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Dynamic exergy analysis of energy systems for a social dwelling and exergy based system improvement

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Abstract

This paper presents a study of the usefulness of the exergy approach in the development of energy systems for the built environment. The energy and exergy performance of five different energy systems for a social dwelling in a multifamily building from 1960's in Bilbao (Spain) are studied; two reference cases as well as three improved options. The total energy chain is considered from the energy demand to the energy resources and the analyses are performed using dynamic simulations. The exergy losses of energy system components are identified and quantified and efficiency values in terms of energy and exergy are evaluated. Based on an analysis of the exergy losses further improvements are investigated. This study has shown the exergy concept to be a useful addition to the energy concept, giving a more rational analysis than an analysis solely based on the energy concept. It has also shown that identification and quantification of exergy losses can support the further improvement of energy system configurations, leading to a further reduction of exergy losses and thus a further reduction of high quality energy use.

KEYWORDS: Exergy Analysis, Building Simulation, Exergy design principles, building retrofitting.

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1 Introduction

Developing sustainable energy systems is becoming more and more important in today's world due to the depletion of fossil energy resources and the global warming problems related to the use of these resources. Reducing the need for energy sources is a key factor in the development towards a sustainable energy future [1]. The built environment uses more than 40% of the total final energy consumption in the European Union [2]. A significant share of the energy use in buildings is related to heating and cooling and thus to near-environmental temperatures at around 20 °C. Due to this temperature level, the energy demand for heating and cooling in the built environment is mainly a demand for "low quality" energy. However, this demand is usually met by high quality energy carriers, such as fossil fuels or electricity. The building sector has a high potential for improving the quality match between energy supply and demand and thereby reducing the required input of high quality energy sources.

Exergy is a thermodynamic concept which can be regarded as the quality of a form of energy, by expressing the maximum theoretical work that can ideally be obtained from it in a given reference environment. In ideal energy conversion processes no exergy is lost, but in any real process exergy destruction takes place; exergy is therefore a more rational measure of the performance of an energy conversion process than energy [3]. Originally the concept was primarily applied to chemical processes and thermal plant analysis [4]. An extensive number of studies has been carried out in the last decades in this field, such as [5,6,7].

The exergy approach in the built environment is relatively new but may be considered an emerging field of science. The concept has been used in building efficiency studies with several international research projects, such as IEA ECBCS Annex 37 [8] and Annex 49 [9]. Also several studies on energy systems used in the built environment can be found in the last years, such as [10, 11, 12, 13, 14, 15, 16], to name but a few. Most exergy studies in the built environment are based on steady state calculations. Exergy analysis may also be fruitfully applied to renewable energy-based systems in order to identify the optimal use of the available renewable sources [17].

This paper applies the exergy approach to the assessment and development of (more efficient) energy systems for a social dwelling located in Bilbao, Spain. The exergy approach used in this study consists of two steps of which this paper describes the second one. In the first step promising energy scenarios were developed based on exergy principles and a steady state evaluation has been performed, as described in a previous research article [18]. In the present paper more detailed dynamic calculations have been performed for the two reference cases and the three most promising solutions presented in [18]. In addition the analysis of exergy losses occurring in each energy system component is used to assist the further improvement of the promising solutions, aiming at a further reduction of exergy losses.

2 Methodology

Like many exergy studies applied in buildings, this work also has been carried out using an input – output approach, described in [10] and [19]. The energy chain considered consists of the energy demand of the users of the building (heating, domestic hot water and electricity - cooling is not considered), the energy transformation components for conversion, storage and distribution of energy, and finally the resources. A scheme of the energy chain is shown in Fig. 1.

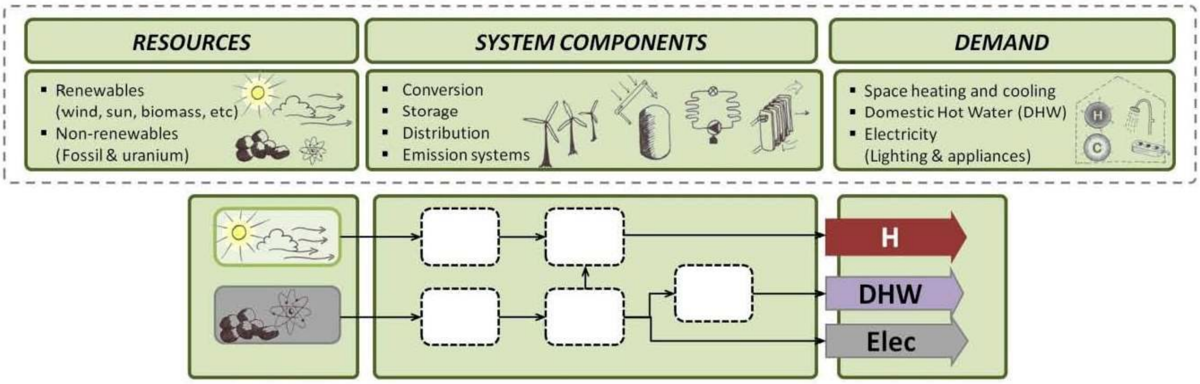


Fig. 1. Scheme of the energy chain

2.1 Dynamic energy simulation

The analysis has been performed using dynamic simulations by means of the well-known transient energy simulation software TRNSYS (V17). The energy demands for space heating are modelled using TRNSYS type 56. The study cases and related systems components, described in section 3, have been modelled and simulated according to the parameters presented in the Appendix. The weather data used for the city of Bilbao are obtained from the Meteonorm database available within TRNSYS.

2.2 Exergy calculation

The exergy values are calculated for each time-step (1-hour) of the simulation, based on the energy values and the relevant temperatures. This means the exergy calculations are in fact semi dynamic. Only sensible heat is taken into account in accordance with [20]. The reference environment is therefore simplified to the reference temperature T_0 only, for which the varying outdoor temperature at each simulation time-step is taken, as recommended in [19].

