This is the accepted manuscript of the article that appeared in final form in **Sustainable Energy Technologies and Assessments** 27 : 119-133 (2018), which has been published in final form at https://doi.org/10.1016/j.seta.2018.04.004. © 2018 Elsevier under CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/)

A symbolic exergoeconomic study of a retrofitted heating and DHW facility

Ana Picallo-Perez*, José M. Sala-Lizarraga, Eider Iribar-Solabarrieta, Juan M. Hidalgo-Betanzos

Research Group ENEDI, Department of Thermal Engineering, University of the Basque Country (UPV/EHU), Alameda Urquijo, S/N, 48013 Bilbao, Vizcaya, Spain

Keywords:

Symbolic Thermoeconomics

Cost formation

Dynamic analysis

Retrofitted facility

ABSTRACT

Thermoeconomic analysis of building energy supply systems are usually performed following the input-output approach, where the supply chain is divided into several subsystems directly related to each other. However, in this paper Symbolic Thermoeconomics has been applied and a dynamic analysis and comparison has been performed between the old and the retrofitted heating and DHW facility of four dwelling blocks located in Bilbao.

Having obtained the heating and DHW demands, the corresponding exergy demands were calculated, both by the simplified and detailed method. Once the productive structure is defined, Symbolic Thermoeconomics is applied. The exergy analysis shows the improvement achieved with retrofitting, going from a 2.55% yearly average exergy efficiency of the old facility to a 4.01% value for the retrofitted.

Then, exergy costs and exergoeconomic costs of the products of each component, particularly the costs of the final products, heating and DHW, are expressed as the amount of external resources required for obtaining them, either in energy or monetary units. As a result, those costs not including the investment costs, are reduced 32.71% for heating and 48.5% for DHW.

Applying a general and rigorous mathematical approach, the thermodynamic nature of costs and their formation process are analysed.

Introduction

Energy analysis in buildings

One of the current main objectives of the European Union is focused on primary energy conservation and the reduction of CO2 emissions, as a consequence of the enduring climate change the world is undergoing. Buildings are responsible for almost 40% of the final energy use in the EU and for 30% of the CO2 emissions in the atmosphere [1], while in Spain, the built environment accounts for 28% of the final energy consumption (18% in dwellings and 10% in tertiary sector buildings) [2].

Therefore, the building sector plays an important role in the total energy consumption and many specialists are working for the im- provement of buildings energetic efficiency. In recent years, great ad- vances have been made in the application of new materials, new façades and roofs and big improvements have been achieved in the energy supply systems; particularly with the integration of renewable energies in the hybrid installations. Nowadays, the aim is to set up nearly zero energy buildings nZEB, which is the first step towards po- sitive energy buildings. That topic has received increasing attention in recent years, until becoming part of the energy policy in several countries [3].

So far, current analyses of energy systems in the built environment are based on the first law of thermodynamics, i.e. they are performed according to the energy efficiencies and based on the primary energy input and CO2 emissions, as in [4]; nevertheless, those analyses do not consider the different qualities of the energies and they only assume as losses those flows of energy which are not used, generally heat flows, without considering the irreversibilities related to equipment im- perfections as additional loss. The quality of energy is given by a combined analysis of the first and second law of thermodynamics; these combined analyses allow deriving the thermodynamic concept of ex- ergy. The exergy aspects of building systems are deeply explained in [5].

Exergy analysis in buildings

Concerning thermal facilities, a significant difference exists between the quality of the energy used for generation, as for example, in a natural gas boiler and the heating and DHW demand, where the aim is to heat a room at about 21 °C or generate domestic hot water at 60 °C. Then, high quality energy is used for producing low temperature thermal energy and, therefore, low quality energy. This situation is clearly exposed when exergy analysis is used [6], because exergy losses clearly pinpoint the locations, causes and sources of deviations from ideal circumstances; moreover, the exergy efficiencies measure the approach to the ideal standard. In such a way, the implementation of a low-exergy building system can be performed [7].

Thermoeconomic analysis in buildings

Most analysts agree that exergy is an adequate thermodynamic property which allocates cost because it accounts for energy quality. There are several exergy based-methods [8] and that which follows the goal of improving energy efficiency, reducing the environmental impact and enhances sustainability for the building energy analysis is Ther- moeconomics. This is the science which connects the physics of buildings with the economy through the second law of thermodynamics [9]. Thermoeconomics suggests that the only rational basis for calculating costs is exergy. Assessing the cost of the flow streams in a plant helps to understand the process of cost formation, from the input resources to the final products.

Even though Thermoeconomics has been widely used on an in- dustrial level [10], it has been less frequently used in the building en- vironment. There are several reasons for this, such as the fact that the energy flows are much lower than those of thermal power plants or those of many industrial processes. In addition, the analysis uses many concepts and definitions that originated in the electrical power and chemical industries, and then, a procedure is required to establish the applicability of those concepts to the built environment. What is more, thermal levels are so low that the choice of environmental conditions can significantly impact the exergy values [11]. However, work based on building systems exergetic performance are rapidly increasing [12–14].

Symbolic thermoeconomic analysis in buildings

Symbolic Thermoeconomics (ST) is a methodology for the analysis of the productive structure and the natural resources consumption in energy systems. Based on the Exergy Cost Theory (ECT), it allows obtaining general equations, which relate the overall efficiency of an energy system and other thermoeconomic variables such as fuel, exergy cost, etc., with the efficiency of each component which forms it. By bringing together ECT and Symbolic Computation (using symbolic computation packages, like Mathematica or Matlab) it is possible to obtain general formulae of any energy system. Examples of ST appli- cation can be found as in the case of the control strategies study of an airport HVAC system in [15] or the analysis of co-generation with gas expansion system [16].

Building dynamic case study

The research in dynamic exergy or exergoeconomic analyses is limited. This paper deals with the energetic, exergetic and thermo- economic comparison of an old facility and the new retrofitted one of four residential blocks in Bilbao (north of Spain) over a typical me- teorological year. Instead of using the usual input-output approach which is suitable for sequential systems, in this paper we make use of ST which allows taking into account the different fictitious junction and branching points that can appear in any functional diagram of facilities.

The paper is organized in six different sections as follows. Section "Energy, exergy and thermoeconomics in buildings" briefly reviews the heating and DHW demands in buildings, goes over the associated ex- ergy demands and refers to ST applied in buildings. Section "Case Study" presents the characteristics of four dwelling building blocks to be simulated by the dynamic simulation software Trnsys v17. This Section "Case Study" also portrays the characteristic of the heating and DHW installation, the old and the retrofitted one, as well as their control systems. In Section "Results and discussion", the conventional energy results obtained through simulation are shown and the exergy results are also displayed and compared with the energy values. In Section "Symbolic thermoeconomic study" the economic costs of the flows are obtained and the exergy costs of the irreversibilities are evaluated and discussed. Finally, the main contributions and discussion of the paper are summarized in Section "Conclusions & discussion".

Energy, exergy and thermoeconomics in buildings

Heating and DHW demands

The heating energy demand is calculated in this work following the ISO 13,790 (2008). According to this, the demand is based on the building characteristics, the local climate and the users' patterns. In this way, the heating demand results from the imbalance between energy losses (transmission, ventilation and infiltration) and energy gains (solar gains and internal gains) as follows:

$$Qheat = Qlosses - Qgains \quad (1)$$

This balance is accomplished in every building zone and gathered afterwards for the whole building demand calculation. The balance of those thermal zones includes flows of heat and matter, such as ventilation and infiltration, but neither humidification nor dehumidification is regarded.

The energy demand for DHW supply is evaluated as a function of the required set-point temperature for DHW use and the demanded mass flow.

For an efficient use of energy in buildings, the energetic needs may be covered by using the least amount of primary energy as possible. For that, the various existing energy quality levels must be taken into ac- count in order to use them appropriately, such as high-quality energy as electricity for lighting and electrical appliances or low-quality energy as waste heat for space heating and cooling. High-valuated energy sources may be used to cover high-valued energy demands and vice versa. This is pointed out through the exergetic analysis of buildings.

Heating and DHW exergy demands

Although the exergetic analysis is less common than the energetic one, authors who apply the exergetic point of view in the building sector are increasingly growing. A thorough literature review on exergy analysis in buildings is found in [17].

Several studies using air source ground source heat pumps can be found [18,19] as well as publications referring to solar thermal col- lectors [20]. Likewise, work analysing the exergetic performance and implementing it in simulation methodologies have been published, as in the case of a hospital trigeneration system in [21].

The exergy demand for heating is calculated on the basis of the heating energy demand and can be defined as the exergy content of this energy, i.e. the minimum amount of work needed to provide the energy demand for heating. In similar terms we define the exergy demand for DHW.

There are two methods for calculating the heating exergy demand: the simplified method, which is mostly used, as in [17], and the de tailed exergy demand calculation method. Both of them are extensively described in Annex 49 [22]. Likewise, in the case of energy, the exergy demand for DHW is evaluated as a function of the required set point temperature and the demanded mass flow, when using the appropriate equation.

One of the aims of this paper is to show the improvement in the energy and exergy performance of the whole energy supply chain in a retrofitted heating and DHW facility, considering both the static en velope demand and the dynamic facility of the building. Then, energy and exergy analysis are performed following the first and the second law of Thermodynamics. This approach is applied considering a dynamic analysis, so that once the general equations are obtained they can be applied to each state of the facility.

