Chapter 5

New Exergetic Methodology to Promote Improvements in nZEB

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Additional information is available at the end of the chapter

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Abstract

The benefits obtained through the application of exergy concept in buildings are currently known, since they contribute to the proper use of energy as well as to a better adequacy of the different energy qualities taking part in a facility. Besides, an exergy analysis supports the identification of both the economic and environmental cost formation in every phase of the energy transformation chain. Those type of studies are known as exergoeconomic and exergoenvironmental analyses. In this work, a nearly zero energy buildings (nZEB) single-family dwelling is analyzed, where heating and DHW exergy demands are hourly calculated. A full exergetic analysis of its building envelope and thermal facility is carried out and exergoeconomic and exergoenvironmental analyses are applied. The aim of this study is to show the enormous possibilities for the energy efficiency improvement that still exist, which cannot be appreciated through a common energetic analysis (being the facility's energetic efficiency of 81% and exergetic one of 13%). In addition, the results of this study indicate the location and the correct assessment of the real inefficiencies.

Keywords: building envelope, building thermal facility, exergoeconomic cost, exergoenvironmental cost, improvements in nZEB

1. Introduction

The energy consumption in buildings has increased rapidly in recent years, among other things, due to the rise in population, higher requirements of healthy, comfortable indoor environments and so on. The situation in Europe indicates that tertiary buildings (residential and services) are responsible for 40% of the final energy consumption and for the 50% of the

CO_2 emissions. In Spain, these buildings account for a smaller 28% of the national global consumption, being 18% used in dwellings and the remainder 10% in services, [1]. In any case, as it is one of the main energy consumers, there is still a great potential for energy improvement in the building sector that should be performed in the coming years.

This context encouraged new European energy saving policies such as the energy efficiency directive (EED) and the energy performance of buildings directive (EPBD). The last update of the EPBD in 2010 established that, from 2020 onwards, all new buildings must be nearly zero energy buildings (nZEB). Therefore, this pressures the necessity to increase greatly buildings energy efficiency [2].

In this context, the Passivhaus standard is considered a very low-energy demand construction often used as a reference for nZEB buildings. That standard is based on an exhaustive procedure, during the project design and construction, which procures buildings with a thoroughly low-energy requirement. Nevertheless, energy is used as the base parameter of building design and, as it will be justified later on, some incongruences can arise within such analysis. One of the aims of this paper is, precisely, to demonstrate the huge potential to improve the energy performance of this type of buildings.

As it is well-known, different types of energy have diverse abilities to transform into other forms. The quality of energy (or what is the same: exergy) identifies the idea of convertibility disparity and, because of that, reflects that the same amount of energy can have different quality according to its ability to be transformed into other forms. In general, among all possible forms of energy the most common reference is *work*, in other words, the quality of energy is expressed by its ability to become useful work.

In this way, exergy is the parameter that reflects the idea of utility since it expresses the capacity of an energy to become work [3]. Some energy forms can be completely converted into work (e.g. electrical energy); consequently, energy is identified with exergy. However, there are other forms of energy (for instance, heat), that only one part can be converted into work; therefore, only a fraction of that heat flow is an exergy flow. Thus, exergy allows to quantitative assess the different levels of energy quality.

In buildings, the energy demands have different qualities and the resources used to supply them are manifold. Electricity is used for lighting and appliances, whereas other types of high-quality energy are used for indoor heating, cooling and domestic hot water (DHW), such as natural gas or fossil fuels. The electric demand is high-quality energy in contrast with the heating, cooling and DHW demands. These last ones are low-quality demands because their objective is to keep the indoor air temperature few degrees above or below the ambient temperature. Accordingly, there is no matching between the generation energy quality and the one for conditioning, as clearly exposed through the exergy analysis presented in [4]. As a consequence, important exergy destructions (quality losses) take place, which are much higher than the energy losses. **Figure 1** illustrates the proper way to use energy according to the supplying source.

The low-ex building, in contrast to nZEB, takes advantage of the different energy qualities for the different types of energy demands. These buildings reduce the energy losses and exergy destructions. Thus, an increase of the system efficiency means reducing irreversible losses, so,

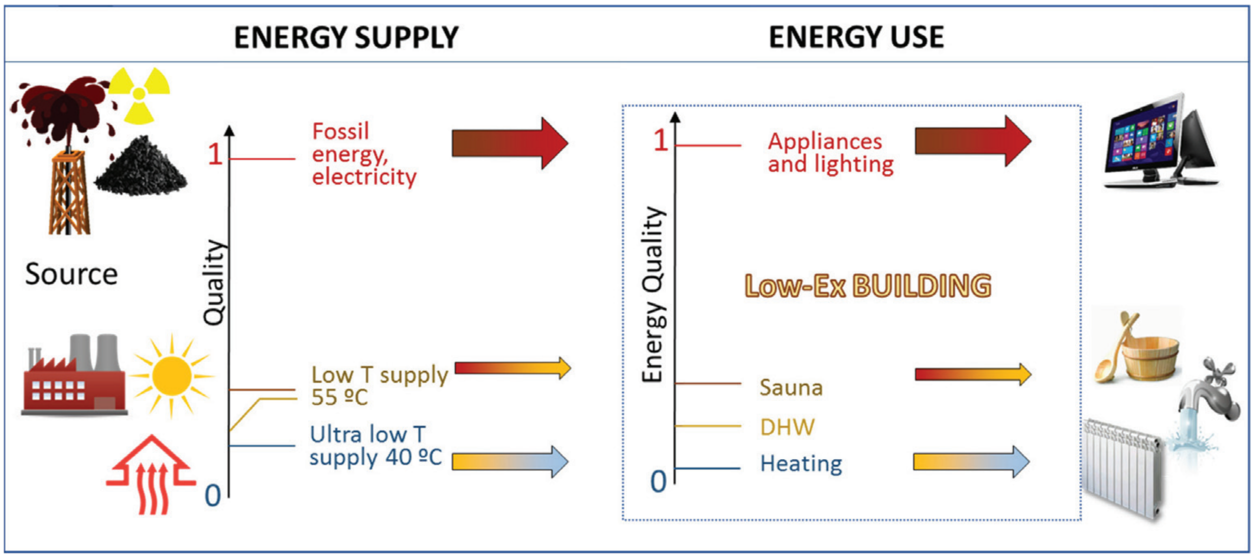

Figure 1. Energy types according to their quality.

ultimately, using energy more efficiently. A work based on building systems exergetic performance is found in [5].

This suggests that in order to reduce energy consumption in buildings as well as to use energy more efficiently, the energetic studies based on the First Law of Thermodynamics should be complemented with exergetic studies, which take into account also the Second Law of Thermodynamics. These analyses should be carried out for both building envelope and its facilities. The objective must be to optimize all the stages of the process: starting with the building design, proceeding with the construction and commissioning phases and improving the control and even the maintenance.

