. Economic parameters may also be introduced into this database.

A second study is directed towards a specification of the general coupling algorithm that is suitable for use in an hourly or bin method, where the variation of the part load efficiencies of the energy converters may be explicit and taken into account in detail.

A third study concerns the use of multi-criteria optimization algorithms in an attempt to reach a result even when the various selection criteria are in conflict.

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Figure Captions

Figure 1. Schematic of a generic hub

Figure 2. Relationships between types of analyses and energy hub forms

Figure 3. Scheme of the resolution process

Figure 4. Space heating load and cooling load profiles of the block of flats (Turin)

Figure 5. Space heating load and cooling load cumulative curves of the block of flats (Turin)

Figure 6. Monthly heating (space+DHW), cooling and electricity energy demand of the block of flats (Turin)

Figure 7. Schematic of the energy hub considered in the block of flats

Figure 8. Performance parameters for water-cooled liquid chiller packages (rating conditions according to the Eurovent certification programme, chilled water at 12/7 °C and condensing water at 30/35 °C) as a function of the heating/cooling capacity

Figure 9. Performance parameters for water-cooled liquid chiller packages (rating conditions according to the Eurovent certification programme, chilled water at 23/18 °C and condensing water at 30/35 °C) as a function of the heating/cooling capacity

Figure 10. Schematic of the energy hub converters selected as a function of the minimum cost: heating season (left), cooling season (right)

Figure 11. Schematic of the energy hub converters selected as a function of the minimum primary energy and emissions: heating season (left), cooling season (right)

