Comments and Suggestions for Authors:

Application of thermoeconomics in HVAC systems

Before answering any point, we would like to thank you for handling our manuscript and thanks also the reviewers for taking time on us.

We believe that due to the enhancements driven by the reviewers our new version of the manuscript can be suitable for publication in Applied Sciences (ISSN 2076-3417).

Reviewer #2:

The authors present a thermoeconomic analysis of a residential building. Although the subject may be of interest, there are already several applications in the literature, and the novelty and contribution of this work should be further justified and supported by a relevant literature review that is currently missing. Moreover, the authors should compare the exergy analysis that they have performed to a traditional energy analysis, since similar result could have been obtained by a normal energy analysis, and so the benefits of this increased complexity are not clear. Without solving these two major issues I don't think that this paper can be accepted for publication in an international journal.

We apologize for the comment of the reviewer. However, we consider all the comments of the reviewer and create a new version of the paper. We honestly think that, thanks to the suggestions given, the work is now enhanced and suitable for the publication.

The issues are bellow answered and justified one by one.

These are the major issues to be addressed:

- *The first part of the introduction should be strengthened, by giving relevant literature sources to support the claims of the authors.*

Following the reviewer's advice, we improve the literature review by erasing the old references and updating them with works that are more recent; specifically, we add 11 more references. Predictably, by including new bibliography, the test is enhanced and the work is now better enclosed in its framework.

Consequently, many works of the bibliography were published in the last four years (from 2016 forward, most of them from 2018-2020). In addition, the following paragraph was added which refers to the most recent book of this topic (dated in 2019).

"Above all, the recent published book of Ref.[5] can be considered one of the most complete works connected with Exergy Analysis and Thermoeconomics of Buildings where all the issues related to design and exergy application in buildings is deeply explained."

- *A proper literature review of similar works is missing.*

The answer is given in the previous comment.

- *Lines 260-262: It seems that the authors have a monitoring system in place to obtain all the measures they need. In this case, why it is necessary to build such a complex simulation model if energy consumption is already available? They should further specify which data they are retrieving from the monitoring system (e.g. provide a table with parameters and time steps) and if the heat demand is simulated by their model or simply computed from monitoring data on water mass flow and temperatures.*

The reviewer is right: the previous sentence was ambiguous and one could think that the data were directly obtained from a monitoring system; unfortunately, the monitoring system of this facility does not provide the data of every flow but only specific thermodynamic values and consumptions. Therefore, in our case study, a Trnsys model was created and the simulation results of each flow were used. That is why we modify the sentence to the following one: "*the required data for the mass, energy and exergy balances are obtained from the software, being basically the flow rates and temperatures of each flow*".

Besides, in order to achieve a faithful simulation-model of the system, some validation proves are required, which are explained in Ref. [13]. Because of space reasons, the modelling explanation does not appear in this paper. Accordingly, in order to justify the simulation, the following is included in the paper: *"[…] transient simulation tool TRNSYS v17 [32] was used to model the heating and DHW thermal facility. […]. Because of space reasons, the method to validate the model does not appear along this work, but is the one developed in Ref. [13], and appears also in Ref. [5]; if the reader wants to deepen on model validation with Trnsys Ref.[33] can also be read."*

In any case, as mentioned, monitored data is many times not enough to have the whole picture of the system since the sensors are located in strategic positions for control purposes. Therefore, apart from real data collection, a "modelling approach" is required to calculate the rest of data; that is, by simulation programs with black-, white-, or grey-box modelling approaches. This fact is included in the methodological section of the paper: *"Indeed, real data collection methodology is often linked to the modelling approach, since the sensors are limited and are usually located in strategic components or pipes for satisfying control purposes."*

On the other side, the heating demand profile was simulated hour by hour by joining the building Autocad model and TrnBuild interface. This was afterward adjusted according to the monthly bills. DHW was calculated following IDAE: *"Besides, the heating demand was calculated hourly by linking building Autocad model with the TrnBuild interface (and by comparing the results with the monthly bills) and the DHW demand was obtained following the recommendations given by the Spanish Institute for Diversification and Energy Saving (IDAE) Refs.[34],[35]. "*

- *I am a little bit puzzled about Table 3. Firstly, I would use "input" instead of "fuel", since most components deal with energy carriers that are no fuels.*

Answering the reviewer's doubt, "fuel" was used instead of "input" because it follows the terminology used in Thermoeconomics. It does not refer to a physical fuel input (fossil fuel, electricity, etc.) but is the word used to identify the resources that feed each component. If "input" would be used instead, the physical incoming flows would be considered (i.e. in a heat exchanger there are 2 incoming flows and one correspond to the fuel and the other one is part of the product) and that does not follow the definition of F.