The exergy of an amount of energy is calculated by multiplying the energy with its related exergy factor (F). For heat at constant temperature T this can be calculated by means of eq. 1; for sensible heat of an amount of matter eq. 2 can be used (see also [10,18,21]).

$$\mathrm{F(Q)} = 1 - \frac{\mathrm{T_0}}{\mathrm{T}} \qquad \textbf{eq. 1}$$

$$\mathrm{F}(\mathrm{Q_{sens}}, \mathrm{T_2} - \mathrm{T_1}) = \left(1 - \frac{\mathrm{T_0}}{\mathrm{T_2} - \mathrm{T_1}} \cdot \ln \frac{\mathrm{T_2}}{\mathrm{T_1}}\right) \qquad \textbf{eq. 2}$$

The Exergy factors of inputs and outputs of the energy system components and of used fuels used are given in the Appendix. For Primary Energy the exergy content equals the energy content, since an exergy factor of 1 is assumed for the primary energy as is further explained in the appendix.

2.3 Electricity Production and calculation of the net primary energy input

In some energy system solutions presented electricity is produced at building level (e.g. by solar PV panels). No electricity storage is considered and therefore in each simulation time step there can be either a need for additional electricity supply from the grid or an overproduction at building level which has to be sent back to the grid. This means on an annual basis the sums of all electricity balances at each time-step results in:

- An annual amount of electricity input delivered by the grid, (E_{del});
- An amount of electricity exported to the grid (E_{exp}).

In order to evaluate the performance of the energy systems components these values are presented separately. However, in order to compare the different case studies the required primary energy input for the same output has to be compared and therefore the “Net Primary Energy Input” (NPE) is calculated using eq.3, according to [22].

$$NPE = \sum\left(E_{del,i} \cdot PEF_{E,del,i}\right) - \sum\left(E_{\exp,i} \cdot PEF_{E,\exp,i}\right) \qquad \textbf{eq. 3}$$

where the primary energy factor for delivered electricity ($PEF_{E,del}$) equals the primary energy factor for electricity exported to the grid ($PEF_{E,exp}$).

3 Description of the Case Studies

The dwelling studied is a social sector dwelling located in a multi-family building built in 1960. The net floor area is 52.52 m^2 and the plan is depicted in Fig. 2. The floor to ceiling height is 2.47 m. The dwelling has 3 external façades, oriented East, West and South, two of them (E and W) having windows. More detailed information about the dwelling the operation schedules (e.g. temperature set-points and internal gains) and the assumed energy systems can be found in the Appendix.

Fig. 2. Plan of the dwelling.

For the analysis only one dwelling is considered and the results are also presented on a dwelling level. The total building however consists of 36 dwellings and for the developed energy concepts the possibility of using the roof of the total building for solar energy as well as the use of larger equipment to serve the whole building is taken into account. The five case studies of this dwelling - two reference cases and three improved cases are described in the following sections and illustrated in Fig. 3. Further optimization of the three improved scenarios is described in section 5.

3.1 Case I and II. Reference Cases

There are two reference situations: Case I corresponds to the original situation of the dwelling, which represents the dwelling without any renovations since it was built in 1960. Case II represents the dwelling after standard renovation carried out by *Bilbao Social Housing*, which includes placement of insulation (4 cm of rock wool installation) replacement of the windows (clear double glazing), central heating using high temperature radiators and a natural gas combi-boiler. Air tightness is improved, and fixed ventilation rates are assumed according to the Spanish Technical Building Code [23]

3.2 Case III. New proposals based on exergy guidelines.

In the previous study [18] six improved scenarios were developed and studied by means of steady state exergy analyses. Three of them have been selected for evaluation under dynamic conditions in the present paper. Option 1 has been selected for it has the second best performance, after option 2, while being financially more feasible. Options 5 and 6 have been selected since these do not require the rather drastic revisions of mechanical ventilation and floor heating. The selected options have been renamed and they will be called Case III Option A, Option B and Option C. For all options increased insulation values of external facades and windows are assumed. The characteristics are described in the Appendix.

3.2.1 Case III- Option A

Case III-Option A represents the case with the most drastic improvements: A ventilation Heat Recovery system and a very low temperature floor heating system (35-30°C) are assumed. The space heating demand is met by a heat pump. Solar thermal collectors and PV panels are included (110 m^2 and 250 m^2 respectively for the whole building of 36 dwellings). The remaining heat demand for domestic hot water is produced by a condensing boiler. Option A corresponds to Option 1 in [18].

3.2.2 Case III - Option B

A moderate improvement has been studied in option B assuming a low temperature heating system (40-35°C), which can be realised with radiators. Space heating and domestic hot water demands are met by a collective combined heat and power unit (CHP), which also produces electricity (see also §2.3). No heat recovery unit is assumed and 360 m^2 of PV panels (for the total of 36 dwellings) is considered. This option corresponds to Option 5 in [18].

3.2.3 Case III - Option C

Case III - Option C is similar to option A but with less drastic improvements at building level; no heat recovery system is assumed and instead of very low temperature floor heating a low temperature emission system (40-35 °C) is regarded. Space heating is generated by a heat pump. The system includes solar thermal collectors for domestic hot water and PV panels (110 m^2 and 250 m^2 respectively). The remaining domestic hot water demand is provided by a condensing boiler. This option corresponds to Option 6 in [18].

3.2.4 Overview of the options

The main features of each studied scenario are presented in Table 1; In the Appendix the details of the energy system components of each case are presented. The schemes of the scenarios are presented in Fig. 3.

Table 1. Highlights of the dwelling for each studied scenario.