The main target of this study is to show a new method that comes up with the real performance values of buildings systems. In such way, structures as nZEB can further develop and optimize to achieve the common desired energy-saving goal.

The article is organized into six different sections as follows: Section 1 contains a brief introduction, Section 2 explains the way to calculate energy and exergy demands in buildings; in Section 3, the facility's exergetic study is outlined by considering the exergoeconomic and exergoenvironmental analysis. A real case study data and results appear in Section 4, where the envelope as well as the facilities is studied energetically and exegetically. Section 5 deals with the findings discussion and, finally, the last part contains the research main conclusions.

2. Energy and exergy heating demands

As already expressed, exergy measures the maximum theoretical useful work that can be obtained from an energy until it achieves the balance with the ambient [6]. Therefore, it is dependent on the environment conditions. This exergy fluctuation according to the environmental temperature variation was analyzed in several studies, such as in building services [7, 8] or in a ground-coupled heat pump [9].

Regarding buildings, the energy demand, $\dot{Q}_{heat}$, is the required amount of energy in order to keep the indoor environment in thermal comfort conditions for the users. Similarly, the exergy demand, $\dot{E}_{heat}$, is the required amount of exergy to maintain the place in comfort conditions; that is, the exergy content of the previously defined energy demand. It can be said also that exergy demand is the minimum work required to ensure the energy demand.

The supplied energy for covering the demand must be the one with the minimum quality required; otherwise, exergy destruction would come up. This happens, for example, when a heating system supplying hot water at 80°C is used to maintain the indoor air at 21°C [10]. Therefore, in an ideal situation, the minimum exergy required to satisfy the comfort conditions should be provided. Any excess exergy supplied will result in utility losses, called exergy destructions, between the heating (or cooling) facility and the demand point.

Moreover, unlike energy, exergy is not conserved but it is destroyed owing to the irreversibility of the process. So a destruction term ($\dot{E}_{D,k}$) appears, when an exergetic balance is applied in k^{th} component, by comparing the input ($\dot{E}_{in,k}$) and output ($\dot{E}_{out,k}$) exergy flows [11]:

$$\dot{E}_{in,k} = \dot{E}_{out,k} + \dot{E}_{D,k} \tag{1}$$

Accordingly, if this equation is applied to the building envelope requirement, two unknowns will appear, namely the exergy demand and the exergy destruction. Therefore, the exergy demand calculation requires knowing first the energy demand values and, later, assessing the exergy estimations.

There are two methods for exergy demand calculation: simplified and detailed. Although the first one is mostly utilized, as in [12], the second one will be used instead. This, developed in Annex 49 [13], differs from the simplified one basically because it separates the exergy demand associated with ventilation from the rest. None of them takes into account the chemical exergy and neither considers the small differences between the heat convection exergy and the radiation exergy exchanged between surfaces with small temperature differences.

Referring to the heating period, the total demand is equal to the total losses (transmission through the inertial walls, ventilation and infiltration) minus the gains (solar and internal). Hence, it is calculated as follows:

$$\dot{Q}_{demand} = \left(\dot{Q}_{trans} + \dot{Q}_{vent} + \dot{Q}_{inf}\right) - \left(\dot{Q}_{g_{solar}} + \dot{Q}_{g_{int}}\right) \tag{2}$$

The quality factor (the relationship between exergy and energy, E/Q) of the *internal energy* of a system at T_{op} is smaller than the quality factor associated with *heat energy* at the same temperature T_{op}. In this way, in order to determine the exergy demand, it will be necessary to evaluate, first of all, which part of the demand is needed to warm up (or cool down) the ventilation air and, after that, provide the remaining heat in form of heat at the operating temperature.

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To sum up, exergy demand calculation should be carried on in two steps: firstly, the ventilation exergy should be accounted (the exergy needed to temperate the air coming from the outside and mixed with the inside); and secondly, if more exergy demand exists, that must be supplied as heat (or cold) (the exergy needed to temperate the room at the operating temperature T_{op}).

When the energy balance is made, the total energy demand $\dot{Q}_{demand}$ is compared first with the ventilation loss. If this is smaller than the total demand, the ventilation air must be warmed up to the operative temperature T_{op}. That implies a minimum contribution of exergy, which can be calculated with the expression:

$$\dot{E}_{vent} = \dot{Q}_{vent} \cdot \left[1 - \frac{T_0}{(T_{op} - T_0)} \cdot ln\left(\frac{T_{op}}{T_0}\right)\right] \tag{3}$$

where $\dot{Q}_{vent}$ is the heat that must be provided to temperate the room air, obtained as:

$$\dot{Q}_{vent} = \dot{m}_{vent} \cdot c_P \cdot (T_{op} - T_0) \tag{4}$$

The difference between the total demand and this $\dot{Q}_{vent}$ must be supplied as heat, at T_{op} temperature, so that the complementary exergy provided is:

$$\dot{E}_Q = \left(1 - \frac{T_0}{T_{op}}\right) \cdot (\dot{Q}_{demand} - \dot{Q}_{vent}) \tag{5}$$

In case that the total demand is less than the ventilation losses ($\dot{Q}_{demand} < \dot{Q}_{vent}$), the air does not need to be warmed up to T_{op}. This means that no additional heat is required, since it is compensated with the internal and solar gains. In such situation, the temperature of the air should be tempered at:

$$\Delta T_{vent} = \frac{\dot{Q}_{demand}}{\dot{Q}_{vent}} \cdot (T_{op} - T_0) \tag{6}$$

and, therefore, the required total exergy is:

$$\dot{E}_{vent} = \dot{Q}_{vent} \cdot \left[1 - \frac{T_0}{\Delta T_{vent}} \cdot ln\left(\frac{\Delta T_{vent} + T_0}{T_0}\right)\right] \tag{7}$$

By comparison, two circumstances can happen in cooling: in the case where $T_0 > T_{op}$, all the natural energy flows represent unwanted gains, so that $\dot{Q}_{demand} > \dot{Q}_{vent}$ will constantly be fulfilled. Hence, the ventilation air will always require to be cooled down to the T_{op} temperature. Conversely, in the situation where $T_0 < T_{op}$, the need for cooling (energy output) will not represent an exergy demand, but rather a cession of unwanted exergy. This exergy is acquired by internal gains and could be somehow collected and taken advantage of it as heat at T_{op}.

In any case, the exergy demand is verified to be about 10% of the energy demand, which obviously depends on T_0 and T_{op}.

3. Building facility study

3.1. Exergoeconomic analysis

Exergoeconomics (or thermoeconomics) is a science that combines thermodynamic and economic analyses by applying the concept of *cost of exergy*. It is an effective tool since it allows determining the production costs of an energy system; as it is the case of [14] where a sugar production process is exegetically analyzed to find out the unit exergy cost of the turbine. In addition, it allows the calculation of the intermediate costs of different flows as well.

The determination of all these streams costs is useful to make trade-off economic analyses of the subsystem components. Hence, thermoeconomics application is a key stage for designing the building thermal systems as a whole [15] or its particular components individually.