Such explanation is given in the "methodological section" of the paper as follows: "*The first stage, to identify the cost formation process, consists of defining the productive structure of the system and this implies the classification of the flows linking components in fuel, F, that is resources* *required in the component to perform the energy conversion and product, P, the flows that are the production objective of each component."*

> *Moreover, from Figure 3 the component M1 seems to receive heat produced from the engines only (C1 and C2) and I don't understand how its energy input could be such high in comparison with the energy output of the engines. The same issue stands from component HC: how can it receive 16 GWh of energy in input if all the generators seem to produce together an order of magnitude less of energy?*

We really like the point of the reviewer. This issue is exactly one of the mayor troubles of thermoeconomic application, which is now described along the "methodology section": *it is related to the definition of productive structure, which is in a way ambiguous. For the moment, although historically many methods exists (such as Last-In-First-Out Approach (LIFOA), [27]; Specific Exergy Costing (SPECO) approach, [28], etc.), there is not an exact definition of how to define the productive structure since it can vary according to the purpose of the analysis and the experience of the researcher. On the contrary, one versatility of structural analysis is that the system can be disaggregated as many times as the problem requires. If, for example, a deep analysis of a boiler wants to be done, it can be separated in different sub-components that are related to a specific process of the burning, as done in Ref. [29], such us mixing of the fuel and air, the combustion process, the heat transmission between fumes and walls, the heat transferred to the water flow, etc. Consequently, a specific F and P would define each of those selected sections. Conversely, if boilers performance are not prominent in the analysis, a single component can encompass all the combustion engines and less mathematical effort would be required. Obviously, the greater disaggregation would suppose a better understanding of the process but would require more data and calculations."*

Accordingly, the reason why the fuel (and not input) of the M1 is high in comparison with the energy product (and not output) of the cogeneration engines is precisely the definition of each F and P: The product of cogeneration engines are defined as the enthalpy increment in between the outgoing flow and the incoming one plus the produced electricity. That is: $P_{C1}= E_1-E_3$ and $P_{C2}= E_2-E_4$. However, the fuel of the M1 is: $F_{M1}= E_1+ E_2$ and that is why both values cannot be directly compared.

Something similar happens in the HC. The fuel was defined as the sum of incoming flows, $F_{HC}= E_{12}+ E_{14}+ E_{17}+ E_{22}+ E_{25}$, and the product as $P_{HC}= E_{15}+ E_{18}+ E_{21}+ E_{20}+ E_{23}$. However, as the reviewer suggests, one can define the HC in another way such as: $F_{HC}= (E_{12}- E_{21})+ (E_{14}- E_{15})+ (E_{17}- E_{18})$ and $P_{HC}= (E_{20}- E_{22})+ (E_{23}- E_{25})$ and different results would appear.

All this explanation is included in the text.

> *This table should be revised, possibly with a chart such as a Sankey diagram where the energy flows are represented (or a Figure similar to Fig. 1).*

The way to represent the productive structure is done by a productive diagram. Therefore, following the reviewer's instruction a Figure with such structure is included in the text with its corresponding explanation. This is: "*Figure 7 represents the structural diagram chosen for the case study: each main component is represented in a box composed by an entering flag (which represents the fuel) and an outgoing flag (the product); besides, diamonds and circumferences are used to reflect the junctions and bifurcations of the flows."*

- *Similar problems arise in Table 4. Additionally, I am not sure that mixing together the energy/exergy output of engines gives a comprehensive view on the system.*

This matter is answered in the previous question.