Symbolic thermoeconomics

The other aim of this paper, and probably the more significant one, is to compare the costs of heating and DHW and of all the intermediate flows in the old and the retrofitted facility.

Thermoeconomics generic overview

Cost accounting consists of procedures for estimating the total cost of production per unit of output in a thermal system. The various methodologies are based on cost allocation rules and calculate costs in an accurate way; unfortunately, they lack a mathematical structure, plus it is not easy to identify the process of cost formation. In order to overcome this challenge, general relationships that relate the cost of the products with efficiency and irreversibilities of each component are required. In this regard, ST, based on the Exergy Cost Theory, provides a rigorous mathematical approach of the process of cost formation.

Thermoeconomics [23] has been applied to the analysis and design of different building energy supply systems and heating and cooling systems, as in refrigeration [24]; in ground-source heat pump systems [25]; in systems containing energy storage [13]; and also in system diagnosis such as in [26–28]. In addition to these, Thermoeconomics has also been integrated into building energy retrofit design, as in the

case of [29]. Nevertheless, in most of these publications the input output approach is used whereas in this paper the use of ST is proposed.

Notwithstanding the lack of ST implementation, there are some papers dealing with it in building energy system refurbishment: as it is the case of [30], where thermoeconomic is used in order to study the waste heat retrofitting cost impact in the renovation of a natural-gas cogeneration system. In this case, the reasonable evaluation for the allocation of residue cost is proposed; whereas [31] presents an in dicator that is presented in order to compare different building energy retrofit designs and determines the one which has the best exergetic and exergoeconomic performance.

ST generalities: Productive structure

When performing a thermoeconomic analysis, a functional model of the facility needs to be defined. From the physical model of the facility this implies defining a productive structure, or Fuel/Product diagram, which shows where the product of each component is used and the origin of the resources of each component. In accordance with this model the production of one component is used as fuel for another component or as part of the total production of the facility.

In this case, the resources required by the system in order to supply the demand for heating and DHW are to be obtained. Those inputs vary depending on the plant structure, which is described through the junction coefficients, the exergetic consumption of each unit and the final output production. This formulation is known as PF or the demand-driven model. If the objective is the opposite, that is, if the goal is to assess the output production depending on a specific entrance of resources, the formulation should be named FP or supply driven model. This, con versely, is described through the distribution coefficients, the exergetic consumption of each component and the input resources consumption [32].

ST study: Exergetic cost

Once the productive structure of the facility is specified, as in sightfully explained in [32], the unit exergy costs of fuels and products, kf and kp , of every component can be calculated. Both exergy costs are associated with the cost of external resources, ke , and the matrix operators |kf ⟩ and |kp ⟩ (which, in turn, contain the marginal exergy consumption of each component κij) through the equations:

$$\mathbf{k}_F^* = |\mathbf{k}_F^*\rangle \cdot \mathbf{k}_e^*$$

$$\mathbf{k}_P^* = |\mathbf{k}_P^*\rangle \cdot \mathbf{k}_e^*$$

(2) and (3)

ST study: Exergoeconomic cost

Likewise, the exergoeconomic costs of fuels and products, c Fi and c Pi , can be related to the unit exergetic costs of the external resources, cei, by using the |k∗ ⟩ and |k∗ ⟩ matrix operators and also the zfi and zpi vectors which stand for the amortization, maintenance and other operating costs of the ith unit, per unit of fuel i or product i respectively [32]:

$$\mathbf{c}_F = |\mathbf{k}_F^*\rangle \cdot \mathbf{c}_e + (|\mathbf{k}_F^*\rangle - \mathbf{U}_D) \cdot \mathbf{z}_F$$

$$\mathbf{c}_P = |\mathbf{k}_P^* \cdot \mathbf{c}_e + (|\mathbf{k}_F^*\rangle - \mathbf{U}_D) \cdot \mathbf{z}_P$$

(4) and (5)

ST study: Total cost

Then, the final costs of fuels and products are easily obtained by multiplying the unit exergoeconomic costs with its corresponding ex ergy of fuels or products as follows:

$$\mathbf{C}_F = \mathrm{diag}(\mathbf{c}_F) \cdot \mathbf{F}$$

$$\mathbf{C}_P = \mathrm{diag}(\mathbf{c}_P) \cdot \mathbf{P}$$

(6) and (7)

Hence, thanks to this formulation, the increase of the flow costs during energy conversions can be easily observed.

As a result of the versatility of ST, the cost formation accuracy raises as the number of the facility's subsystems increases. That is, with a more detailed definition of the subsystems, a greater understanding for the cost formation process is achieved.

To sum up, the extra insight over basic Thermoeconomics, and also the main objective of the ST methodology, is the obtainment of a cost formation process. Thanks to this tool, the interrelation between com ponents, based on the productive structure of the system, is symboli cally displayed. This way it can be easily seen how the whole plant efficiency changes when the efficiency of any component varies. As ST is joined together with ECT, the change in cost can also be checked when a parameter varies [32]. So, one objective of this work is to analyse how the cost varies from an old facility to the renovated one.

Case study

The case study refers to four dwelling blocks with a common heating and DHW supply system. Those blocks located in northern Spain, Bilbao, were built in the 70 s; one block (I) has 190 residents, two of them (identified as II and III) have 108 residents each and the fourth one (block IV) has 160, see Fig. 1. The energy supply system has been recently retrofitted and the boilers and circulating pumps have been removed as is explained later on.

Building's general description

The four buildings have the same structural characteristics, see Table 1.

The energy performance of the buildings has been analysed by means of the dynamic simulation tool Trnsys v17 [33]. The building model is based on the multi-zone building component with energy balance in each zone; all the architectural properties and thermal characteristics of materials can be faithfully represented. More details can be found in the Trnsys User Manual where a mathematical de scription of the models and the energy balances are presented.

The weather data has been introduced on an hourly basis in the simulation so the heating demand is also calculated hourly. Bilbao's weather data was taken from METEONORM software [34] which pro vides the yearly data based on the last 30 years of weather data averages. To define the simulation condition (ventilation, infiltrations and thermal gains), the values of Appendix C of the Technical Building Code HE1 have been adopted [35]. A 20 °C thermal comfort tempera ture has been considered and the night setback is regarded from 11p.m. to 6 a.m. allowing a temperature drop of 4 °C during those hours. The heating timetable is from November 1st up to April 30th and the heating is turned on when the outside temperature is below 15 °C, or when the average temperature of the last eighteen hours is less than 15 °C.

DHWcalc tool [36] has been used for the calculation of the DHW [l/ h] demand. The program distributes DHW draw-offs throughout the year by statistical means. Thus, considering the number of dwellings in every block and therefore the number of inhabitants, the DHW demand profile for an entire year has been hourly extracted, being the DHW provided at 55 °C. Fig. A.1 represents the annual demand for heating and DHW.

Fig. 1. Four blocks case study.

Table 1. Structural characteristics for the blocks.

Structural Characteristics		
Group	Description	Transmittance
Façades	Double brick walls with no insulation	1.68 W/m^2K
Flat roof	Treated with thermal insulation & protected with waterproof cement mortar	1.51 W/m^2K
Windows	Original outside frames were wooden made & windows were monolithic. Over time some were replaced with better thermal performance ones	2.89 W/m^2K

Building thermal facility

Driven by current building regulations, building energy retrofit is largely reliant on maximizing thermal efficiency of the building's en velope before heating system improvements are introduced. In spite of this, due to the problems of the old heating installation and the lack of resources, the neighbourhood community decided to proceed with the heating installation improvements first. For this reason, the heating and DHW demands remained the same, due to the fact that the buildings had only a retrofitted energy supply system.

① There were three fuel oil boilers in the old facility, two 2325 kW boilers and one of 1162 kW. Those boilers have been replaced with natural gas boilers, two low-temperature boilers of 1900 kW each and a 1150 kW condensing boiler ② provided with a heat recovery heat exchanger that condenses the combustion exhaust gases.

The hydraulic circuit of both facilities, the old and the retrofitted one, is the same. The boilers are connected to the distribution circuit by means of a hydraulic collector whose aim is to separate the heating and the DHW circuits. The heating distribution is branched into four hy draulic circuits, one for covering the heating demand of each block. The DHW distribution is split into two branches: one goes to the lower floors and the other one supplies the DHW demand to the higher floors. Likewise, the lower floor's circuit contains two 3500 l storage tanks and the higher floors have one 4000 l storage tank.

③ The circulating pumps in the old circuit were constant flow pumps while the new ones are variable speed pumps. This means that the old heating circuit branches were provided with 3-way valves in order to match the heating temperature to the requested set-point. The retro fitted facility takes advantage of the new pumps variability so the 3-way valves are avoided.

The various components appearing in the study case are simulated using adapted models available from the Trnsys library. Fig. 2 depicts the new facility where, additionally, the renovations are highlighted with purple dotted circles, besides Table 2 summarizes the enhance ments from the old one, see also Fig. B.1 where the old facility scheme is depicted.

The master control of the facility can be outlined as follows: DHW takes precedence over heating and DHW is enabled over the whole year whilst heating is turned on during the heating period. The storage tanks are continuously monitored to be at a temperature beyond 60 °C in order to avoid legionella. If during the heating season the temperature in the collector is lower than 60 °C, the boilers are switched on fol lowing a cascade control.