As it was said before, on one side, full systems can be studied, such as solar energy based heating systems [16], HVAC systems [17], air conditioning systems [18, 19], absorption cooling systems [20], etc. On the other side, generating and intermediate engines can be analyzed, namely micro-trigeneration machines [21], ground and air source heat pumps [22–24], heat exchangers [25], thermal energy storage modules [26] and so on.

The procedure created for the cost study is based on the exergetic cost theory (ECT) which provides the extra equations needed (apart from the exergy balance one, Eq. (1)) for solving the unknown costs of every flow. In order to apply that ECT, a *functional model* of the system must be set up from its physical model. That last physical model is used to determine simply the entering and outgoing flows of a component, or what is the same, it serves to define the typical Eq. (1) balance.

On the other hand, instead of distinguishing the flows between the ins and outs, the functional analysis classifies them among fuel (F), product (P) and residues (R) [27]. This satisfies the statement that the exergy of resources must be equal to the exergy of products plus residues plus irreversibities, as follows:

$$F = P + R + I \tag{8}$$

Once the flows are grouped according to their purpose, F_k represents the required resources for the development of the k^{th} component objective; and P_k reflects the flows that constitute the production objective. If the fuel and product are evaluated using energy parameters, the ratio between P_k and F_k would represent the energy efficiency η_k; whereas if it is defined with exergy values, the ratio would refer to the exergetic efficiency ε_k. If no exergy losses are assumed, the difference between F_k and P_k reveal the exergy destruction, $B_{D,k}$ and then:

$$\varepsilon_k = \frac{P_k}{F_k} = 1 - \frac{E_{D,k}}{F_k} \tag{9}$$

Although the exergy of a flow is a thermodynamic property that depends on its state and composition, the cost (and the environmental impact) is a function of the specific process followed by that flow production. Consequently, the same flow can have different exergy costs (or environmental impacts) according to the procedure used for its creation [28].

For this reason, the exergy cost of a flow, which is the amount of exergy required to produce it, incorporates the accumulated irreversibilities until arriving to it. Consequently, the exergy cost increases during the energy transformation chain; this fact is a result of the exergetic destructions gathered during the formation path. Consequently, this parameter shows the direct and indirect influence of the equipment interconnections, as well as the justification of different costs in each flow.

Once the productive structure of the system is specified, by following the guidelines detailed in [29], the unit exergy cost of the fuels and products of each component, $k^*_{F,k}$ and $k^*_{P,k}$ $(-)$, can be calculated. Similarly, the exergoeconomic cost of fuels and products of each component, $c_{F,k}$ and $c_{P,k}$ (€/kWh), can be obtained. These values are associated with the unitary exergoeconomic costs of the i external resources, $c_{e,i}$ (€/kWh), and the inversion, maintenance and other operating costs of every component Z_k (€/kWh). Accordingly, the total costs of fuels and products, $C_{F,k}$ and $C_{P,k}$ (€), are obtained simply by multiplying the unitary exergoeconomic cost by the corresponding exergy of fuel or product.

In such way, exergoeconomics allow to assign monetary costs to the different flows, as well as to the irreversibilities. Similarly, it assesses the consumed resources costs, either in terms of energy or in economic parameters. The destroyed exergy is considered inside this resources cost due to the encountered inefficiencies. Therefore, this information helps knowing in which way the resources can be adapted to save energy more effectively. Likewise, intermediate monetary costs express the economic effects of the inefficiencies and enable to improve the performance, and, hence, the cost of the processes. Then, this methodology provides information that cannot be obtained with the conventional energy study.

3.2. Exergoenvironmental analysis

The exergoenvironmental analysis is based on a modification of the previous analysis as it evaluates the ecological impact instead of the cost problem [30]. That is, the consumed resources effect is given in terms of environmental impact. Once again, exergy is the fundamental basis since it represents the appropriate parameter to allocate both costs and environmental impacts, over the components of any energy conversion process.

The exergoenvironmental analysis proposed in [31] consists of the following three steps: first, a detailed exergy study is made; then, the environmental impact values of each component are calculated. These impacts are determined by applying the appropriate method to quantifying the environmental impact, which in many cases, the Eco-indicator 99 is used together with the life cycle analysis (LCA) method; in the last step, the environmental impact related to every component product is measured. In addition, the exergoenvironmental variables, which are analogous to the exergoeconomics, are evaluated.

As already said, the variables in the exergoenvironmental analysis maintain a similarity with those obtained by means of the exergoeconomic analysis: the specific environmental impact of fuels and products ($b_{F,k}$ and $b_{P,k}$), like to the specific cost ($c_{F,k}$ and $c_{P,k}$), consider the relative position of each component and its interconnections with the rest of the equipment. These environmental values are connected with the unitary exergoenvironmental impacts of the i external resources, $b_{e,i}$ (pts/kWh), and the impacts associated with the equipment that consider the construction stage, maintenance and other operation as well as the disposal stages of every k^{th} component Y_k (pts/kWh).

The increase of those specific environmental impacts between the fuel and the product of the component ($b_{P,k} - b_{F,k}$) represents the environmental impact related to that element. In the same way, the specific cost difference ($c_{P,k} - c_{F,k}$) represents the costs of irreversibilities due to the inefficiencies and technological limitations. Finally, the specific impact of fuel ($b_{F,k}$) equally to its cost ($c_{F,k}$), takes into account the accumulated impacts until the creation of that fuel.

3.3. Application in buildings thermal facilities

There are many works containing exergy analysis in industrial applications, such as in PEM fuel cells [32], in a sugar plant [33] or in a drying plant [34]. Even being scarcer, the concepts associated with exergy in buildings are becoming known so, as aforementioned, it is already common to consider some low-energy buildings as low-ex buildings.

Exergy analyses help showing the low effective performance of many building services: for instance, a DHW production can have an exergetic efficiency of 3.2–10.8% [35]; a heating system ranges from 2.5 to 7.4% [36] or a common air conditioning system is about 3.4% [37]. More information of building systems exergetic particularities can be found in [38].

Despite this considerable interest of exergetic application, the implementation of exergoenvironmental or even exergoeconomics analyses in buildings is still under research and it is rarely used in the daily practice. Besides, there are still many methodological aspects that must be solved.

For the adequate management of a building facility, the appropriate sensors need to be installed in both the envelope and the facility. The building is a dynamic system itself because it is directly dependent on the changing outside conditions and the user's unpredictable requirements. Therefore, it must be studied dynamically (or quasi-statically).

By an appropriate monitoring system, the exergy destruction taking place in the building thermal envelope and the energy supply system of a building can be quantified.

Through the application of the exergoeconomics and exergoenvironmental analysis, the costs and impacts can be calculated, that is, €/kWh of heating, €/kWh of DHW and so on. The knowledge of these costs provides the bases for thermoeconomic operation diagnosis [39],

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which allows identifying the causes of the efficiency degradation of the building energy supply system. Moreover, the assessment of its effects in terms of additional fuel consumption can be also acquired. The understanding of costs helps, in turn, with the optimization of control strategies that will guarantee lower energy consumption (or economic or CO_2 emissions), always satisfying the user demands.