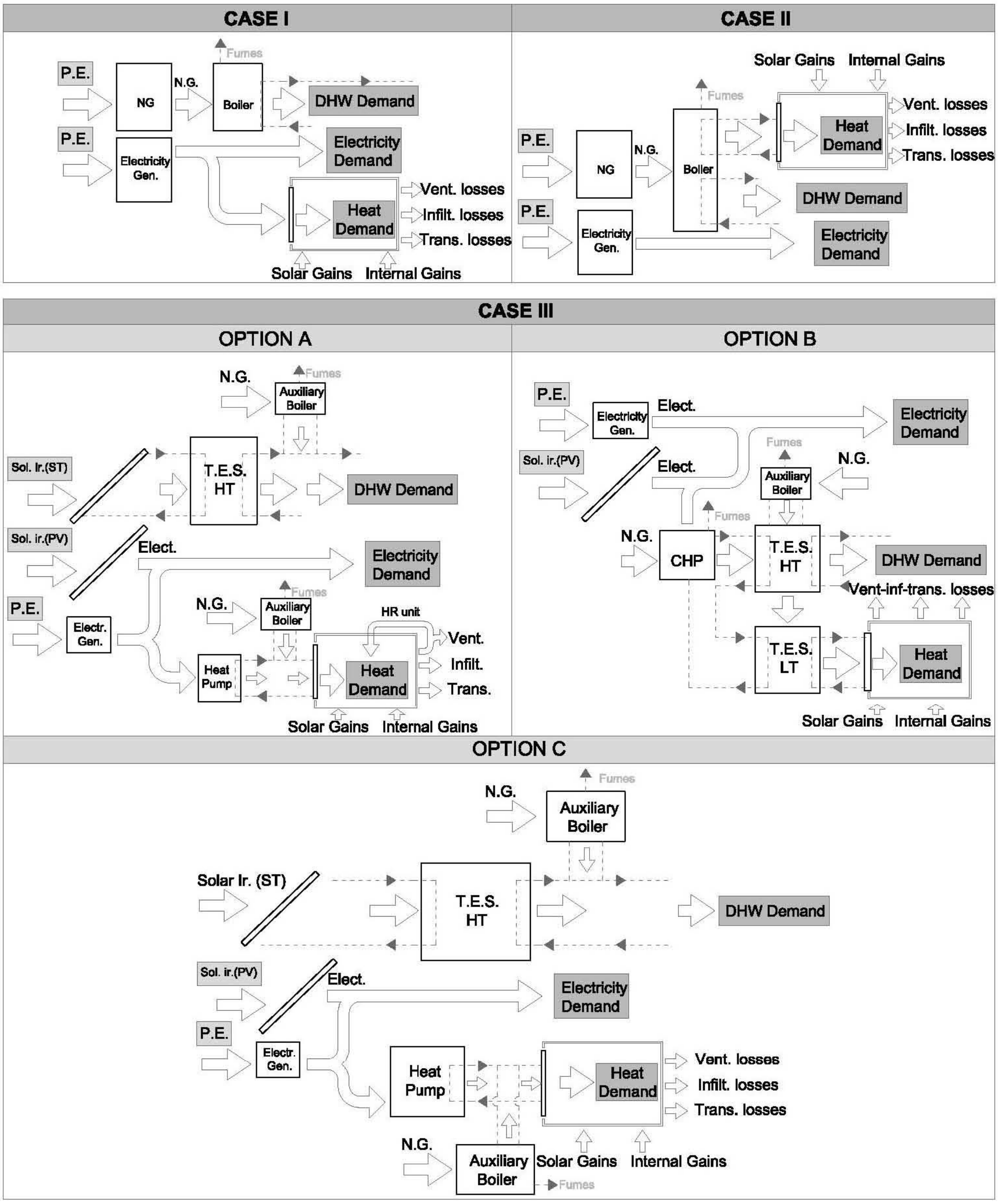


Fig. 3 Detailed schemes of the reference cases (Case I and II) and the improved options selected (Case III, options A, B and C).

4 Dynamic analysis: results and discussion

4.1 General results

In Table 2 the resulting energy demands as well as primary energy input for all cases is presented.

Table 2. Annual energy and exergy demands and P.E inputs [†].

The energy demand of Case I is 26.166 MJ/year and in case II it is reduced to 16.044 MJ/year. The exergy values are 1035 and 613 MJ/year respectively. Case III-Option A results in a demand for space heating of 7560 MJ/year due to the use of ventilation heat recovery, while cases III- Options B and C have a space heating demand of 14375 MJ/year, being a little lower than Case II. The exergy demand of all cases is considerably lower than the energy demand, as is previously explained in [18]. As can be seen all improved options (Cases III) include electricity exported to the grid. The net primary energy input is calculated as explained in 2.3.

The resulting net primary energy input as obtained from dynamic analysis confirm the results obtained in the previous steady state study. As could be expected, Case III-Option A is the best performing case, because it includes ventilation heat recovery and very low temperature (floor) heating emission system. As described in [18] the results are quite sensitive to the actual components characteristics as well as on the primary energy factor for national electricity production. The detailed analysis of the losses can be found in the next paragraph.

4.2 Detailed analysis of exergy losses of system components

The related values for energy and exergy for each component in every case can be found in Table 3 and Table 4. The different calculation assumptions are explained in the Appendix.

Of each case the performance of the energy system components is summarized (Table 3 and Table 4), by using the following parameters:

- η - (annual) energy efficiency, defined as: (used energy output) / (total energy input)
- L - (annual) energy losses, defined as: (total energy input) – (used energy output)
- ψ - (annual) exergy efficiency, defined as: (used exergy output) / (total exergy input)

[†] Authors' note: The results presented in this paper are somewhat different than those presented in [18], showing slight differences in three energy demand values. This is caused by the fact that the results in [18]were obtained using a 0.25h-timestep, although it mistakenly stated that a 1 hour timestep was used. These minor differences do not influence any of the conclusions or relevance of either paper.