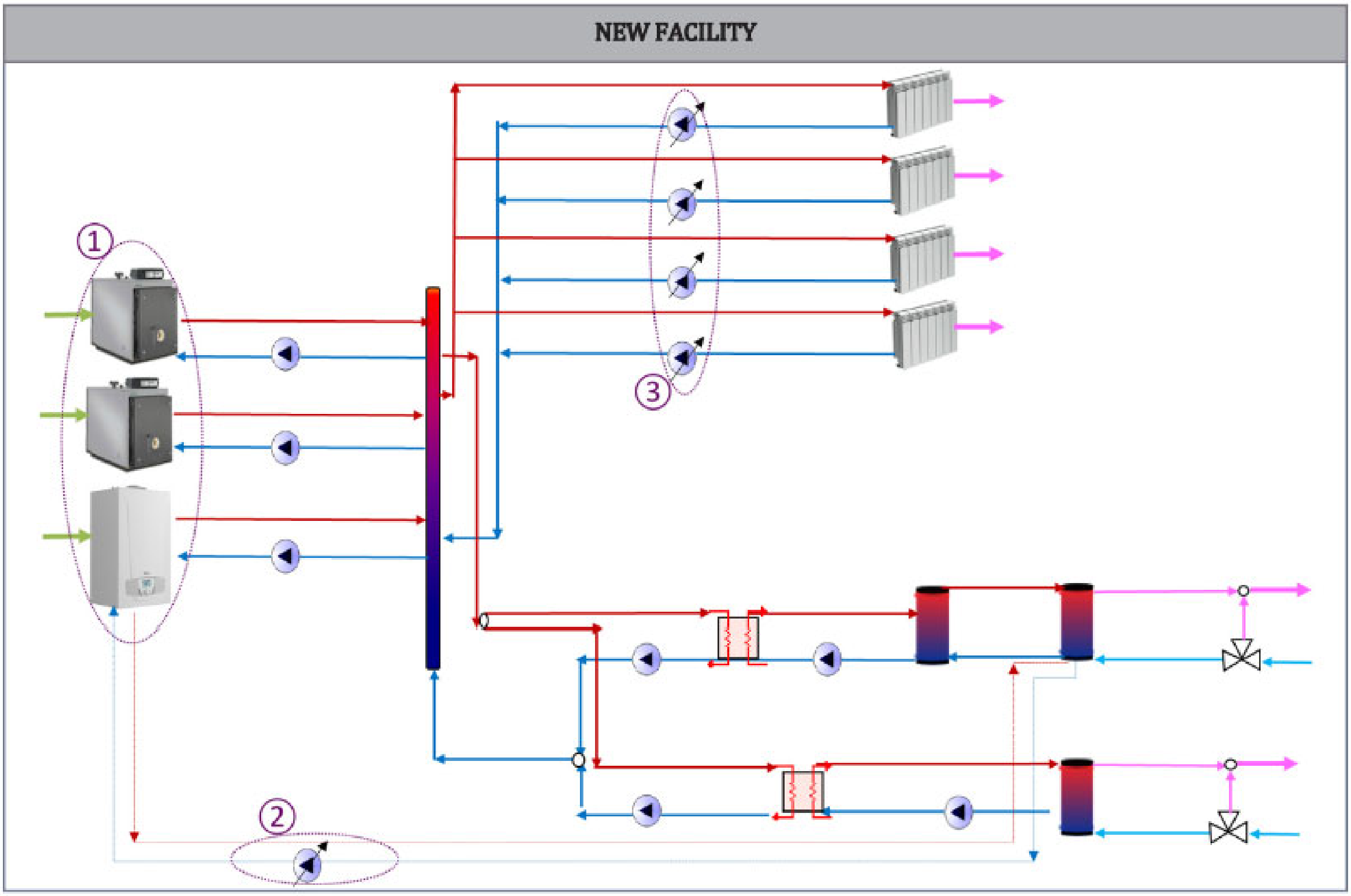


Fig. 2. Scheme of the New facility. Renovations are highlighted with purple circles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2. Summary of the renovations.

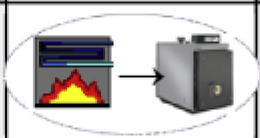
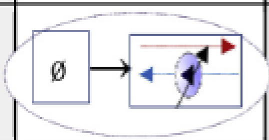
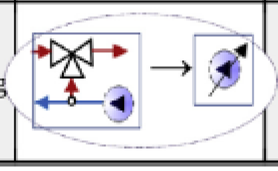
	RENOVATIONS IN THE FACILITY		
	OLD		NEW
①	Fuel Oil boilers		Gas Natura Boilers
②	Ø		Heat Recovery HX
③	Constant flow pumps for heating + V3V		Variable speed pumps

Table 3. Subsystems of the new facility.

Facility's common groups			
Group	Description	Group	Description
B1	Boiler 1 + Boiler Pump 1	T1	Tank 1 + low DHW Pump 6
B2	Boiler 2 + Boiler Pump 2	T2	Tank 2+ (recovery Pump 7)
B3	Boiler 3 + Boiler Pump 3	T3	Tank 3 + high DHW Pump 8
C	Collector	DHW L	DHW in low floors
H1 br.	Heating branch Distrib. I	DHW H	DHW in high floors
H2 br.	Heating branch Distrib. II	H1	Emission system of Block I + BI Pump 9
H3 br.	Heating branch Distrib. III	H2	Emission system of Block II + BII Pump 10
H4 br.	Heating branch Distrib. IV	H3	Emission system of Block III + BIII Pump 11
HX1	Low HX + low HX Pump 4	H4	Emission system of Block IV + BIV Pump 12
HX2	High HX + high HX Pump 5		

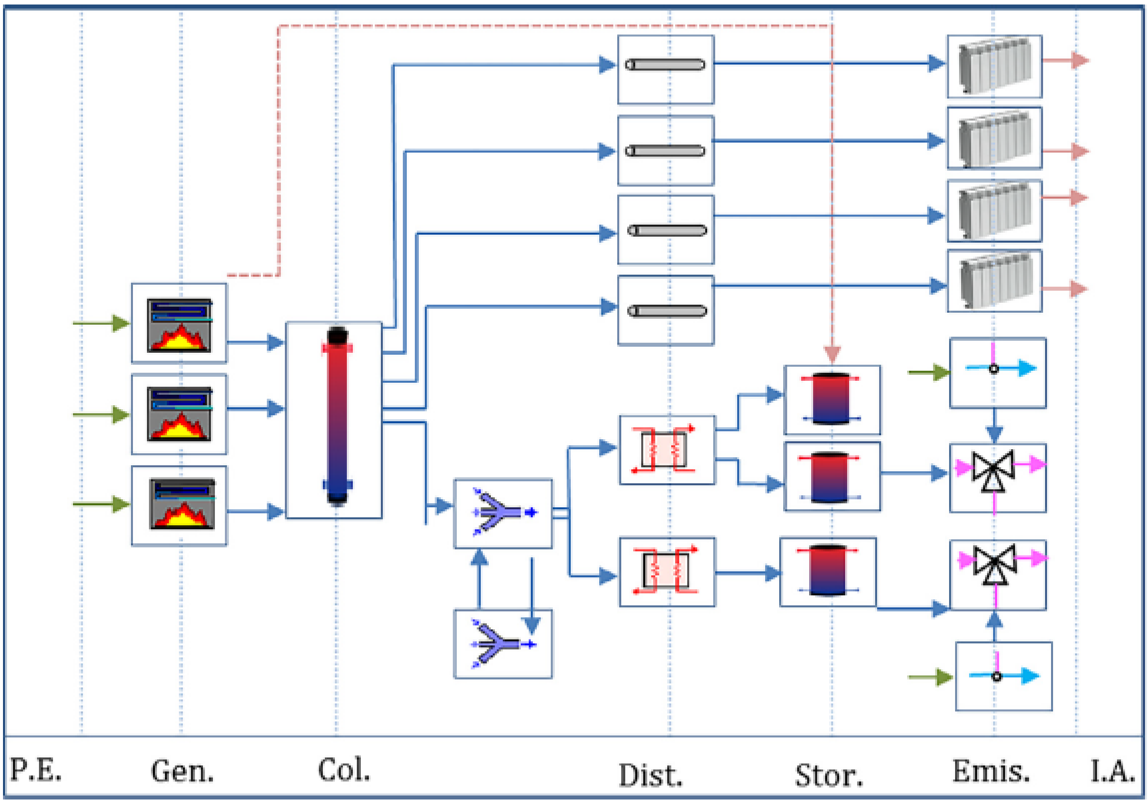


Fig. 3. Productive model of both facilities.

ST generalities: Productive structure

As previously mentioned, the accuracy of the cost formation process directly depends on the chosen productive structure. This case study deals with two facilities so that different productive structures are de fined for the old and the retrofitted facility.

The old facility is specified by 27 subsystems, 70 flows and 7 out puts (4 heating outlets and 2 DHW exits, see Fig. B.1 where the flows and component are represented) whereas the new facility contains 20 subsystems, 62 flows and 7 outputs.

Although having different symbolic structures, the subsystems were later combined into specific groups in order to make the comparison between both facilities clearer. The list of the particular groups used for both analyses is given in Table 3 where a key naming and a brief de scription of each component are represented.

The conventional energy transformation phases in a building facility are graphically depicted in Fig. 4. As can be seen, it is divided into the following layers: Primary Energy (P.E.); Heat Generation (Gen.); Col lector (Col.); Heat Distribution and DHW Primary Circuit (Dist.); Heat Distribution and DHW Storage System (Stor.); Heating Emission and DHW Supply (Emis.); Room Air (R.A.) and Envelop (Env.).