4. Case study—data and results

The theory explained above was applied to a nZEB in order to become more familiar with the method and understand better the exergy use in buildings. It is a single-family dwelling (**Figure 2**) with 176 m^2 of net floor area, located in Álava (northern Spain), in a D1 climatic zone.

The thermal facility consists of a biomass stove (2.4–9 kW) for the heating coverage. The domestic hot water (DHW) is obtained by the combination of a solar panel (with a 2.3 m^2 module) that preheats the water and an air-water heat pump (3.6 kW) with an internal 300 l DHW storage, see **Figure 3**. The house includes ventilation with heat recovery system and

Figure 2. Single-family house located in Álava.

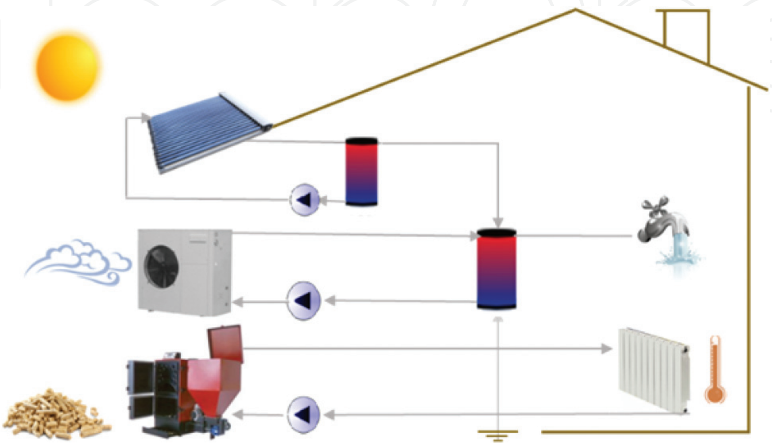

Figure 3. Heating and DHW facility of the case study.

summer bypass and there is no active cooling. The annual heating demand is less than 15 kWh/m^2·y and it has the Passivhaus certification [40].

4.1. Energy and exergy demands

First, a dynamic thermal modeling of the single-family house is performed using the EnergyPlus software. In this case, the model was calibrated by the data obtained during one-year monitoring [41]. By comparing the results obtained from the model with the monitored data, solar gains, ventilation and transmission losses were adjusted. In this way, the different components of the heating demand were hourly obtained. This is carried on according to the balance represented in Eq. (2) where the incoming flows are compensated with the outgoing flows.

The exergy heating demand has been calculated following the detailed exergy demand calculation method, as previously explained. **Figure 4** shows the accumulated annual energy balance per m^2 and, in contrast, **Figure 5** depicts the exergy balance.

It is worth noting the enormous difference among these values, as well as the fact that the exergy destruction term is about the 21% of the total exergy demand. Therefore, considerable improvements can be done to avoid those destructions.

In addition to all these, **Figure 6** shows the monthly energy gains and losses and **Figure 7** presents those gains and losses in exergy values. In both cases, the outdoor air temperature (T_{ext}) and the indoor operative temperature (T_{op}) profiles were added so that the profile of the demand could be better understood.

It should be noted that the scale of the kWh/month in the exergy graph (**Figure 7**) is five times smaller.

In order to show the hourly behavior, in **Figure 8** the heating energy and exergy demands are hourly presented. A typical winter day was chosen for that, namely February 15th. In this plot,

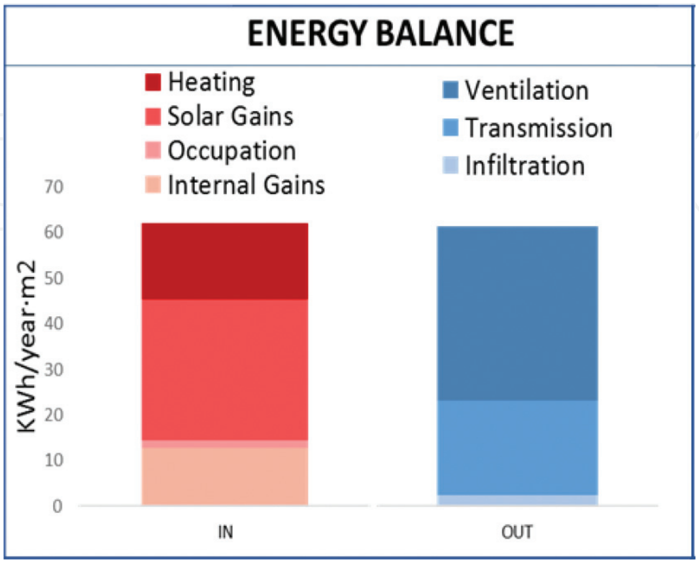

Figure 4. Energetic balance of the building.

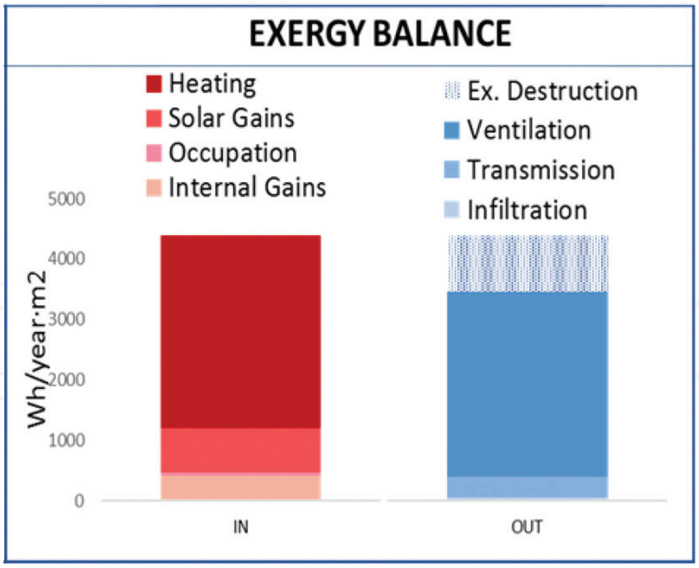

Figure 5. Exergetic balance of the building.