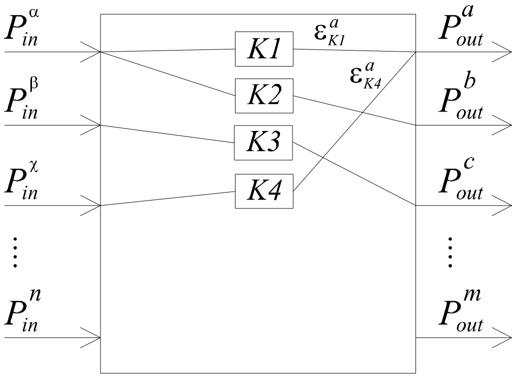

Figure 1. Schematic of a generic hub

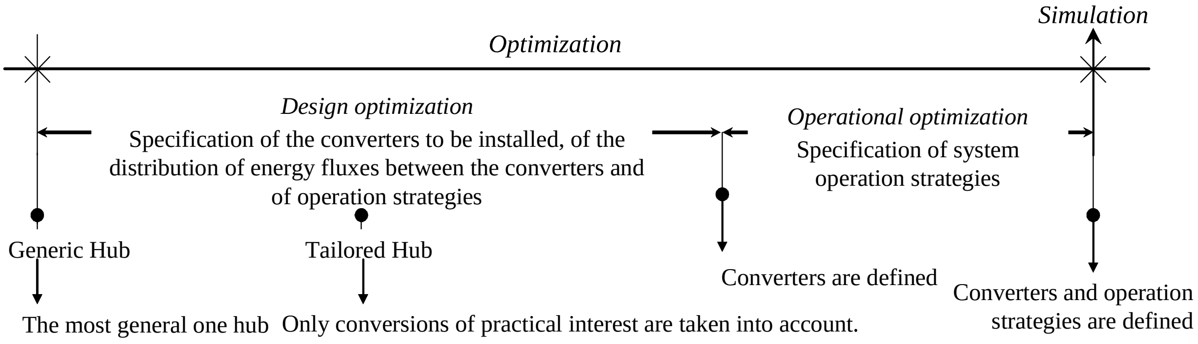

Figure 2. Relationships between types of analyses and energy hub forms

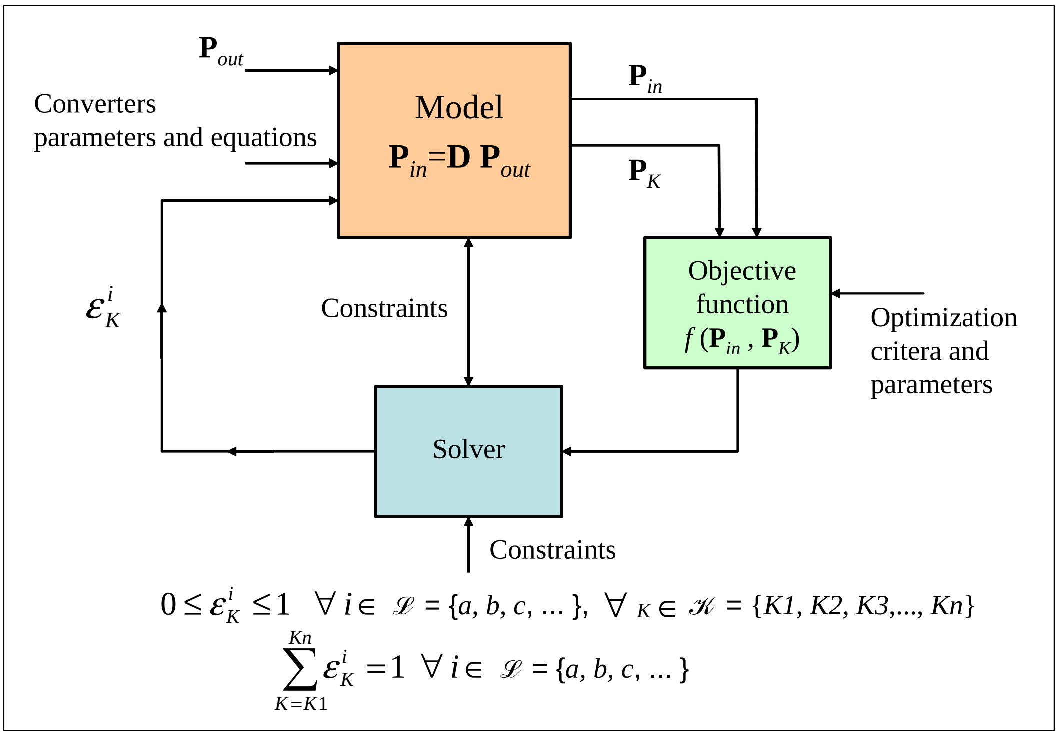

Figure 3. Scheme of the resolution process

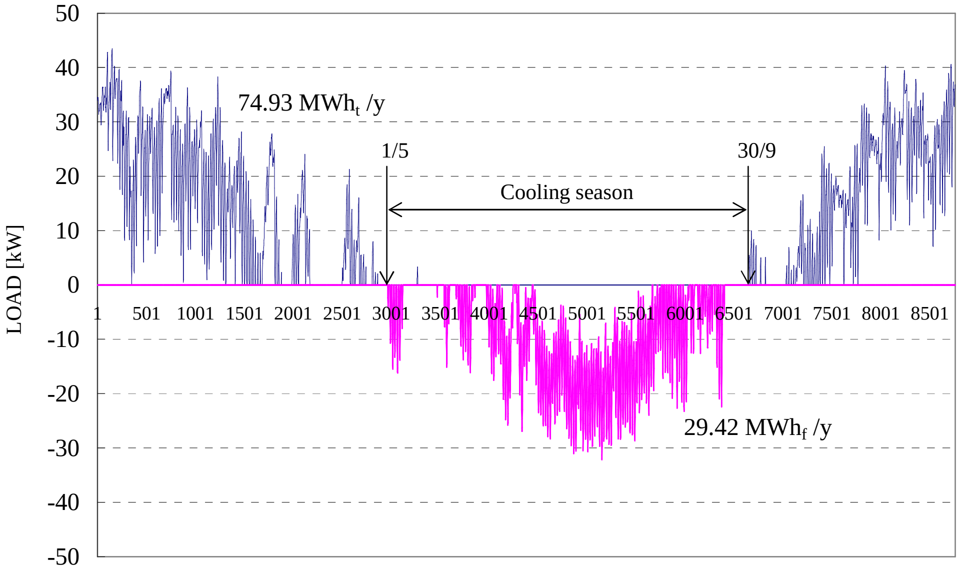

Figure 4. Space heating load and cooling load profiles of the block of flats (Turin)