- D - (annual) exergy destruction, defined as: (total exergy input) – (used exergy output)

4.2.1 Detailed results of Case I and Case II.

The results of Case I and Case II are presented in Table 3. In this table energy and exergy efficiency values (η and ψ respectively) as well as energy losses (L) and exergy destruction (D) in each component are presented.

Table 3. Annual performance of the energy system components used in cases I and II. (η = energy efficiency; L = energy losses; ψ = exergy efficiency; D = exergy destruction)

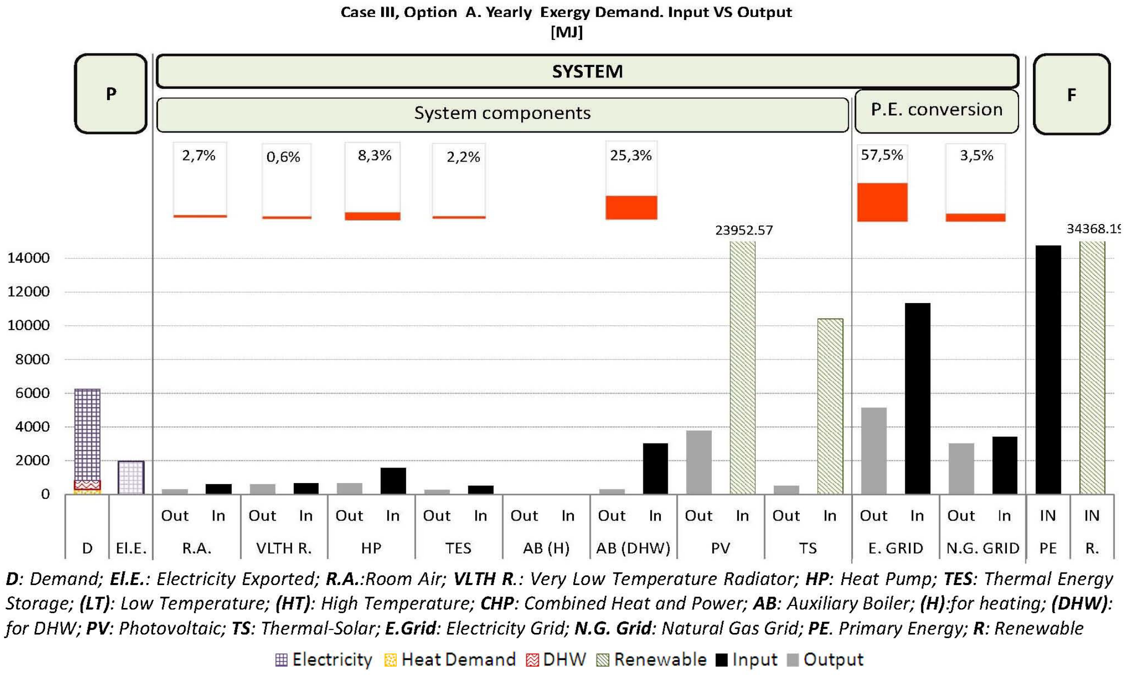
For both reference cases the largest energy losses occur in the primary energy conversion for electricity production. From the exergy values however it can be seen that apart from the electricity production large thermodynamic losses are present in the conversion of either electricity (Case I) or gas (Case II) into heat. These heating methods (resistance heating and combustion for heating) are therefore avoided in the improved options. Also, for both reference cases the losses in the component 'room air', showing the mismatch between the temperature of the heat supplied to the room and the temperature of the heat required, are significant: in Case I (where 150 °C on the heater surface is considered) the exergy output of the electrical heater is 8712 MJ/year to cover an exergy heat demand of 1035 MJ/year, which means that almost a 90% of the exergy is lost in the mismatch. Case II shows smaller losses (also due to a lower demand), but there is still a significant mismatch between demand and supply. This is also improved in Cases III by using low temperature heating systems.

4.2.2 Detailed results of Cases III (A, B, C)

As in the previous section, energy and exergy efficiency, energy losses and exergy destruction values are presented in Table 4. This table is based on all the flows depicted in Fig. 3 and calculated by TRNSYS V17.

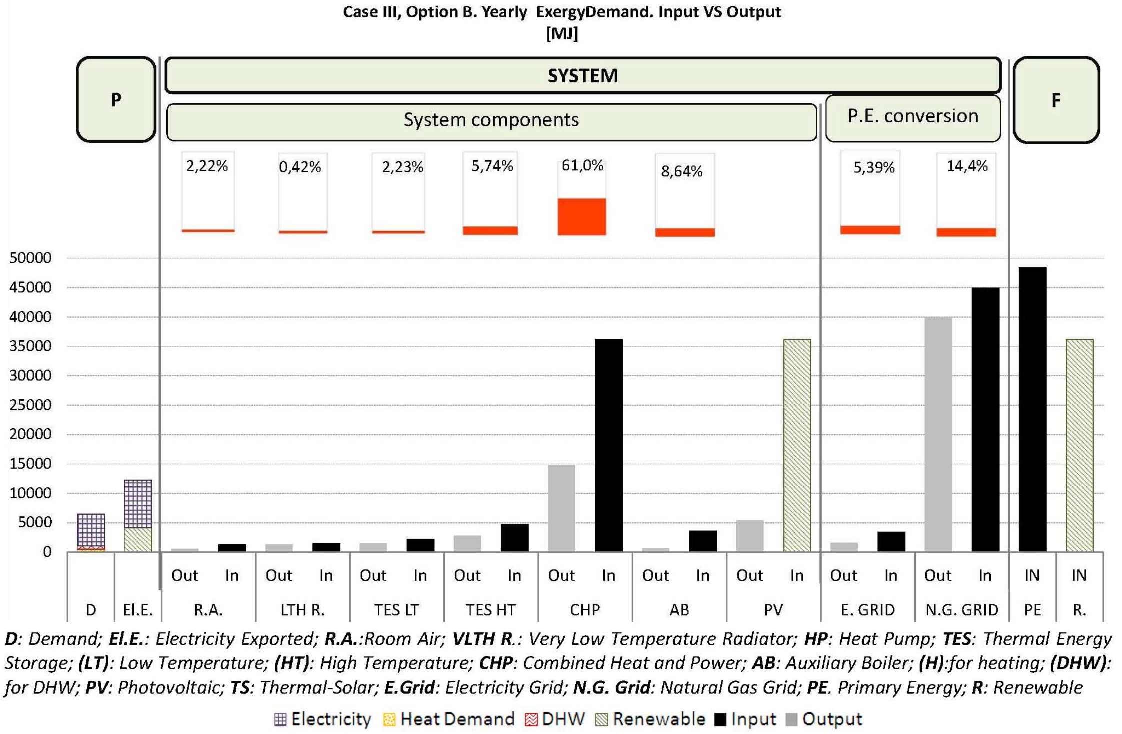
The results of Case III (Options A,B and C) are also graphically shown in Fig 4, Fig 5 and Fig. 6, where the losses occurring in each system component are presented. Also the relative contribution of each component to the total exergy losses of non-renewable primary energy is shown in the red bars in the upper part of each figure.