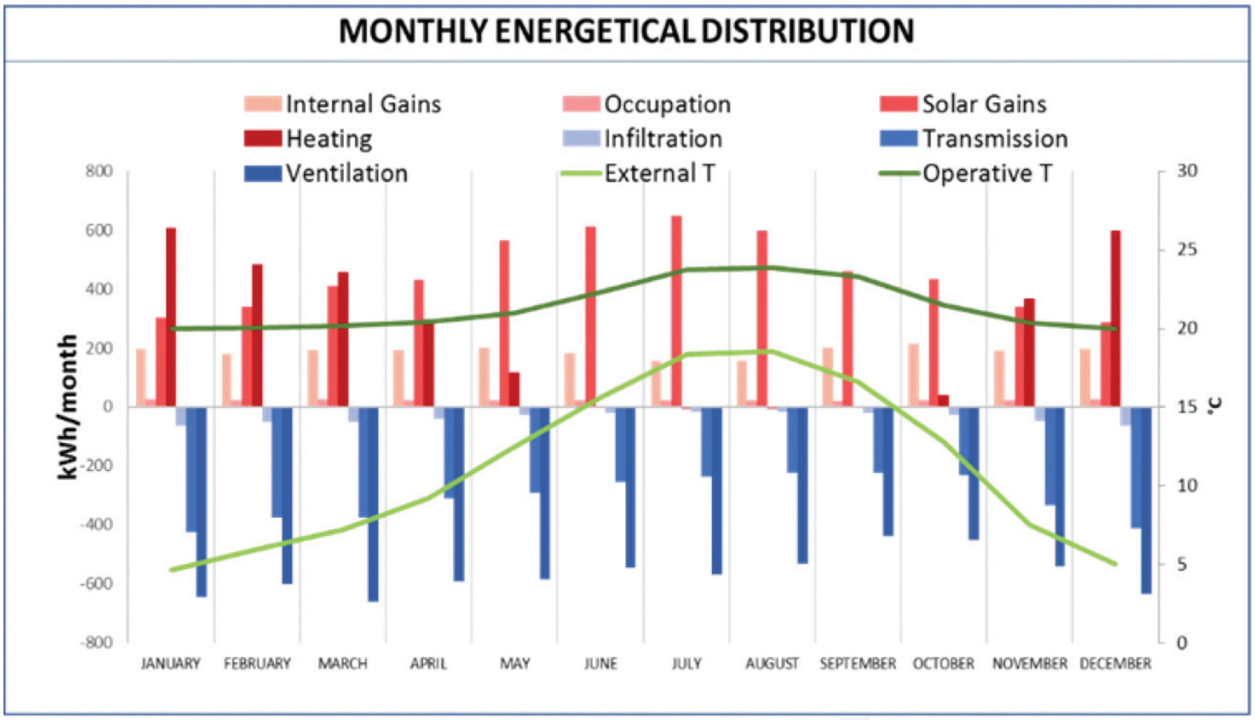

Figure 6. Energy gains and losses every month.

T_{ext} as well as the exergetic factor (the ratio between the exergy and the energy demand) were added.

In a similar way, the DHW demand is obtained based on a standard hourly profile defined by IEA-SHC Task26 software [42]. The annual DHW energy demand is 459 kWh/y·pers and the exergy demand is 46 kWh/y·pers. Then, **Figure 9** represents the energy and exergy DHW

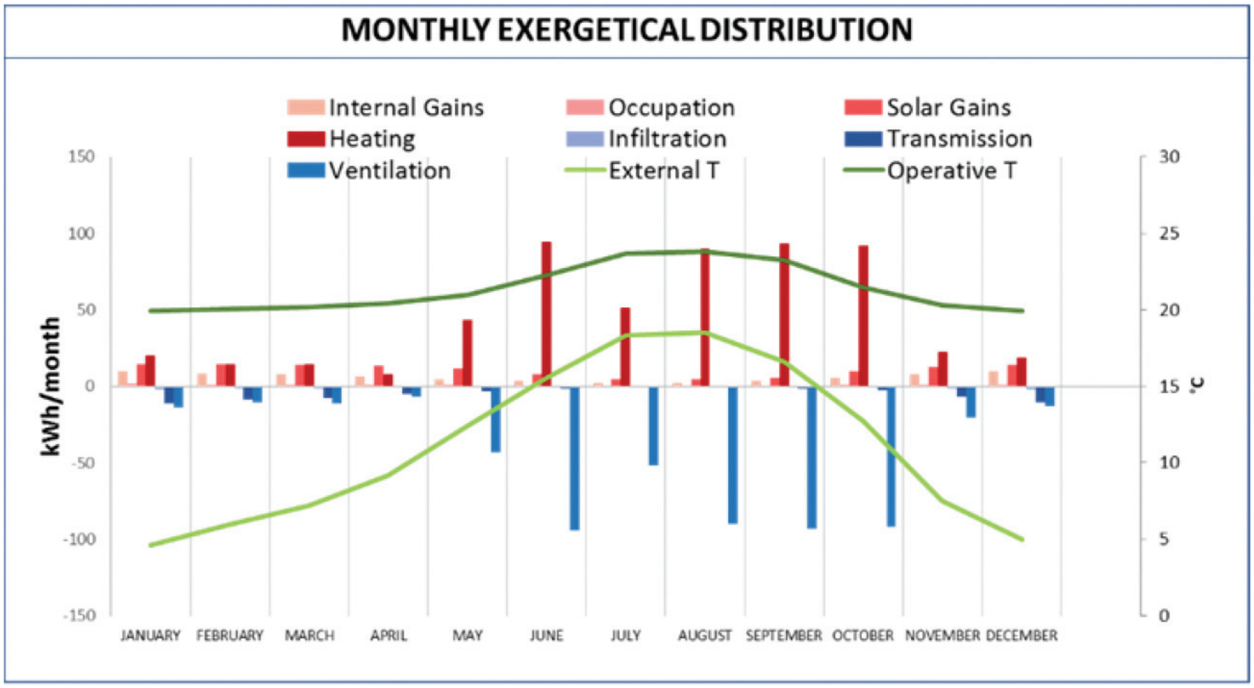

Figure 7. Exergy gains and losses every month.