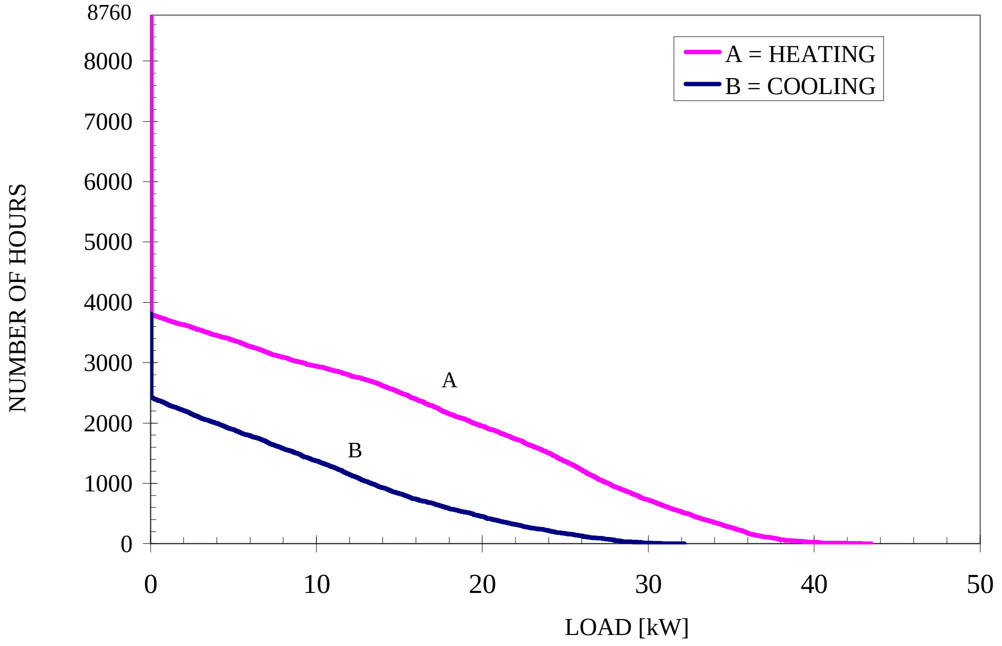

Figure 5. Space heating load and cooling loads cumulative curves of the block of flats (Turin)

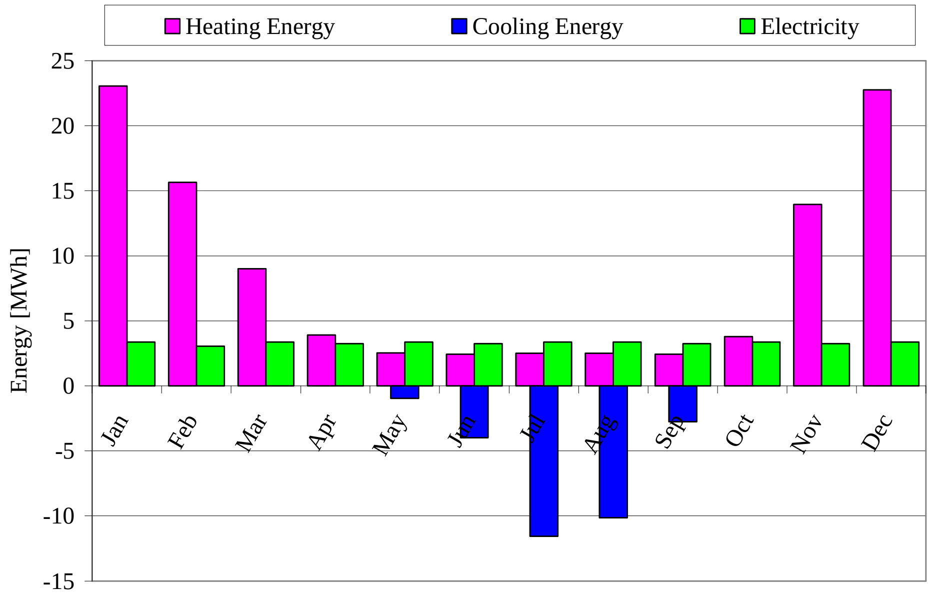

Figure 6. Monthly heating (space+DHW), cooling and electricity energy demand of the block of flats (Turin)