Table 4. Annual performance of the energy system components used in case III, options A, B and C. (η = energy efficiency; L = energy losses; ψ = exergy efficiency; D = exergy destruction)



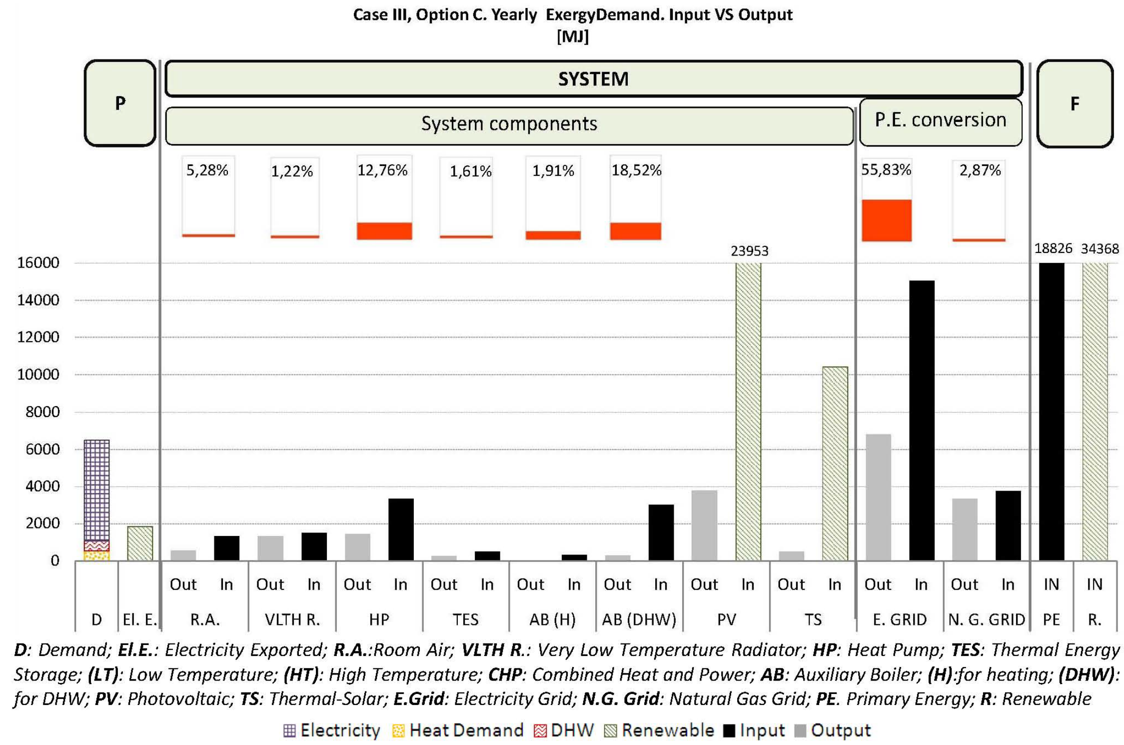
D: Demand; El.E.: Electricity Exported; R.A.:Room Air; VLTH R.: Very Low Temperature Radiator; HP: Heat Pump; TES: Thermal Energy Storage; (LT): Low Temperature; (HT): High Temperature; CHP: Combined Heat and Power; AB: Auxiliary Boiler; (H):for heating; (DHW): for DHW; PV: Photovoltaic; TS: Thermal-Solar; E.Grid: Electricity Grid; N.G. Grid: Natural Gas Grid; PE. Primary Energy; R: Renewable

Fig. 4. Detailed analysis of the input and output in each component of the system. (Case III-Option A)



D: Demand; El.E.: Electricity Exported; R.A.:Room Air; VLTH R.: Very Low Temperature Radiator; HP: Heat Pump; TES: Thermal Energy Storage; (LT): Low Temperature; (HT): High Temperature; CHP: Combined Heat and Power; AB: Auxiliary Boiler; (H):for heating; (DHW): for DHW; PV: Photovoltaic; TS: Thermal-Solar; E.Grid: Electricity Grid; N.G. Grid: Natural Gas Grid; PE. Primary Energy; R: Renewable

Fig. 5. Detailed analysis of the input and output in each component of the system. (Case III-Option B)