The generically grouped productive model common for both facil ities is graphically depicted in Fig. 3. The red arrows highlight the system production that goes to the R.A. while the green arrows re present the incoming resources, i.e. combustibles for boilers (continued lines), electricity input for pumps (dotted lines) and cold water for DHW circuit (grated lines). Additionally, there is also a dotted red arrow that represents the extra input coming from the condensing boiler recovery system of the new facility. As can be seen, a simple input-output analysis typical for a sequential system could be used for everything except for the 3-way valves in the old facility and the DHW storage system in the new one.

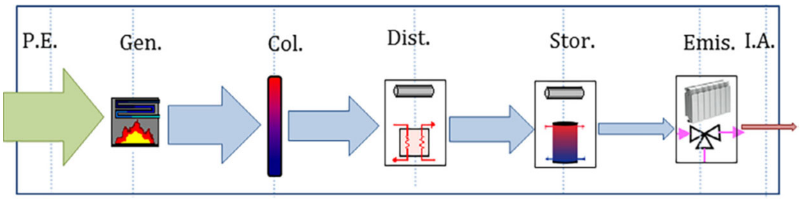


Fig. 4. Common transformation phases in a building facility.

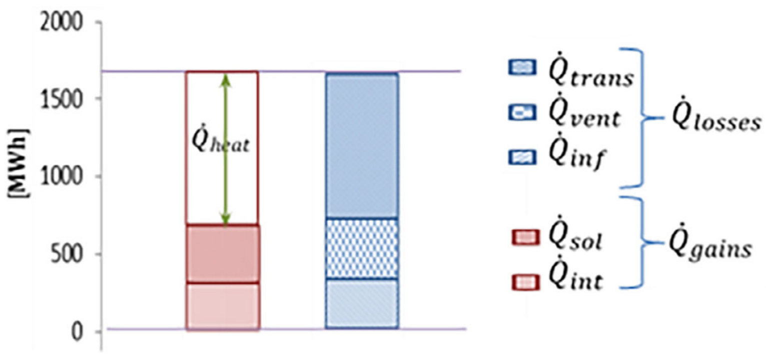


Fig. 5. Energy balance.

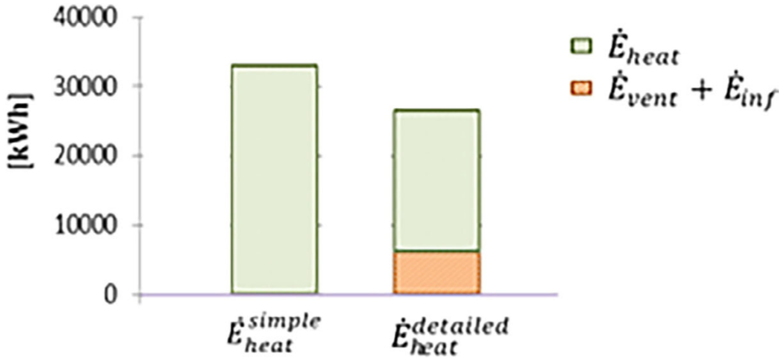


Fig. 6. Exergy balance.

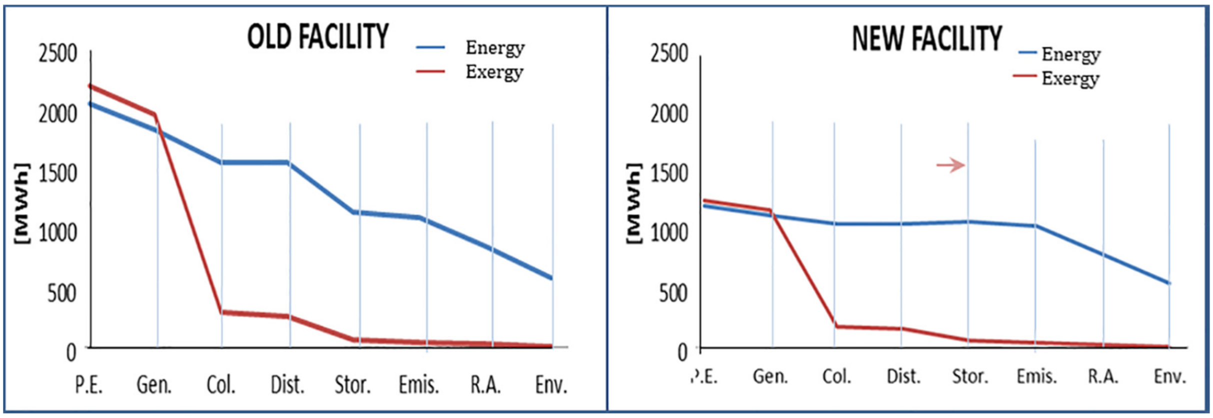


Fig. 7. Energy and exergy flow diagram in the old and the new facility.

Results and discussion

Heating and DHW demands

Heating demand is obtained using Trnsys v17 simulation software with a 1 h time-step and follows a typical profile of Northern Spain dwellings [37]. As already mentioned, DHWcalc tool has been used for the DHW calculation. Both demands are hourly stored to be im plemented in the simulation of both heating supply systems.

The yearly energy balance is depicted in Fig. 5. Losses, represented in the right column, are heat transfer from the building envelope, Qtrans (965MWh); sensible heat losses from ventilation air, Qvent (410MWh), and losses owed to uncontrolled flow of air through cracks in the building Qinf (332MWh). Conversely, the gains are due to solar gains Qsol (386MWh) and internal gains Qint (312MWh) and are depicted in the left blue part of Fig. 5. Additionally, the vertical green arrow stands for the required yearly heating demand (1,009MWh).

Once the heating demand has been calculated, the exergy demand, Eheat , is obtained according to the simplified and the detailed approach. The results obtained by both methods are shown in Fig. 6. As re commended in [22] the surrounding outdoor air has being taken as the reference environment.

The yearly exergy demand obtained by the detailed approach (26,804kWh) is significantly lower than the value obtained by the sim plified approach (33,074kWh). This is explained as ventilation and in filtration losses are larger than the net heat demand, due to solar and internal gains, and as a result, ventilation air does not need to be pre heated to the interior temperature but to a lower temperature that varies according to each hourly thermodynamic characteristic.

Besides that, as justified in [22], the closer the operative tempera ture Top is to the environment's temperature the bigger the difference is between the simplified and detailed approach. Consequently, the de tailed method is applied from now on in the study.

In Table 4 the yearly heating and DHW demands in energy and exergy terms are presented. As shown in energy terms, DHW represents 28.1% of the heating demand, whereas in exergy terms that percentage increases to 69.2%.

Table 4. Yearly energy and exergy DHW and heating demands.

	Demand [*MWh/year*]	
	DHW	Heating
Energy	284	1009
Exergy	18	26

Energy and exergy analysis of both facilities

The two facilities have been simulated during a year with a 0.5 h time-step, according to the demand calculated in the previous section, QD = Qheat + QDHW . Those simulations enable the gathering of the thermodynamic parameters needed to calculate the energy and exergy of all flows.

The study has been dynamically processed and afterwards the an nual values were accumulated. Owing to the huge number of data, only the hourly energetic and exergetic study corresponding to the 5th of February has been depicted in Figs. C.1 and C.2 following the same layer structure as the rest of the graphics.

In Table 5A), the annual energy and exergy values of primary re source input, the energy and exergy inputs and outputs and the effi ciencies of the main sections as well as the constituent components are displayed for the old facility, whereas in Table 5B) those values refer to the new facility. Both Tables are subdivided in the layers represented in Fig. 4, and the red box reflects the extra input coming from the con densing boiler recovery system. The coefficients used to obtain the primary energy are 1.12 for fuel oil and 1.07 for natural gas, whereas the quality coefficients are 1.07 and 1.04 respectively.

Likewise, Fig. 7 has been built in order to pictorially summarize all the information. This is an overview which allows both the comparison between energy and the exergy conversions and the distinctiveness among the old and the new facility. These graphs are divided into the same layers as the above tables and Fig. 4.

By contrasting the energy behaviour of the old and the new facility the following can be concluded:

- A 35% primary energy savings has been reached with the refurb ishment, not only because the natural gas has replaced the fuel oil, but also because the new boilers have a better energy performance. Moreover, contrary to the oversized old facility, where the second boiler was always turned off, the three boilers now intervene in heat production (see P.E. row in Tables).
- In the heat distribution system, higher losses appear in the old facility (see their Dist. Heat performance in Table 5A)). This is because 3-way valves are modulating when following the demand, instead of the variable flow pumps which are in the new facility.
- The DHW tank's performance is also enhanced due to the extra heat inserted by the HR (see red box in Table 5B) and red arrow in Fig. 7).