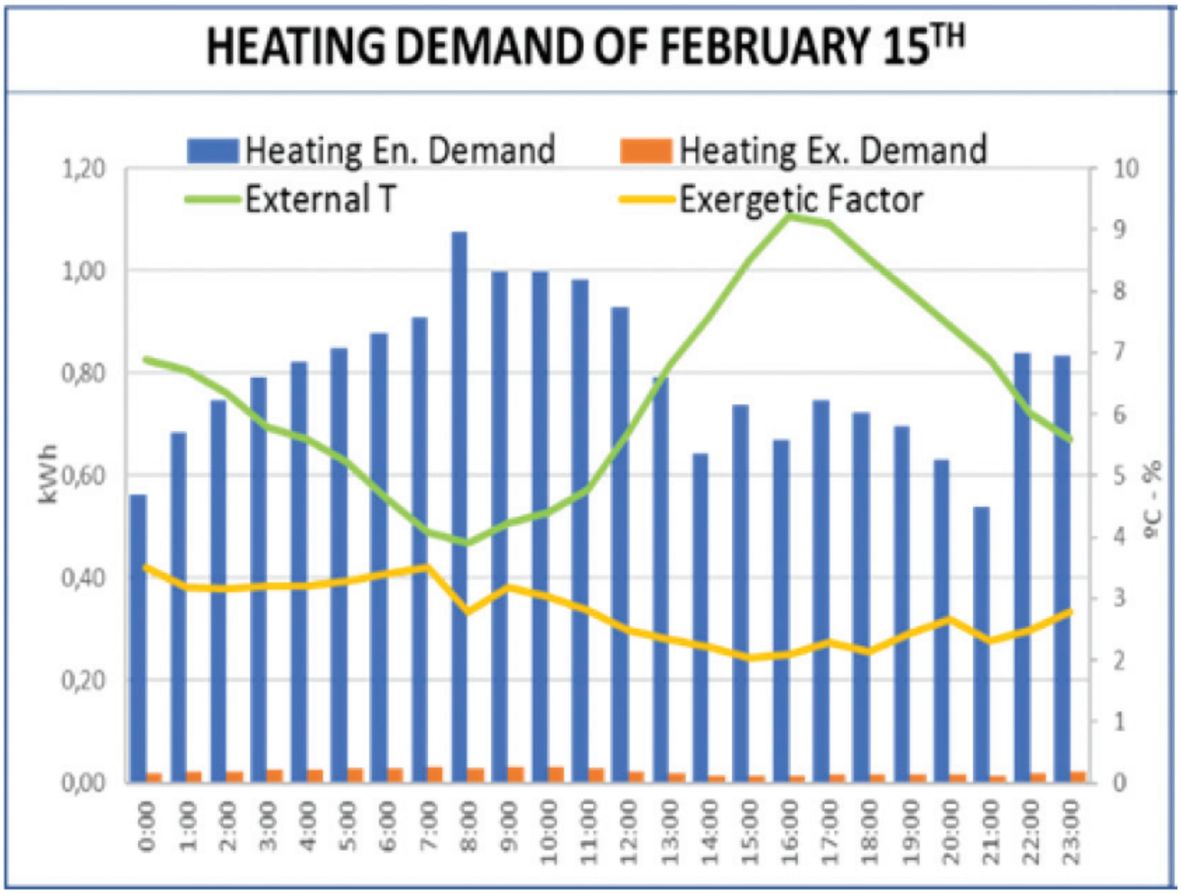

Figure 8. Q and E heating demand for winter typical day.

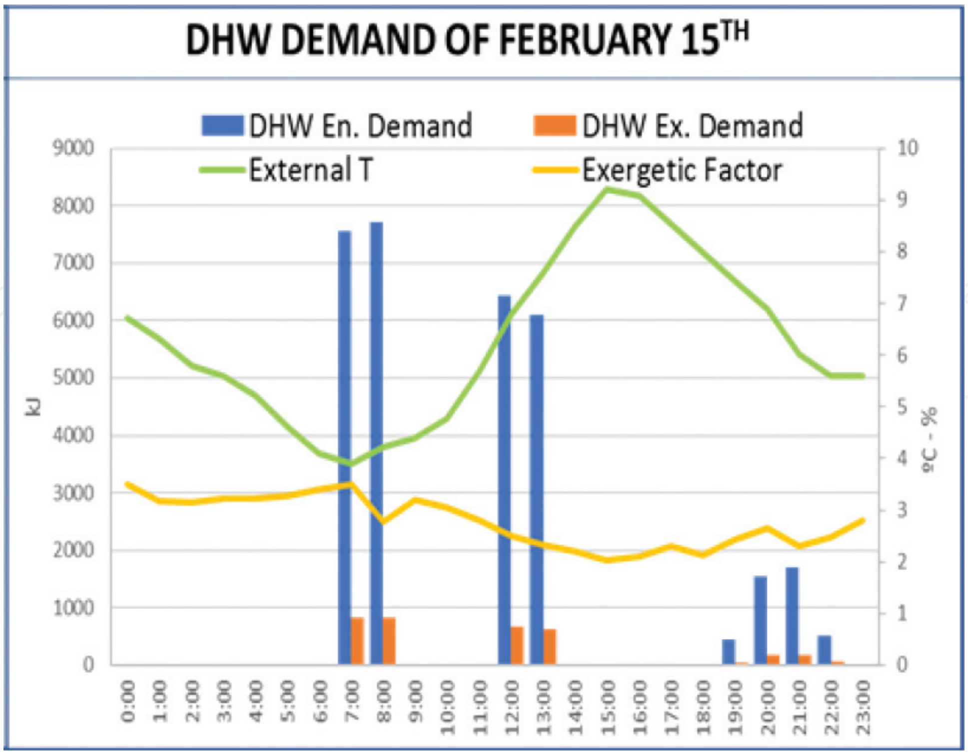

Figure 9. Q and E DHW demand for winter typical day.

demands for the same day February 15th as well as the external temperature and the exergetic factor for DHW.

4.2. Study of the facility

The facility portrayed in **Figure 3** of the previous section was simulated by means of TRNSYS v17. As it is shown, there are two principal circuits: the heating and the DHW branch. The heating demand is mainly covered by a biomass boiler whereas the DHW is provided by a combination of solar panels and an air-to-water heat pump. This circuit incorporates also two tanks: one for the solar income and the other one for the DHW storage.

The various components appearing in the case study were simulated using simplified models available in the TRNSYS software library, which try to represent their real performance as faithfully as possible. In addition, the calculated DHW and the real heating demands were simultaneously inserted in that simulation. The modeling was implemented for a period of a year with one-hour time step.

Once the simulation was performed, the thermodynamic data of every flow was extracted and the energy and exergy hourly values were registered. Hence, considering the Q and E yearly accumulated values **Figure 10** was constructed. In that **Figure 10** five stages were taken into account, moving on from the resource acquisition to the product fulfilling: primary energy, generation, distribution, storage and demand.