D: Demand; El.E.: Electricity Exported; R.A.:Room Air; VLTH R.: Very Low Temperature Radiator; HP: Heat Pump; TES: Thermal Energy Storage; (LT): Low Temperature; (HT): High Temperature; CHP: Combined Heat and Power; AB: Auxiliary Boiler; (H):for heating; (DHW): for DHW; PV: Photovoltaic; TS: Thermal-Solar; E.Grid: Electricity Grid; N.G. Grid: Natural Gas Grid; PE. Primary Energy; R: Renewable

Fig. 6. Detailed analysis of the input and output in each component of the system. (Case III-Option C)

4.2.3 Discussion

The reduced demands of case III are discussed in the previous paragraph. Related to the exergy losses of system components also many improvements can be identified: Due to the low temperature heating system the losses in the 'room air' component are reduced compared to Cases I and II: the output of the low temperature floor heating is 598 MJ/year (Table 4) to cover the exergy demand for heating of 302 MJ/year, which means an exergy loss of about 50% in the mismatch, quite less than the case I and II.

The negative energy losses of the heat pump presented in Table 4 are the result of not considering the free energy taken from the environment. In exergy terms the energy of the environment is by definition 0 exergy, thus the exergy losses of the heat pump represent the true exergy losses. The heat pump appears on the energy analysis to be the best performing component; however, in the exergy analysis it can be seen that there are still thermodynamic losses and the related ideal improvement potential can be identified.

From Fig. 4-6 it becomes clear that for Case III options A and C, (using a heat pump) the largest energy losses take place in the primary energy conversion for electricity i.e. the national electricity grid. The other losses are in energy terms all rather insignificant. In exergy terms however the losses of the auxiliary boiler are also important, which is even more striking when considering the small contribution of the auxiliary boiler to meet the total demand (see Fig. 4-6 and Table 4). Also the heat pump has significant losses according to the exergy principle.

In Case III Option B the biggest losses take place in the CHP, which also supplies most of the demand. It has to be taken into account that these losses from table 5 relate to the losses related to the total output including the large amount of electricity exported (see 3.3.3). Other relevant losses include the primary energy transformation and the thermal energy storage components.

5 Further improvements

The losses discussed in the previous section represent the thermodynamic ideal improvement potential of the system under consideration and point out the directions for improvement. In section 5.1 recommendations to further improve case III Options A, B and C are given. In section 5.2 some recommendations for Case III Option A have been tested using dynamic analyses. Case III Option A has been chosen since it represents the most ambitious energy concept and further improving it will show the highest potential of the exergy approach.

In practice the optimization of energy concepts usually has multiple criteria, such as costs or environmental impact. Some optimization strategies based on the exergy approach can be found in literature [24, 25, 26] but this is not further treated in this paper. The improvements sought in this research article relate to thermodynamic improvements, i.e. the reduction of exergy losses leading to a reduction of the input of (non-renewable) resources.

5.1 Recommendations based on analysis of exergy losses

From the identified exergy losses the directions for further improvements can be found. For the heat pump cases (Case III, options A and C) a main objective could be to minimize the use of the auxiliary boiler, for example by preheating the DHW using the heat pump. Furthermore the primary energy conversion losses are very large. It can be investigated whether increasing the ratio of PV on the roof will improve the total performance, although a negative consequence due to increased use of the auxiliary boiler should be avoided.

For option B a CHP with a higher electrical efficiency will increase the exergy efficiency of the CHP and thereby of the total system. The overproduction of electricity will however only make sense when a nearby electricity demand can be met.

For both options increasing the input of renewables (for example electricity from a nearby wind mill or biomass for the CHP) will decrease the primary energy input.

The exergy losses of renewable resources are also quite substantial. This is due to the fact that solar radiation is also high exergy and in case of the solar thermal collectors the output is low exergy heat. However, its exploitation with low exergy efficiencies has not the same relevance as in the case of fossil fuels. Solar energy is abundant and its destruction takes place anyway, regardless of human caption. The main problem with renewable sources is their availability. For this reason, more exergy studies in detail about storage systems and their repercussion on the global performance of the system could be interesting in further investigations.

Greater improvements can be achieved when the system boundaries of the improvements are shifted from the building level to the community level, since this increases the potential of for example using waste heat or applying the principle of cascading [19, 27].

5.2 Further improving Case A

According to the aforementioned recommendations, further improvements of Case A have been simulated. Three improved configurations have been evaluated.

5.2.1 Improvement 1. Increasing the PV area

As previously stated, the highest losses in option A take place in the production of Electricity from the Grid. For that reason, reducing the electricity need from the grid will be a good strategy to reduce P.E. input. For this aim, increasing the ratio of PV area on the roof in order to improve the total performance has been considered as potential improvement. However, this strategy can have a negative impact due to the reduction of supply from solar thermal panels (ST), which implies the increased use of the auxiliary boiler for DHW. Therefore a sensitivity check of the influence of the ratio PV-ST on the global performance has been performed.

Simulations with different PV to Solar thermal area (ST) ratios area have been carried out in this sensitivity check. ST collectors are assumed in the east side of the roof, as explained in [18]. The results are depicted in Fig. 7.

In this figure, X-axis shows % of available roof area with Solar thermal / PV. Assumed available roof area is 360 m^2, which equals 80% of the total roof surface of the building. The P.E (black line) depicts total Primary Energy input into the system, both regarding to NG and Electricity. The Net P.E. Input (green line) is calculated as described in section 2.3. The purple line is the electricity produced (Elect. Prod.) by the system (by PV), both used onsite and exported. The grey dashed line represents the annual electricity exported to the grid (electricity which is not demanded by the system at the moment that it is produced).