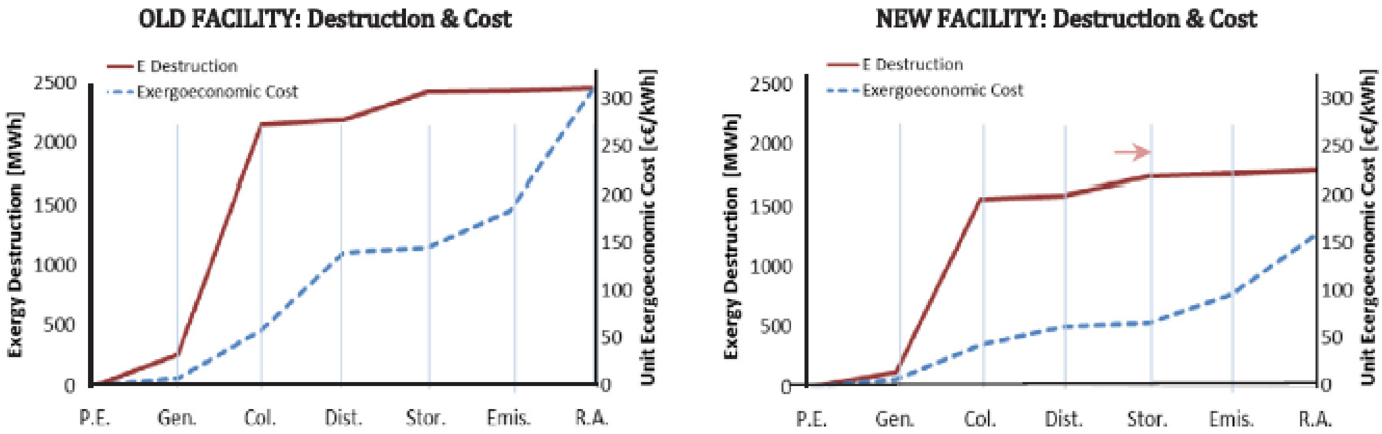


Fig. 8. Exergy destruction and unit exergoeconomic cost in the old and new facility.

Table 5. Annual energy and exergy values of the old A) and new facility B).

		(A) OLD FACILITY					
		ENERGY [kWh]			EXERGY [kWh]		
		Q_{out}	Q_{in}	η %	E_{out}	E_{in}	ψ %
P.E.	B1	2108	2361	-	2255	2526	-
	B2	-	-	-	0	0	-
	B3	89	99	-	95	106	-
Gen.	B1	1791	2108	85	334	2255	15
	B2	-	-	-	0	0	-
	B3	75	89	85	13	95	14
Col.	C	1858	1867	100	313	347	90
Dist. Heat	H1 br.	398	581	68	16	96	16
	H2 br.	142	205	69	6	34	16
	H3 br.	122	206	59	5	34	14
	H4 br.	408	546	75	16	90	18
Dist. DHW	HX1	185	185	100	26	33	80
	HX2	134	134	100	23	26	90
Stor.	T1+T2	166	185	90	14	624	2
	T3	125	134	93	12	23	52
Emis. Heat	H1	386	398	95	13	16	80
	H2	135	142	95	4	6	77
	H3	116	122	95	4	5	78
	H4	388	408	95	13	16	79
Emis. DHW	DHW L	164	166	99	10	14	74
	DHW H	120	125	97	8	12	64
R.A.	Block I	386	386	100	10	13	83
	Block II	129	135	96	3	4	76
	Block III	111	116	95	3	4	74
	Block IV	383	388	99	10	13	83
Env.	Heat	698	1009	69	0	27	-

		(B) NEW FACILITY					
		ENERGY [kWh]			EXERGY [kWh]		
		Q_{out}	Q_{in}	η %	E_{out}	E_{in}	ψ %
P.E.	B1	271	290	-	282	302	-
	B2	124	133	-	129	138	-
	B3	1041	1113	-	1082	1158	-
Gen.	B1	255	271	94	42	282	15
	B2	117	124	94	20	129	16
	B3	1032	1041	99	174	1082	16
Col.	C	1344	1347	100	199	226	88
Dist. Heat	H1 br.	411	412	100	17	60	29
	H2 br.	142	142	100	6	21	29
	H3 br.	122	123	100	5	18	29
	H4 br.	408	408	100	17	59	29
Dist. DHW	HX1	127	127	100	17	19	89
	HX2	129	130	99	20	21	92
Stor.	T1+T2	164	184	89	13	28	49
	T3	121	129	94	10	20	52
Emis. Heat	H1	391	411	95	13	17	73
	H2	135	142	95	4	6	71
	H3	116	122	95	4	5	71
	H4	388	408	95	13	17	73
Emis. DHW	DHW L	164	164	100	10	13	77
	DHW H	120	121	100	8	10	75
R.A.	Block I	386	386	99	10	13	83
	Block II	129	135	96	3	4	76
	Block III	111	116	95	3	4	74
	Block IV	383	388	99	10	13	83
Env.	Heat	698	1009	69	0	27	-

Table 6. Unit exergy costs of F and P of the old A) and the new B) facility.

(A) OLD FACILITY [-]					
n	k^*_F	k^*_P	n	k^*_F	k^*_P
B1	1	6.76	T1	9.19	14.72
B2	-	-	T2	9.46	19.88
B3	1	7.20	T3	8.27	16.30
C	6.77	7.50	DHW L	17.48	22.34
H1 br.	22.37	23.12	DHW H	16.17	22.97
H2 br.	22.87	23.36	H1	23.12	46.22
H3 br.	26.64	27.36	H2	23.36	46.63
H4 br.	21.26	21.98	H3	27.36	55.24
HX1	7.45	9.46	H4	21.98	43.07
HX2	7.36	8.40			

(B) NEW FACILITY [-]					
n			n		
B1	1.00	6.69	T1	7.66	12.69
B2	1.00	6.36	T2	7.02	17.26
B3	1.00	6.23	T3	7.74	15.44
C	6.33	7.20	DHW L	15.56	20.15
H1 br.	6.74	6.74	DHW H	15.30	20.27
H2 br.	6.43	6.43	H1	6.74	25.41
H3 br.	6.33	6.33	H2	6.43	25.19
H4 br.	6.73	6.73	H3	6.33	25.20
HX1	6.93	8.25	H4	6.73	25.37
HX2	6.89	7.99			

Table 7. Unit exergy costs of F and P of the old A) and the new B) facility.

(A) OLD FACILITY [$c€/kWh_{ex}$]					
n	c_F	c_P	n	c_F	c_P
B1	8.53	57.62	T1	90.75	125.85
B2	-	-	T2	80.70	169.67
B3	8.53	61.38	T3	82.97	139.33
C	57.77	63.99	DHW L	163.67	190.87
H1 br.	190.75	197.17	DHW H	153.28	196.47
H2 br.	195.01	199.21	H1	197.17	395.22
H3 br.	227.14	233.29	H2	199.21	399.73
H4 br.	181.32	187.45	H3	233.29	473.44
HX1	75.58	80.70	H4	187.45	368.45
HX2	74.73	71.76			

(B) NEW FACILITY [$c€/kWh_{ex}$]					
n	c_F	c_P	n	c_F	c_P
B1	4.76	31.84	T1	49.08	62.42
B2	4.77	30.32	T2	48.68	83.86
B3	4.79	29.84	T3	49.60	75.33
C	30.26	34.44	DHW L	92.38	98.35
H1 br.	44.09	44.09	DHW H	91.21	99.04
H2 br.	42.33	42.33	H1	44.09	123.55
H3 br.	41.80	41.80	H2	42.33	124.08
H4 br.	44.01	44.01	H3	41.80	124.63
HX1	45.08	39.89	H4	44.01	123.43
HX2	44.84	38.71			

Table 8. Cost of heating and DHW.

NEW FACILITY		
n	[$c€/kWh_{en}$]	[€/year]
DHW L	7.62	16,228
DHW H	7.86	12,336
H1	6.40	26,308
H2	6.70	9,542
H3	6.80	8,326
H4	6.39	26,072

By contrasting the exergy behaviour of both facilities, the following comments can be made:

- Huge irreversibilities are encountered in the heating production system (see the low exergetic performance of boilers in tables and the low value of the Gen. layer in Fig. 7). This emphasises the idea of the strong irreversibilities that take place in the mixing, combustion and heat transfer processes that take place in the boilers.

- Even if the space heating radiators' system has an energy efficiency of almost 95%, its exergetic efficiency is substantially lower (~71%). There are also big exergy destructions in the air room (~77%) because the operating temperature is sensibly lower than the average surface temperature of the radiators' system.
- The exergetic performance reduction in DHW tanks is also remarkable because not only the exergy losses associated to heat losses are considered but the irreversibilities arising from flow mixtures inside the tanks as well. (see the exergetic efficiency in Stor. box in Table 5A) and B)).

Symbolic thermoeconomic study

Exergetic cost

The unit exergetic costs of fuels and products, k_f and k_p, of every subsystem have been calculated and collected according to the common groups in Table 3 ($k*$ vector and $|k*$) matrix used for the resolution of Eqs. (2) and (3) can be found in Tables D.1 and D.2). The following Table 6A) and B) contain the unit exergy cost values for the old and retrofitted facility respectively. Every subsystem's irreversibility is pointed out through the increment of the unit exergy cost emerged from its fuel consumption to its product.

The highlighted blue boxes in the tables indicate the unit exergetic cost of DHW in the low dwellings circuit and in the high dwellings circuit. Equally, the emphasised red boxes show the unit exergetic costs in each block heating circuit. As heating demands are at the end of the energy conversion chain, they display the bigger values since they in corporate all the exergy destructions picked up along the way.

If the old and new facility values are contrasted, important exergy savings can be noticed either in heating or DHW. Whereas in the old facility, the heating average unit exergetic cost is 47.8, in the new one it is 25.3. In the same way, the DHW average unit exergetic cost in the old facility is 22.7 whereas in the new one it is 20.2. Referring to Table 6B), note that the cost saving emerged from the heat recovery in T2 $K_{ft2,new}$ = 7.02 is lower than $k_{ft2,old}$ = 9.46 due to the new input of the condensing boiler.