- *Why the PV panels are not considered in this model? I expect that during the times in which they can fulfill the electricity demand of the building, the use of engines would not be required, am I right?*

We agree with the reviewers comment: PV panels can also provide electricity. In fact, the PV installation was designed with the idea of selling the electricity but, during the execution process, the economic incentives were eliminated, which seriously affected the expected profitability. It was evaluated to redesign the installation for self-consumption but, because of the multiple inconveniences, the initial purpose was kept. The remuneration received is equal to the market price (approx 5 c€/kWh), much lower than the remuneration that was originally planned with bonuses. Nevertheless, this fact is out of the scope of the paper.

Answering the reviewer's first question, the performance of PV panels was not analysed because only the heating and DHW thermal-demands were taken into account (i.e. users' electric demand was not considered). Despite this, the electricity produced by cogeneration (as a by-product) was considered because hydraulic pumps are fuelled by it.

Considering the reviewer's comment the following footnote was included in the work: "*This work focuses only on the heating and DHW thermal demands so, as electric demand is not considered, the implications of PV panels are not taken into account. Nevertheless, the cogeneration engines produce simultaneously electricity, which is used as fuel of hydraulic pumps of the facility.*"

According to the second question, the reviewer is right: during the times in which PV panels can fulfil the electricity demand of the building, the use of cogeneration engines is not required. Such matter is directly related to the control of the system. As said, the cogeneration engines follow the heating-demand (and not the electric-demand) while the PV panels cover electricity-demand. Therefore, the switching on and off of the cogeneration engines are associated to the thermal-demand of the building (and electricity appears as a by-product). That is why the following is included in the text: "*The control system is programmed in such way that the priority is given to cogeneration engines, which are able to cover 90 % of the DHW demand. They turn on at any time when there is heating or DHW demand, since they are the priority units as they simultaneously produce electricity and heating.*"

- *The paper lacks information on the energy demand of the building, to compare heating and electricity demand and properly understand the final results. Some demand profiles should be included, since the authors claim they have calculated hourly profiles (e.g. an example of a winter day compared to a spring/summer day, the monthly consumption of heating, DHW and electricity). This would give a better framework of the case study.*

We go along with the reviewer's suggestion: a better framework of the case study will help to the system comprehension.

To begin with, a more specific explanation of the building envelope was given in order to justify the building modelling: "*The facades are made up of prefabricated concrete panels with an interior formed by a plasterboard panel and high levels of insulation; its transmittance value is 0.35 W/m2K. Special attention has been paid to correctly insulate the edges of the slabs in the encounter with the concrete panels in order to minimize thermal bridges. Because of the same* *reason, the encounters of the exterior carpentry of the façade are also made very carefully. The exterior carpentry is made of aluminum with frames whose transmittance is 1.9 W/m2K. The frame and glass assembly has a transmittance for the gap of 1.5 W/m2K. In the case of the roof, the transmittance is less than 0.24 W/m2K; all these values were below the regulatory requirements at the time of construction*."

Then, the way of achieving heating and DHW profiles was explained: "*Considering the building architecture, Autocad software was used to build the geometric model of the buildings. Then, the physical properties of the envelope and the users' profile were introduced through the TrnBuild interface of the transient simulation tool TRNSYS v17 [36]. The weather data of Vitoria-Gasteiz was also included in the simulation by the Typical Meteorological Year provided by the software. Accordingly, the heating demand was calculated hourly. That consumption was compared to the monthly bills, which were at the same time related with specific meteorological conditions, in order to adjust the building-model parameters. In addition, the DHW demand was obtained following the recommendations given by the Spanish Institute for Diversification and Energy Saving (IDAE) Refs.[38],[39], which considers the use of the building, the distribution of the dwelling and the number of tenants.* "

Finally, following the reviewer's advice, some demand profiles corresponding to a winter and a summer week were included. As previously commented, electric demand was not incorporate in the figure since only thermal demands are analysed in this work. Accordingly, the following paragraph was included: "*The heating and DHW demands and the outside temperature during a winter week (from 1st of January to 7th) and a summer week (from 1st of August to 7th) appear in Figure 5. As mentioned, the electric demand is not included since only the thermal demand, covered by boilers and cogeneration engines, was analysed".*