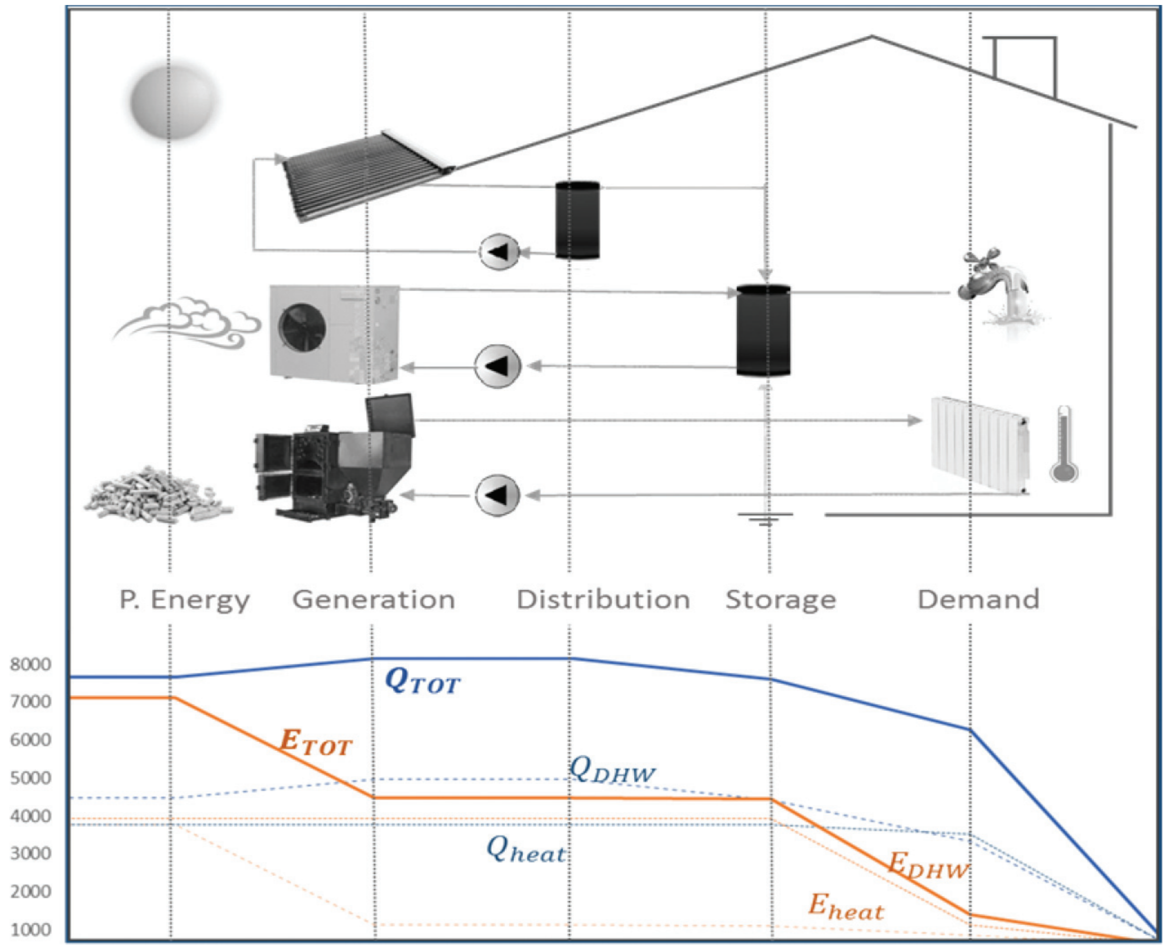

Figure 10. Energy and exergy transformation chain during the thermal facility.

The blue line illustrates the energy transformation chain whereas the orange one symbolized the exergetic one. Likewise, the full lines allude to the total results (Q_{TOT} and E_{TOT}), the dotted lines represent the DHW (Q_{DHW} and E_{DHW}) circuit, while the blinking ones refer to the heating branch (Q_{Heat} and E_{Heat}). This is a decisive graph in order to understand the quality of the energy used to provide the demand; as it can be observed, the exergy curve is notably lower than the energy one.

It may appear strange the opposite direction the Q_{TOT} and E_{TOT} lines have between the Primary Energy and Generation transformation phase, as the first one goes upwards and the second's tencency is downward. This is because, in this stage, the heat pump's coefficient of performance (COP) is considered. That value is determined by the ratio between the heat extracted from the condenser of the unit and the energy usage of the compressor. For instance, a COP value of three means that the consumption of 1 kW of electrical energy releases 3 kW of heat at the condenser. Therefore, it is always a factor higher than the unit.

However, if the quality factor of the energy is considered (i.e. the exergy amount), the value would radically decrease. This happens because electricity is pure exergy and only a part of heat energy can become in useful work, so that, by definition, the exergetic efficiency will be always less than one. In this example, whereas the yearly average COP of the heat pump is 2.85, the exergetic efficiency is $\varepsilon_{HP} = 0.28$.

Something similar occurs with storage units: as the only losses considered in energy analysis are the thermal losses, their efficiencies are close to the ideality of 100% (as it is the case of adiabatic tanks). Nevertheless, the irreversibilities occurring due to the mixing of flows at different temperatures are not contemplated there, as it happens in the cases of cold water flow mixing with the tank's hot water. In this example, the yearly average energy efficiency of the DHW storage tank is $\eta_{T1} = 81\%$ and the exergetic efficiency is $\varepsilon_{T1} = 54\%$.

All in all, the overall energy performance of the whole facility is $\eta_{TOT} = 81\%$, whereas the exergetic efficiency is $\varepsilon_{TOT} = 13\%$, as the energy conversion irreversibilities are now accounted. Likewise, the simple observation of the exergy profile E_{TOT} indicates where the greatest exergy destructions occur: during the transformation from primary energy to the warming up of the circuit and from the tank output to user's final demand. Similarly, the large-scale differences between exergy and energy are shown.

4.3. Cost and environmental impact analyses

As mentioned before, the exergoeconomic analysis was carried out in order to account the intermediate and output product flow costs. As the facility is very simple and there are only a few units, the final demand results have been presented directly.

The heating unitary (referred to energy) average cost appears to be $c_P^{heat} = 6.89 \frac{c€}{kWh}$, whereas the DHW unitary (referred to energy) cost is $c_{P,HP}^{DHW} = 21.81 \frac{c€}{kWh}$ when the demand is exclusively generated by means of the heat pump and it is diminished to $c_{P,S}^{DHW} = 17.99 \frac{c€}{kWh}$ thanks to the solar thermal collectors.

To obtain these results, the acquisition, amortization and maintenance costs of every equipment have been taken into account. Furthermore, an effective annual rate of 0.05 and 20 years of useful life were considered so that results in a recovery factor of 0.08. If those fixed costs were not contemplated, the solar collector contribution would be null, or what is the same for free.

In spite of the heat pump's irreversibilities, heating production is less expensive than DHW generation since fewer equipment are connected between the primary energy consumption and the demand side. After all, as mentioned before, the cost is related to its formation process, and consequently, lower irreversibilities are accumulated along the heating path.

Discussing about environmental impact, the following considerations can be forwarded: first, it must be noted that performing a LCA for each component of the system requires a learning time and a knowledge that are not the objective of this work. Besides, the results obtained in other studies show that the environmental impact the units have in the final products is really small. For these reasons, the exergoenvironmental analysis has been carried out considering only the CO_2 emissions associated exclusively with the input resources, $b_{e,i}$ (CO_2/kWh) and not with the equipment that make up the energy facility.

Following those simplifications, the analysis was carried out and the average results were obtained. For instance, the environmental impact related to the heating branch is $b_P^{heat} = 0 \frac{kg_{CO_2}}{kWh}$. This null effect is because biomass is considered as a renewable source with a neutral CO_2 emission balance. On the other way round, the DHW environmental impact corresponding to the heat pump generation is $b_{P,HP}^{DHW} = 0.65 \frac{kg_{CO_2}}{kWh}$ while the DHW coming from the solar panel is zero as the sun is a sustainable source.