Exergoeconomic cost

As Eqs. (4) and (5) exhibit, two components intervene in the exergoeconomic costs: one is associated to external resources, c_e , and the other one to the amortization and maintenance costs of the units, z_i . The exergoeconomic costs associated with the external fuels c_e are obtained from their market prices and their values are c_{old} = 8.52c €/kWhex and c_{new} = 4.75c €/kWhex for the combustibles and c_e = 12.21c €/kWhex for the electricity. The main water stream is a non-exergy-related cost that affects the total cost, being that cost equal to 51.97c €/m3.

In order to compare the costs of both facilities, only the external resource costs are taken into account. The values obtained are depicted in Table 7A) and B).

As can be seen, due to the different prices of the fuels used and mostly thanks to the reduction of irreversibilities achieved with more efficient components, the economic saving in the retrofitted facility is quite relevant. The unit exergoeconomic heating cost in the new facility is almost 69% lower than in the old one (see red boxes) whereas the unit exergoeconomic DHW cost has practically been cut in half (see blue boxes).

All these results are graphically outlined in Fig. 8. Besides the unit exergoeconomic cost, the cumulative exergy destruction has also been portrayed for the old and new facility.

Total cost

Eq. (7) enables the calculation of the heating and DHW unit costs and total costs. Now the vector containing the amortization, main tenance and other operating cost values zi have been considered. This Z vector can be found in Table D.3 where the whole unit exergoeconomic cost vectors of fuels and products are also shown. A 30 year useful life has been assumed and an annual interest of 5% and a maintenance cost of 2.5% of the total inversion have been estimated. The total unit costs, in an energy base, of each demand c PTOT , containing both the cost due to the external fuels ce and those associated with z , are shown in the first column of Table 8 while in the last column the yearly costs of each block demand are summarized.

Even if the DHW unit cost of the higher floors is slightly higher than the lower floors' unit cost, the total yearly cost is lower because more demand is supplied by the low circuit, i.e., more users are supplied by it. Something analogous occurs with the heating demand. The biggest irreversibilities encountered by the heating distribution system are lo cated in block III and therefore cPTOT = 6.80c €/kWhen takes the biggest value. Although blocks II and III have similar architectural structures, the heating demand depends on the building occupation and orienta tion and so the lowest heating demand is in block III as is its yearly cost.

Conclusions & discussion

Overall findings

Conventional energy analysis is based on the first law of Thermodynamics, so, it is restricted to simple energy accounting, which quantifies the energy inputs and outputs in a system or a building. In this way, the energy extracted from resources (fuels, electricity, matter flows and so on) must be converted in products or by-products. Under this perspective, the outputs which are not used are simply considered as losses.

Similarly, the performance or efficiencies of processes and equip ment is usually expressed by coefficients based on the first law. Although there are various ways of expressing these efficiencies, none of them take into account the quality of energy.

By contrast, exergy-based efficiency definitions more thoroughly describe the use of those resources and give a clearer guidance of the possible improvements throughout the system. This is especially useful in buildings were low quality energy demands are required, such as heating and DHW. Therefore, as stated in the second law of Thermodynamics, the real energy requirement of a building can be measured and the real losses (the exergy destructions) can be quantified and located. Moreover, the exergy destruction is a valid measure of the irreversibility of a process since it directly evaluates the decrease of the available work.

However, while working with a whole system, the exergetic method does not allow the effect of each component's irreversibilities on the global resources consumption to be determined, that is to say, it does not enable to designate the part of the cost of fuel consumption caused by each equipment exergy destructions. To achieve this goal, Thermoeconomics has been broadened and it combines the second law of Thermodynamics with economic concepts. Hence, the exergetic cost concept was developed, which represents the required exergy to pro duce a flow calculated from its formation process. This exergetic cost is the weighted factor of each irreversibility over the global resources consumption, and in order to determine those exergy costs, a produc tive structure of the facility must be defined. Symbolic Thermodynamics (ST) allows this analysis to be conducted and is par ticularly suitable for large scale installations.

In conclusion, Thermoeconomics is an exergy based science which, among other applications, enables the exergetic and exergoeconomic costs of all the flows along the system. Besides that, ST is a methodology used to obtain general equations, which relate the overall efficiency of a facility and other thermoeconomic variables with the efficiency of each component that forms it.

Specific findings

As a case study, the old and the retrofitted heating and DHW facility of four block buildings located in Bilbao have been studied and com pared. The presence of 3-way valves in the circuits and the heat re covery in the condensing boiler suggest the use of ST instead of the most common input-output approach.

The heating and DHW energetic and exergetic demands have been calculated, having identified the detailed exergetic demand method as more appropriate than the simple one due to the big losses associated with ventilation and infiltration. The exergy analysis shows the im provement achieved with retrofitting, going from a 2.55% yearly average exergy efficiency of the old facility to a 4.01% value for the retrofitted one (the energy performance raises from 59.90% to 91.64%). As expected, the biggest irreversibilities are encountered in the boilers which account for 81% of the total exergy destruction. The heating distribution and emitters also have high irreversibilities and they amount to 11%.

Once the productive structures of the facilities have been defined in the demand-driven mode, the exergetic costs and the exergoeconomic costs of every flow were calculated. Referring to the final products of the old and retrofitted facility, the values obtained are 47.8 and 25.3 for heating and 22.7 and 20.2 for DHW respectively. These values show the big improvement achieved with the refurbishment. Similarly the values obtained for the unit exergoeconomic costs, not including the invest ment costs are 15.93 c €/kWhen and 5.21 c €/kWhen for heating and 10.04 c €/kWhen and 4.87 c €/kWhen for DHW, highlighting once again the big savings in fuel costs achieved with the new facility.

Finally, the total costs of heating and DHW for the new facility have been obtained and the values referred per energy unit are presented. Small differences in heating costs depending on the branches of the circuit can be noticed and in the DHW, differences are observed be tween the lower and higher floors as well. The application of ST allows these different values to be obtained, whereas if an input-output ana lysis had been performed instead, even if the results would be similar, these small discrepancies could not have been observed.

Thanks to the detailed results that ST enables the cost formation process to be obtained in a way where every cost increment can be detected and ascribed to a specific cause. The exergy destruction in every component can be identified and the cost increment, due to an unexpected fault, can be recognized.

Acknowledgments

The author, A Picallo, acknowledges the support provided to her by the Ministry of Education of the Spanish Government through a scholarship granted to complete her PhD degree. The authors also ac knowledge the support provided by the Laboratory for the Quality Control in Buildings of the Basque Government.

Annex A

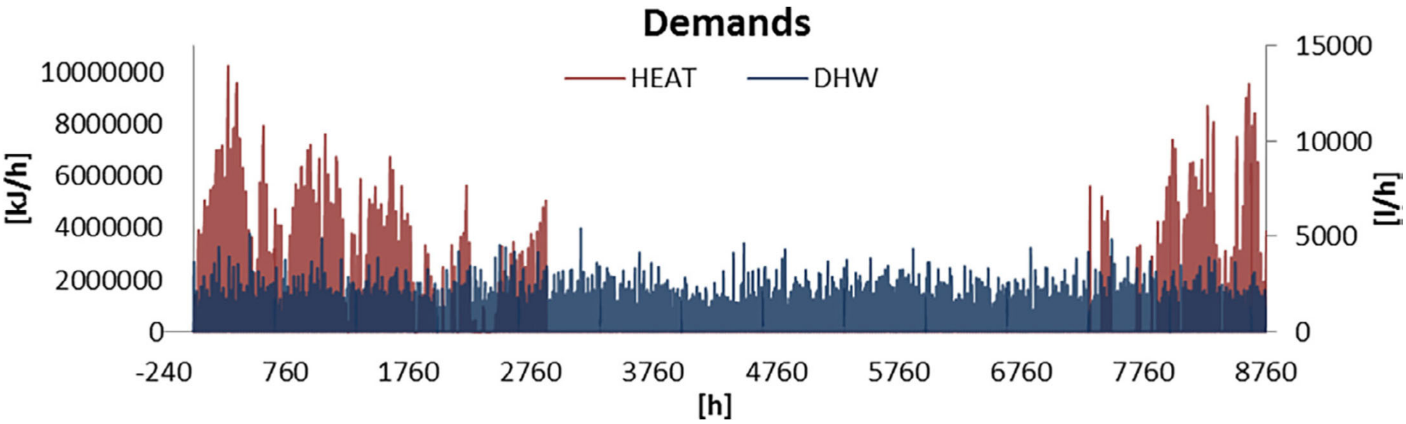


Fig. A.1. Total heating demand [kJ/h] and DHW demand [l/h] during the year.