- *Finally, the results of the exergy analysis need to be compared with the results of a traditional energy analysis, to justify the value added by this approach, which is currently difficult to notice from the final results that are presented.*

We agree with the comment. After all, the objective of the paper is to highlight the extra information that is achieved applying exergy analysis. That is why the following is included: *"Compliant with the results, we have seen that the energy efficiency of boilers are higher than those of cogeneration engines, while the opposite happens with the exergy efficiencies. This means that, even if in terms of energy boilers seem to have better performance, the real losses are higher there than in cogeneration engines […].The energy efficiency for electricity production in the cogeneration units is 39.8% and the exergy efficiency 38.3%, the efficiency for producing heat and DHW is 86.4%, and the exergy efficiency is 4.2%. Finally, as a whole, the average energy efficiency of the energy supply system is 89.4% whereas its exergy efficiency is 7.1%."*

The conclusion section also incorporates the comparison: "*Although the average energy efficiency of the cogeneration engines (80%) is slightly lower than that of the boilers (92%), the results obtained prove that micro-cogeneration engines not only save energy (weighted by its quality) because they have better exergy efficiency (36%) than boilers (15%), but economically are attractive, even if they require a relatively higher investment. Indeed, according to the results, the combustion boilers are the lesser efficient components."*

Nevertheless, we want to make a step forward and go beyond the exergy analysis by applying thermoeconomics. Therefore, the rest of the analysis focuses on thermoeconomic results.

- *Please double check the English since there are some typos in the manuscript.*

The work has been reviewer by a native speaker in order to check the English of the manuscript.

Some further minor issues:

- *I suggest removing all the capital letters in the title of the paper.*

We accept the suggestion: all the capital letters are removed from the title

- *The abstract should be shortened, and ideally reduced to a single paragraph.*

Following the reviewers advice the abstract was shorten and condensed in one paragraph.

- *Section 1.1 (and/or 1.2) should be supported by the equations at the basis of the definition of the concept of exergy, to help the readers in understanding the representation of Figure 1.*

We agree that equations help the readers in understanding the Figure 1. Nevertheless, because of the lack of space and in order not to mislead the attention of the readers, the references that contains the mathematical support are given. Indeed, as mentioned, the most recent book published of this topic (dated in 2019) gathers all the detailed information.

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- *Figure 2 is a render and not a photo. Are these buildings existing or just under design/development?*

The buildings exist; therefore, a real photo is now substituting the previous render figure.

- *Line 239: What are the electric and thermal efficiency of the engines?*

That information is now included: *"Each of the combined heat and power engine can provide 5.5 kW of electricity, with a nominal electric efficiency of 27%, and 12.5 kW of heat, with a nominal thermal efficiency of 61%."*

- *Lines 348-350: This is true, but it should be discussed in a context where a PV system is already existing. How engines compare with boiler+PV as long as heating and electricity are concerned?*

The reviewer is totally right in the comment: combinations of different technologies should be discussed in order to provide the better configuration that minimizes the costs. Indeed, different control strategies are the key point for reducing energy consumption.

However, in any case and without considering the acquisition costs, providing heat with cogeneration would be always better than providing heat by boilers. After all, thermoeconomic assigns costs to the products according to the irreversibilities encountered along the system and boilers exergetic unit cost is greater than that of cogeneration. That is precisely what thermoeconomic allows: it makes a cost rational-sharing considering the irreversibilities of each component. That is included in the text like this: "*So, if only exergetic cost is considered (i.e. without considering acquisition costs), producing heat with cogeneration would always be more* *beneficial because there are less irreversibilities. However, cogeneration requires a relatively high investment, if we compare its purchase cost with the cost of buying a boiler with the same thermal power. Nevertheless, the net savings are positive*."

If one wants to include the analysis of the users' electric demand, the performance of PV panels should be included. Because of that fact, the following paragraph was added after the thermoeconomic analysis: "*On the other hand, one cannot forget that the electricity demand can also be fulfilled by the production of the PV panels. After all, the best configuration and the best control that minimizes the energy consumption needs to be analysed, but that is out of the scope of this work*".