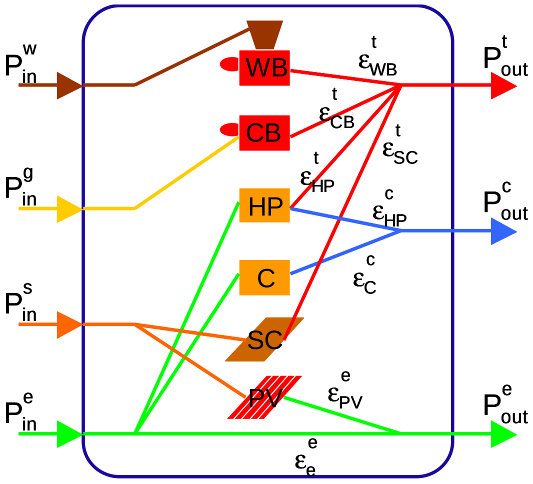

Figure 7. Schematic of the energy hub considered in the block of flats

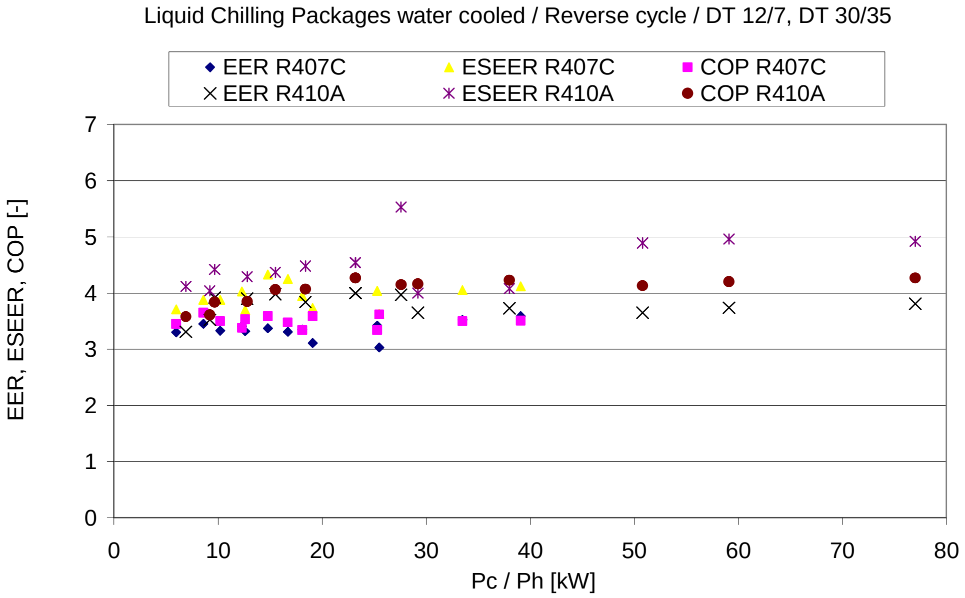

Figure 8. Performance parameters for water-cooled liquid chiller packages (rating conditions according to the Eurovent certification programme, chilled water at 12/7 °C and condensing water at 30/35 °C) as a function of the heating/cooling capacity