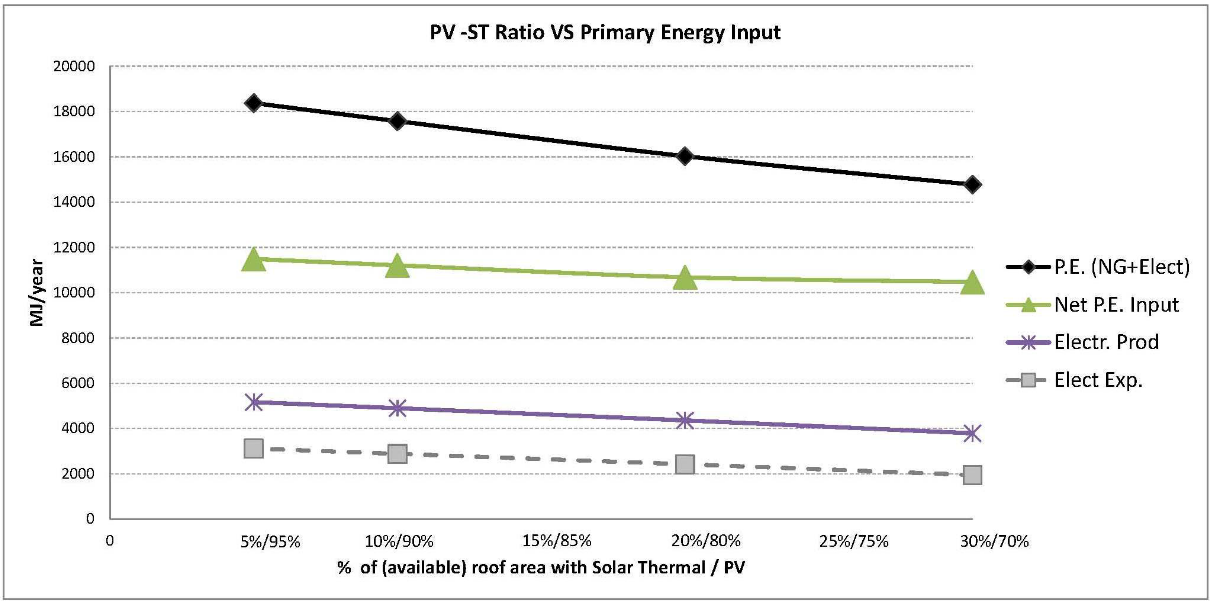


Fig. 7. ST-PV Ratio Vs Primary Energy input

As shown in Fig. 7, the smaller the area covered with solar thermal (or what is the same, the greater the area with PV), the higher the electricity produced as well as exported (grey line), as could be expected. However, a smaller area with solar thermal collectors also implies a higher total Primary Energy input from the grid (Black line) as well as a higher net primary energy input (green line), due to higher use of the Auxiliary Boiler.

According to this sensitivity evaluation, it can be confirmed that reducing ratio of solar thermal collectors in favour of more PV area in this option A does not involve improvements in the reduction of the net P. E. input.

5.2.2 Improvement 2. Using the Heat Pump to preheat DHW

Another possibility to improve the exergy performance of the option A is to minimize the use of the auxiliary boiler. For this aim, the use of the heat pump for preheating the DHW supply has been studied, assuming the heat pump to preheat the water before entering the thermal energy storage system (TES), as is shown in Fig. 8. This configuration is chosen in order for the heat pump to function as much as possible at the lowest temperatures (between the delivery temperature of the water and 30-35 degrees), where it performs best (i.e. reaches higher COP's). Occasionally in summer this has the effect that the water is preheated by the HP while the solar energy would have sufficed, but this rarely occurs, also since the temperature of supply of the water in summer is already quite high and the HP is used little as a consequence.

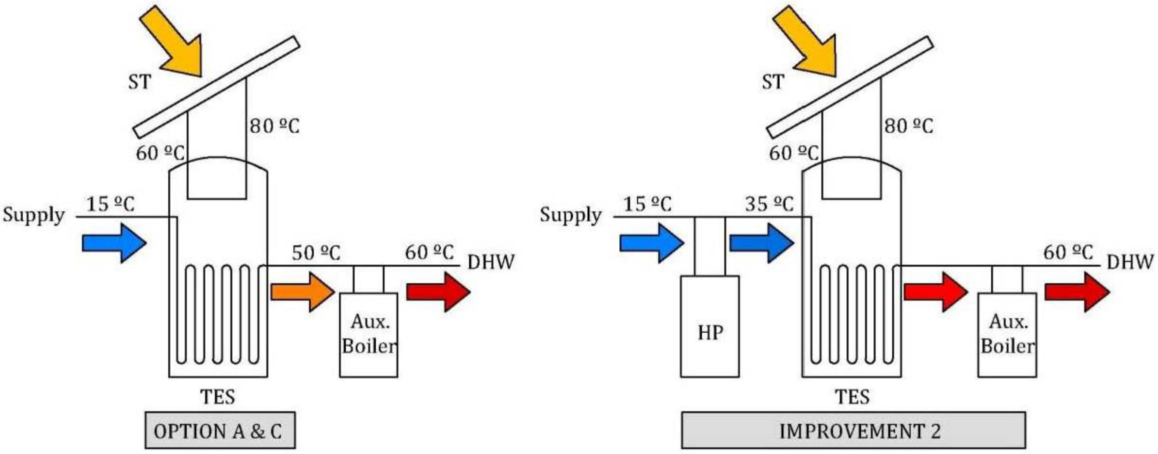


Fig. 8. Scheme of the 2nd improvement. The left picture depicts the system in option A and C, and right picture depicts the improvement.