Annex B

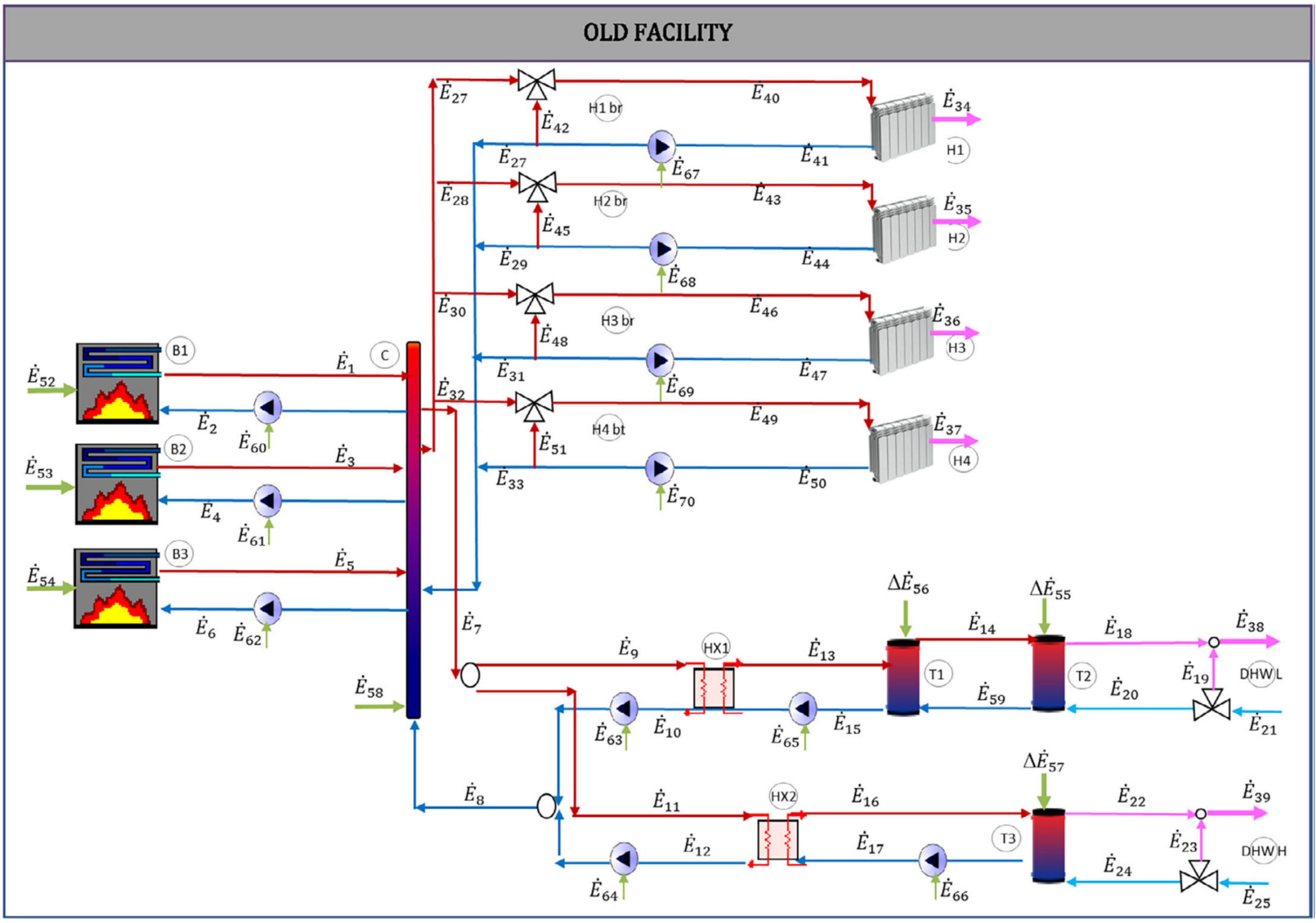


Fig. B.1. Old energy supply system. Representation of components and fluxes.

Annex C

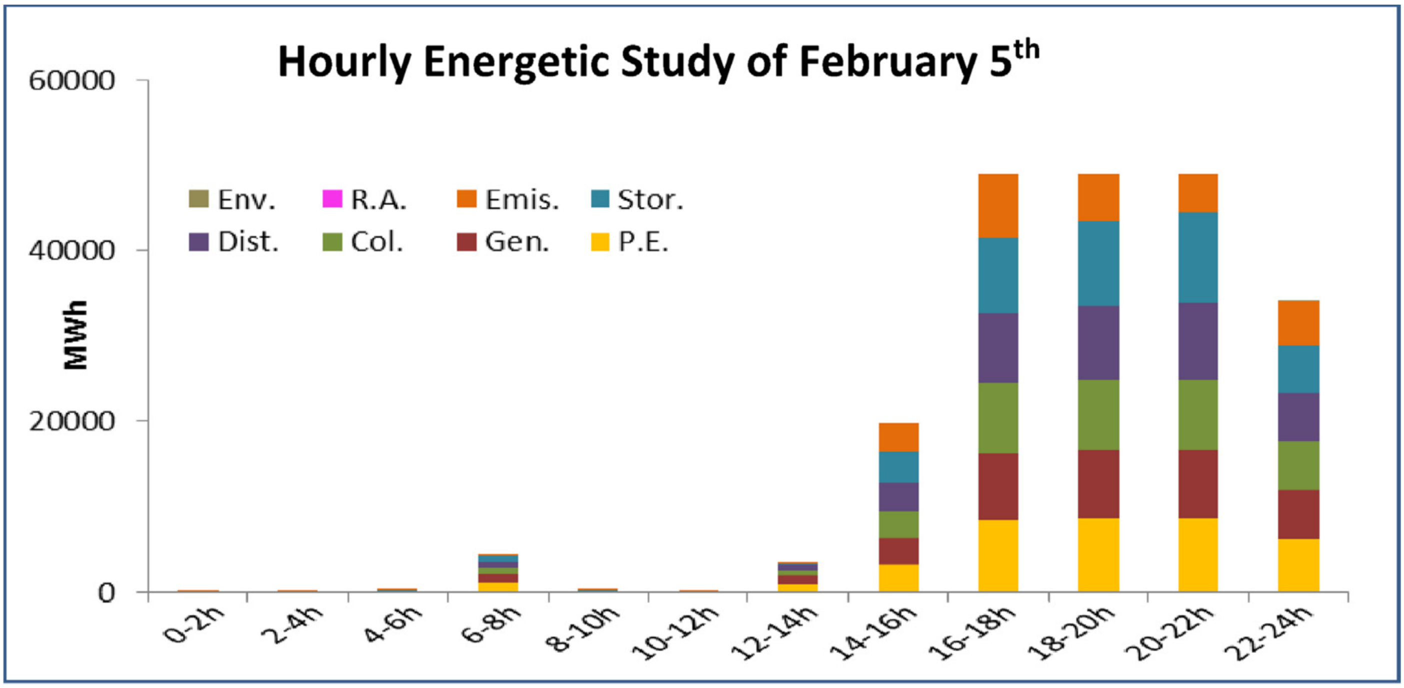


Fig. C.1. Hourly study which shows the exergetic transformation chain of February the 5th .

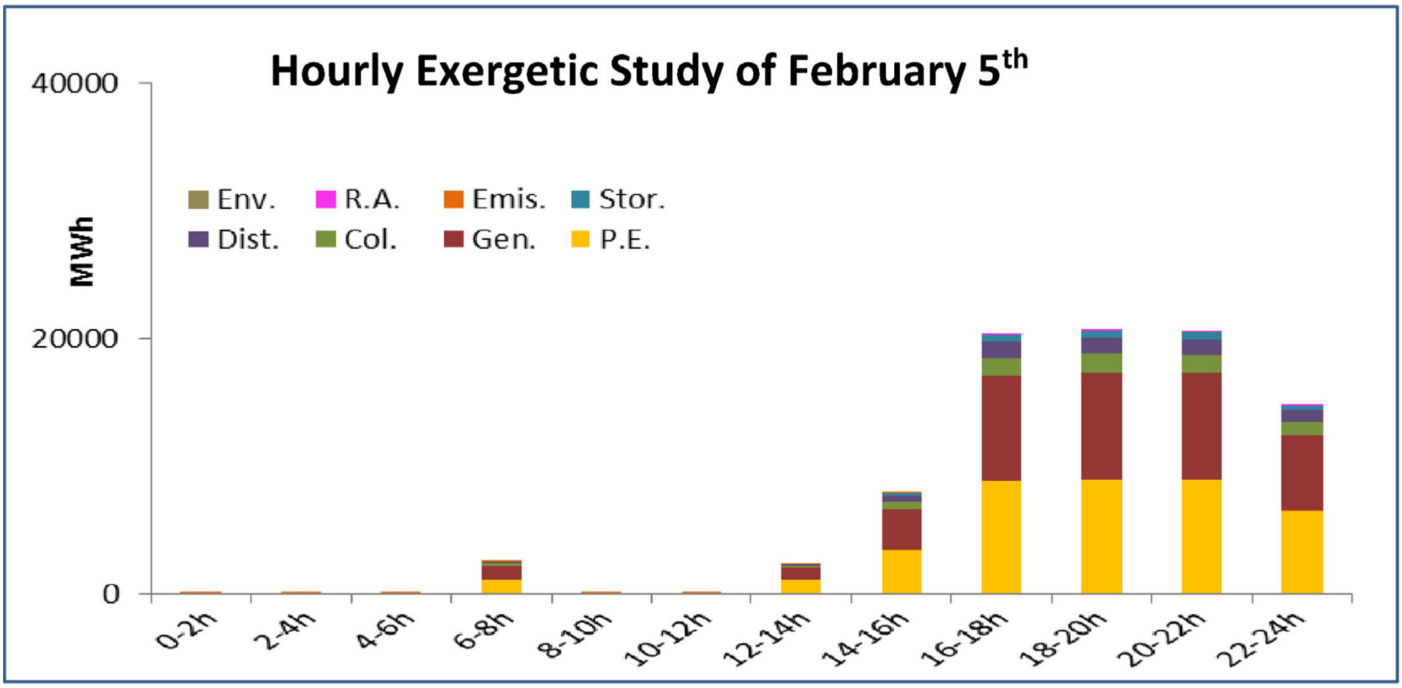


Fig. C.2. Hourly study which shows the energetic transformation chain of February the 5th .