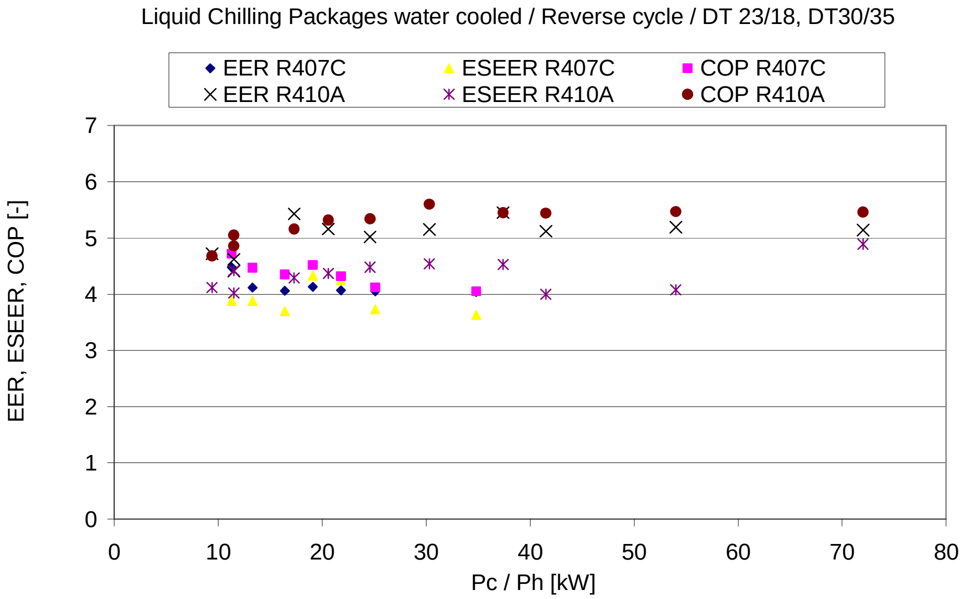

Figure 9. Performance parameters for water-cooled liquid chiller packages (rating conditions according to the Eurovent certification programme, chilled water at 23/18 °C and condensing water at 30/35 °C) as a function of the heating/cooling capacity

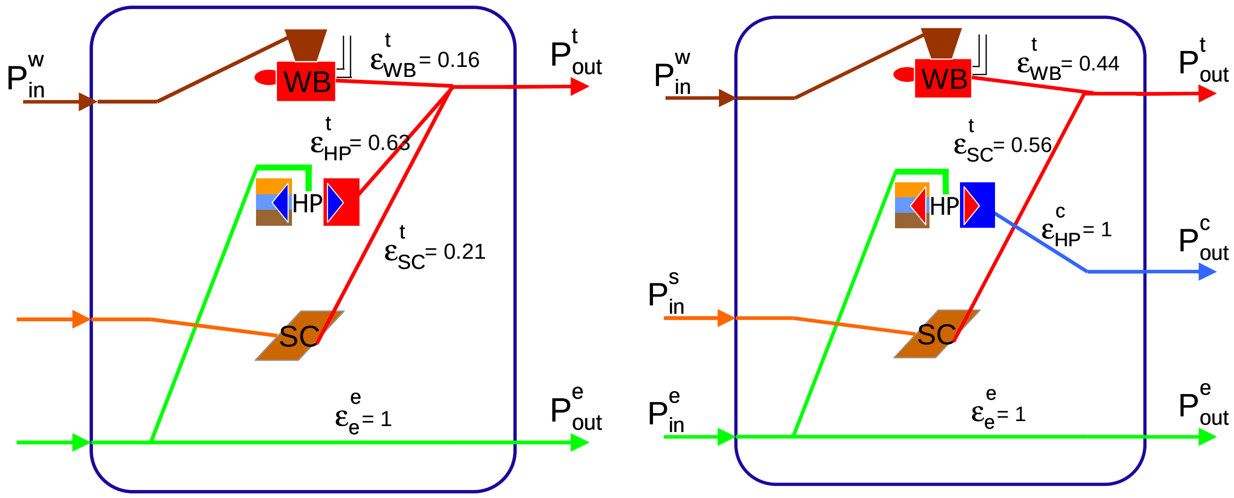

Figure 10. Schematics of the energy hub converters selected as a function of the minimum cost: heating season (left), cooling season (right)