5. Results and discussion

The building sector is responsible for almost a third of the total energy consumption over the world and this justifies the great concern for the improvement of their energetic efficiency. For this reason, great advances have been prompted in energy regulations during the last decade; moreover, the Directive 2010/31/UE already lays down a broad definition of a nZEB and establishes the 31st of December of 2020 as the deadline for making all new buildings nZEB. Nevertheless, it allows the Member States to draw up national plans for increasing the number of nZEB and, undoubtedly, this is the first step toward the positive energy building. In that context, many authors have worked in the optimization and design of thermal systems for buildings, but unfortunately, most of them were done from a purely energetic point of view.

One of the aims of this paper is to show the differences between the energy and exergy performance of the whole energy supply chain of buildings. For that, the whole way from the primary energy until the demand covering is considered. In this regard, energy and exergy analysis are performed to a recognized a nZEB situated in Álava, Spain, (*with* Passivhaus certificate) following the First and the Second Law of Thermodynamics through a yearly dynamic analysis.

The yearly heating demand amounts $Q_{heat} = 2.96\ GWh/y$ and the yearly DHW demand is $Q_{DHW} = 2.76\ GWh/y$. Translated into exergy values those demands are $E_{heat} = 0.56\ GWh/y$ and $E_{DHW} = 0.27\ GWh/y$, respectively, being evident the low-quality factor of both. The energetic performance of the heating circuit is $\eta_{heat} = 93\%$ and the exergetic efficiency $\varepsilon_{heat} = 17\%$. Meanwhile, the DHW generation circuit efficiencies are $\eta_{DHW} = 71\%$ and $\varepsilon_{DHW} = 0.09\%$.

As a result, even being a nZEB, energy saving enhancements can be accomplished as long as the energy quality is considered in both the building thermal envelope and the thermal facility. A reduction of the exergy resource consumption implies that less high-quality energy is needed and, thus, low-quality energy sources can be used instead (such as residual heat) to cover the demand.

Besides, one of the outcomes of the exergoeconomics and exergoenvironmental analyses are the allocation of costs and environmental impacts, to final products and intermediate flows, based on physical criteria. In this way, the heating and DHW final specific costs depending on their cost formation were obtained and shown in Section 4.3.

Thus, the use of exergy as a base variable supports both the energy efficiency (focusing on the required energy reduction) and the enhancement of the use of renewable energy, both in economic and environmental terms. The European directives related to energy efficiency in buildings should contemplate, therefore, the exergy as an additional basis of study.

6. Conclusions

The conventional energy studies are based on the First Law of Thermodynamics. This type of analysis is confined to a simple energy accounting, which quantifies the energy inputs and outputs of a system and particularly of a building. In this way, the energy given to the processes through fuels, electricity, flows of matter and so on, must appear into the final products or by-products. Under this perspective, energy losses are the not used heat flows. Thus, the analysis based on the First Law suggests that the loss of efficiency of an equipment or a process is a consequence of those waste heats.

There are currently different ways to state the energetic efficiency of a system or component based in this First Law and none of them takes into account the quality of energy. Thus, with those efficiency definitions the same weight can be assigned to different forms of energy, regardless of their quality. Correspondingly, this conveys some drawbacks, for example, the fact that the performance of the Carnot engine is the Carnot factor instead of the unit (which is what one expects for the perfect engine); or even the point that the heat pumps efficiency is expressed through the COP (an index always greater than unity) and so on. Furthermore, large thermoelectric plants, which are regarded among the most efficient energy conversion systems, have low performances (between ~ 40 and 55%); while typical individual hot water boilers, which are thermodynamically much less efficient devices, appear to have higher performances (~90%), a fact that seems contradictory.

By contrast, the exergy-based efficiencies describe better the way in which the resources are used and provide a clearer guidance about the possible improvements. Both, the exergy destruction and the entropy production, are valid measures for the irreversibility of a process. However, the use of entropy makes difficult to assign a meaning to the loss due to the encountered irreversibilities. On the other side, the exergy method allows assessing directly the real losses of a process, that is, it evaluates the decrease in the available work because of the process transformation irreversibilities. Accordingly, the irreversibilities measure the system inefficiency and the exergy method quantifies them and enables identifying their location.

Notwithstanding these advantages, the exergetic method does not allow determining the effect of each equipment irreversibilities over the required additional consumption; it does not permit determining the impact of an improper operation due to a particular equipment. To achieve that objective, exergoeconomics was developed, which is a science that combines the Second Law with economic concepts. It develops the concept of exergetic cost, which reflects the required exergy to produce any flow, calculated from its formation process. Consequently, this exergetic cost is the weighting factor for accounting every irreversibility regarding the global resource consumption. To determine those exergetic costs, in addition to the exergy flows, the productive structure of the installation must be defined [27].

Based on the same exergetic fundaments, Exergoenvironmics was evolved which accounts for the irreversibility formation in terms of environmental impacts. These types of analyses are especially suitable for larger scale installations, such as district heating systems. Both Exergoeconomics and Exergoenvironmics can also be used in energy audits, since they allow detecting the places where losses occur and quantifies their costs and environmental impacts. This fact makes easier to propose profitable improvements. Likewise, they can be applied to the design and synthesis of energy plants as they provide the designer with information about the cost formation process, the interactions among thermodynamics, economics, environmental impacts and the interactions among the plant components. This information is especially useful for the design of energy supply systems.

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Abbreviations

EED	energy efficiency directive
EPBD	energy performance of buildings directive
nZEB	nearly zero energy buildings
DHW	domestic hot water
ECT	exergetic cost theory

Nomenclature

$\dot{Q}_{demand}$ (kW)	energy demand of the building
$\dot{Q}_{trans}, \dot{Q}_{vent}\ \dot{Q}_{inf}$ (kW)	transmission, ventilation and infiltration losses
$\dot{Q}_{g_{solar}},\ \dot{Q}_{g_{int}}$ (kW)	solar and internal gains

T_0, T_{op} (K)	ambient temperature and building operative temperature
$\dot{m}_{vent}$, $\dot{Q}_{vent}$,$\dot{E}_{vent}$ (kg/h) (kW)	ventilation mass flow rate, energy and exergy
$\dot{E}_{in,k}$, $\dot{E}_{out,k}$ (kW)	input and output exergy flow of kth component
$\dot{E}_{D,k}$ (kW)	exergy destruction of kth component
F_k, P_k, R_k, I_k (kWh)	fuel, product, residues and irreversibities of kth component
η_k ε_k (%)	energy and exergy efficiency of kth component
$k^*_{F,k}$ $k^*_{P,k}$ $(-)$	unit exergy cost of the fuels and products of kth component
$c_{F,k}$ $c_{P,k}$ (€/kWh)	unit exergoeconomic cost of fuels and products of kth component
$c_{e,i}$ Z_k (€/kWh)	unit external resources cost and inversion, maintenance and other operating costs of kth component
$b_{F,k}$ $b_{P,k}$ (pts/kWh)	specific environmental impact of fuels and products of kth component
$b_{e,i}$ Y_k (pts/kWh)	unit external resources exergoenvironmental impact and construction stage, maintenance, operation and disposal impacts of kth component

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