Annex D

Table D. 1 $|k_P^*$ matrix of the new facility

$\|k_P^*$	B1	B2	B3	C	DHW H/L div	DHW H/L mix	HX1	HX2	T1	T2	T3	DHW mix L	DHW L	DHW mix H	DHW H	H1	H2	H3	H4	Recovery
B1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
B2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
B3	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C	0.21	0.10	0.82	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DHW H/L div	0.21	0.10	0.83	1.01	10.40	9.40	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DHW H/L mix	0.21	0.10	0.83	1.01	10.40	10.40	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HX1	0.24	0.12	0.94	1.14	11.74	10.61	1	0	0	0	0	0	0	0	0	0	0	0	0	0
HX2	0.23	0.11	0.91	1.10	11.36	10.27	0	1	0	0	0	0	0	0	0	0	0	0	0	0
T1	0.37	0.18	1.42	1.73	17.87	16.15	1.52	0	1	0	0	0	0	0	0	0	0	0	0	0
T2	0.28	0.13	2.31	1.31	13.51	12.21	1.15	0	0	1	0	0	0	0	0	0	0	0	0	1.23
T3	0.45	0.22	1.74	2.11	21.84	19.74	0	1.92	0	0	1	0	0	0	0	0	0	0	0	0
DHW mix L	1.40	0.19	2.58	1.86	19.24	17.39	1.64	0	0.44	0.84	0	1	0.01	0	0	0	0	0	0	1.04
DHW L	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
DHW mix H	0.59	0.28	2.28	2.77	28.66	25.90	0	2.52	0	0	1.31	0	0	1	0.01	0	0	0	0	0
DHW H	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
H1	0.74	0.36	2.87	3.49	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
H2	0.73	0.35	2.82	3.43	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
H3	0.73	0.35	2.82	3.42	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
H4	0.74	0.36	2.87	3.48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Recovery	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Table D. 2 k_e^* vector of the new facility

k_e^*	6.69	6.36	6.23	0	0	0	0	0	0.14	0	0	0	1	0	1	0	0	0.56	0	0

Table D. 3 Z vector of the new facility

Z [€/*year*]	4,417	4,417	4,231	885	206	180	523	523	772	772	815	470	470	828	828	885	661	661	885	1,058
c_F [c€/ kWh_{ex}]	4.76	4.77	4.79	35.92	42.49	42.56	52.55	52.26	60.06	60.41	60.48	115.76	16.45	112.29	16.45	50.46	48.35	47.72	50.37	32.27
c_P [c€/ kWh_{ex}]	42.30	52.06	32.27	41.33	42.56	42.61	51.85	55.00	97.38	121.53	105.08	154.40	364.90	159.44	850.64	152.71	158.68	160.95	152.58	42.06

Fig. C.2. Hourly study which shows the energetic transformation chain of February the 5***th***.

References

[1] Yang Liu, Yan Haiyan, Lam Joseph C. Thermal comfort and building energy con sumption implications–a review. Appl Energy 2014;115:164–73.

[2] Energy Rehabilitation Catalog. Basque Government (2016) ISBN 978-84-15914-13-6.

[3] Garshasbi Samira, Kurnitski Jarek, Mohammadi Yousef. A hybrid Genetic Algorithm and Monte Carlo simulation approach to predict hourly energy consumption and generation by a cluster of Net Zero Energy Buildings. Appl Energy 2016;179:626–37.

[4] Stephan André, Crawford Robert H, Myttenaere Kristel De. A comprehensive as sessment of the life cycle energy demand of passive houses. Appl Energy 2013;112:23–34.

[5] Shukuya M. Exergy concept and its application to the built environment. Build Environ 2009;44(7):1545–50.

[6] Wang, Jiang-Jiang. Energy and exergy analyses of an integrated CCHP system with biomass air gasification. Appl Energy 2015;142:317–27.

[7] Meggers F, Ritter V, Goffin P, Baetschmann M, Leibundgut H. Low exergy building systems implementation. Energy 2012;41(1):48–55.

[8] Rocco MV, Colombo E, Sciubba Enrico. Advances in exergy analysis: a novel as sessment of the Extended Exergy Accounting method. Appl Energy

2014;113:1405–20.

[9] Gaggioli RA, Wepfer WJ. Exergy economics: I. Cost accounting applications. Energy 1980;5(8–9):823–37.

[10] Bühler Fabian, Nguyen Tuo-Van, Elmegaard Brian. Energy and exergy analyses of the Danish industry sector. Appl Energy 2016;184:1447–59.

[11] Caliskan Hakan, Hepbasli Arif. Energy and exergy analyses of ice rink buildings at varying reference temperatures. Energy Build 2010;42(9):1418–25.

[12] Cheng W, Ji H, Di A. Thermoeconomic analysis of air conditioning systems. Adv Mater Res 2014:1662–8985. ISSN.

[13] Caliskan Hakan, Dincer Ibrahim, Hepbasli Arif. Thermoeconomic analysis of a building energy system integrated with energy storage options. Energy Convers Manage 2013;76:274–81.

[14] Gholampour Maysam, Ameri Mehran. Energy and exergy analyses of Photovoltaic/ Thermal flat transpired collectors: experimental and theoretical study. Appl Energy 2016;164:837–56.

[15] Du Zhimin, Jin Xinqiao, Fang Xing, Fan Bo. A dual-benchmark based energy ana lysis method to evaluate control strategies for building HVAC systems. Appl Energy 2016;183:700–14.

[16] Kostowski Wojciech J, Usón Sergio. Thermoeconomic assessment of a natural gas expansion system integrated with a co-generation unit. Appl Energy 2013;101:58–66.

[17] Yildiz A, Güngör A. Energy and exergy analyses of space heating in buildings. Appl Energy 2009;86(10):1939–48.

[18] Ally Moonis R. Exergy analysis of a two-stage ground source heat pump with a vertical bore for residential space conditioning under simulated occupancy. Appl Energy 2015;155:502–14.

[19] Li Rongling, Ooka Ryozo, Shukuya Masanori. Theoretical analysis on ground source heat pump and air source heat pump systems by the concepts of cool and warm exergy. Energy Build 2014;75:447–55.

[20] Park SR, et al. Energy and exergy analysis of typical renewable energy systems. Renew Sustain Energy Rev 2014;30:105–23.

[21] do Espirito Santo, Boschiero Denilson. An energy and exergy analysis of a high efficiency engine trigeneration system for a hospital: a case study methodology based on annual energy demand profiles. Energy Build 2014;76:185–98.

[22] www.annex49, info.

[23] Serra, Luis, and César Torres Cuadra. Structural theory of thermoeconomics 2015: ISBN 978 1 84826 165 5.

[24] Farshi L Garousi, Seyed Mahmoudi SM, Rosen MA. Exergoeconomic comparison of double effect and combined ejector-double effect absorption refrigeration systems. Appl Energy 2013;103:700–11.

[25] Kwak, Ho-Young. Thermoeconomic analysis of ground-source heat pump systems. Int J Energy Res 2014;38(2):259–69.

[26] Picallo-Perez A, Sala-Lizarraga JM, Iribar-Solabarrieta E, Odriozola-Maritorena M. Application of the malfunction thermoeconomic diagnosis to a dynamic heating and DHW facility for fault detection. Energy Build 2016;135:385–97.

[27] Piacentino A. Innovative thermoeconomic diagnosis of multiple faults in air con ditioning units: methodological improvements and increased reliability of results. Int J Refrig 2013;36:2343–65.

[28] Piacentino A, Talamo M. Critical analysis of conventional thermoeconomic ap proaches to the diagnosis of multiple faults in air conditioning units: capabilities, drawbacks and improvement directions. A case study for an air-cooled system with 120 kW capacity. Int J Refrig 2013;36(1):24–44.

[29] Kerdan IG, Raslan R, Ruyssevelt P, Gálvez DM. An exergoeconomic-based para metric study to examine the effects of active and passive energy retrofit strategies for buildings. Energy Build 2016;133:155–71.

[30] Luo, Xianglong, et al. Improved exergoeconomic analysis of a retrofitted natural gas-based cogeneration system. Energy 2014;72:459–75.

[31] Kerdan, Iván García, et al. An exergoeconomic-based parametric study to examine the effects of active and passive energy retrofit strategies for buildings. Energy Build 2016;133:155–71.

[32] Picallo A, Escudero C, Flores 1, Sala JM. Symbolic thennoeconomics in building energy supply systems. Energy Build 2016;127:561-70.

[33] Transient System Simulation Too!Tmsys, Thennal Energy Systems Specialists, Madison, USA 2009.

[34] http://www.meteononn.com.

[35] HE Basic Document. Spanish Ministry of Public Works and Transport. Documento Básico HE. Ministerio de Fomento. España 2013

[36] Jordan U, Vajen K. Manual. Too!for the Generation of Domestic Hot Water (DHW) Proffies on a Statistical Basis. Version 1.10 2003.

[37] Energy keys of the housing sector in the Basque Country. Claves energéticas del sector doméstico en Euskadi. EVE. (2013).