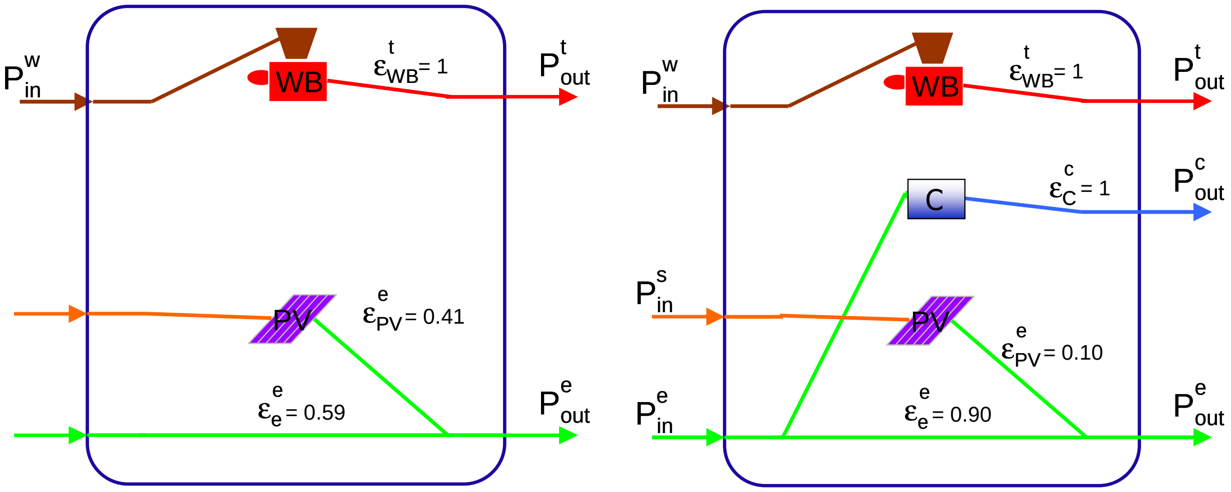

Figure 11. Schematics of the energy hub converters selected as a function of the minimum primary energy and emissions: heating season (left), cooling season (right)

Table 1 – The assessment of the building energy use in terms of peak loads and energy demands of the block of flats for the Torino location

Peak load [kW]	Design	Heating season	Cooling season
Space heating load	65.2	43.5	0
Cooling load	35.6	0	32.2
Electricity	30.0	30.0	30.0

Energy demand [MWh]	Annual	Heating season	Cooling season
Space heating energy	74.9 (61 $\mathrm{kWh_t/m^2}$)	74.9	0
DHW heating energy	29.5 (24 $\mathrm{kWh_t/m^2}$)	17.1	12.4
Cooling energy	29.4 (24 $\mathrm{kWh_f/m^2}$)	0	29.4
Electricity	39.60 (30 $\mathrm{kWh_e/m^2}$)	22.97	16.63

Table 2 – Design efficiencies and mean seasonal efficiencies of the heat pumps and chillers

Conversion efficiency	Design value [-]	Mean seasonal value [-]
η_{WB}	0.75	0.65
η_{CB}	1.05	0.90
COP_C	3.50	4.00
COP^t_{HP}	4.30	4.30
COP^f_{HP}	3.50	4.00
η_{PV}	0.15	0.15
η_{SC}	0.70	0.30

Table 3 – Specific investment costs and life times of energy converters of the hub

Converter	c^{K}	y^{K}	Converter	c^{K}	y^{K}
	[€/kW]	[y]		[€/kW]	[y]
WB	250	20	PV	6000	20
CB	100	15	SC	600	15
C	250	15	e	90	25
HP	250	15			

Table 4 – Values of factors ε that minimize the objective functions

Selection criteria	Heating season								Cooling season							
	heat				cool		electr.		heat				cool		electr.	
	WB	CB	HP	SC	C	HP	e	PV	WB	CB	HP	SC	C	HP	e	PV
Init guess	¼	¼	¼	¼	½	½	½	½	¼	¼	¼	¼	½	½	½	½
Economy	.16	0	.63	.21	-	-	1	0	.45	0	0	.56	0	1	1	0
Energy	1	0	0	0	-	-	.59	.41	1	0	0	0	1	0	.10	.90
Environ.	1	0	0	0	-	-	.59	.41	1	0	0	0	1	0	.10	.90

Table 5 – Values of the objective functions for the scenarios of Table 4

Selection criteria	Value of the economy objective function [k€/y]	Value of the energy objective function [MWh/y]	Value of the environmental objective function [t_{CO2}/y]
Initial guess	14.12	133.98	23.92
Economy	11.55	169.13	28.29
Energy	16.95	73.63	12.81
Environmental	16.95	73.63	12.81