Fig. 9 shows the HP input during a year. The grey line represents the HP input in the scenario of Case III-Option A, and the black one depicts the HP input in this scenario with improvement 2. The results show that in this way the heat pump can be used more often as it is used for preheating the DHW before entering the storage (TES). Consequently, the use of the auxiliary boiler is reduced, and the exergy input of natural gas from the grid decreases with about 65% in energy terms, from 3193 MJ/year to 1097 MJ/year. (in exergy terms, from 3033 MJ/year to 1042 MJ/year). The exergy output of the auxiliary boiler for DHW also decreases significantly, with about 59% (from 299 MJ/year to 124 MJ/year). The exergy efficiency of the Auxiliary Boiler is also improved (from 0.10 to 0.12) since the ΔT is reduced (inlet-outlet)

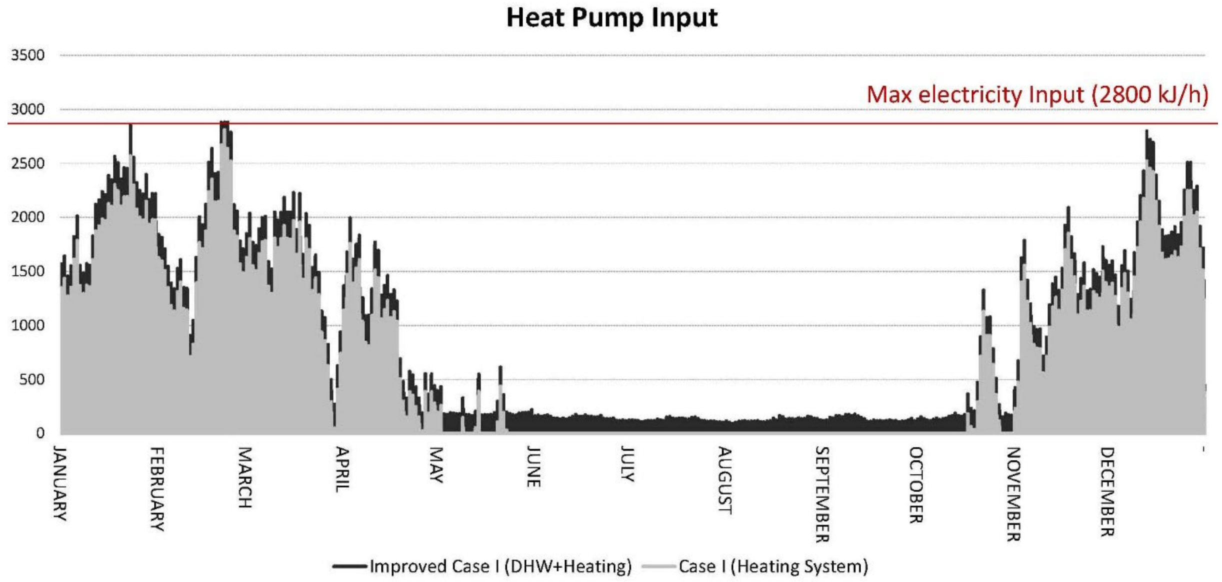
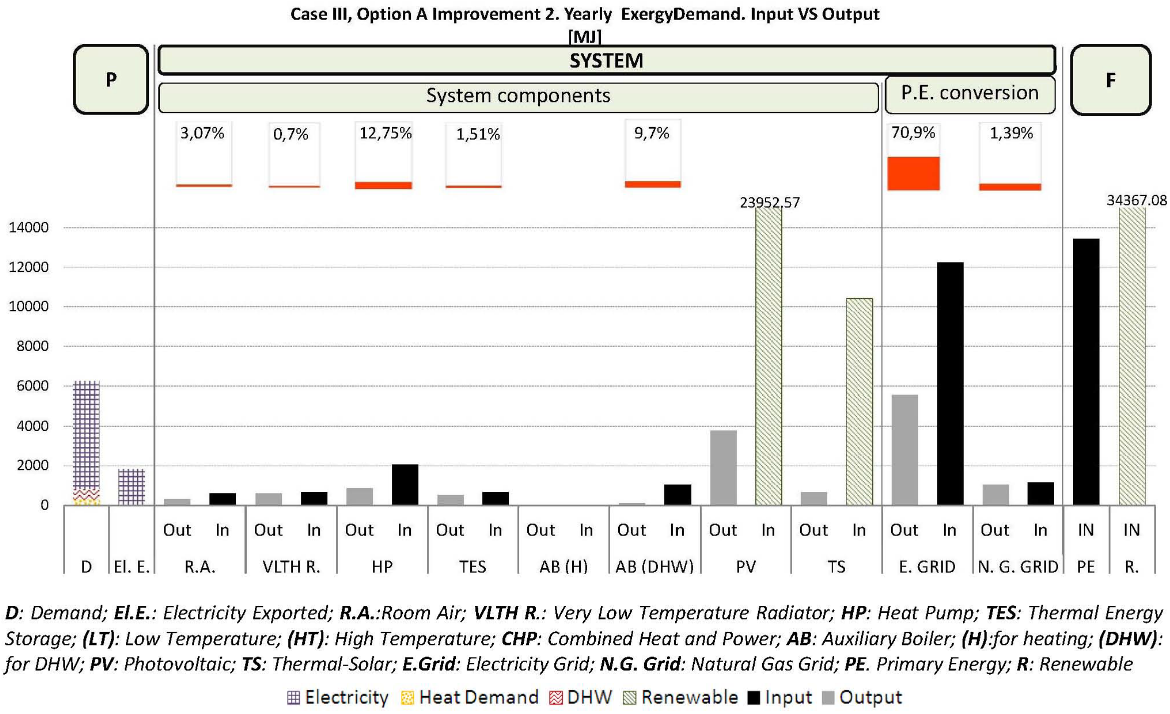


Fig. 9. Heat Pump input (Case I, in grey, Improved Case I, in Black)

This significantly reduced use of the auxiliary boiler results in a reduction of the net P.E. input of more than 10%, from 10470MJ/year to 9361 MJ/year, as shown in Table 5. A detailed scheme of the improved system demand, component exergy losses and primary energy input is shown in Fig. 10.

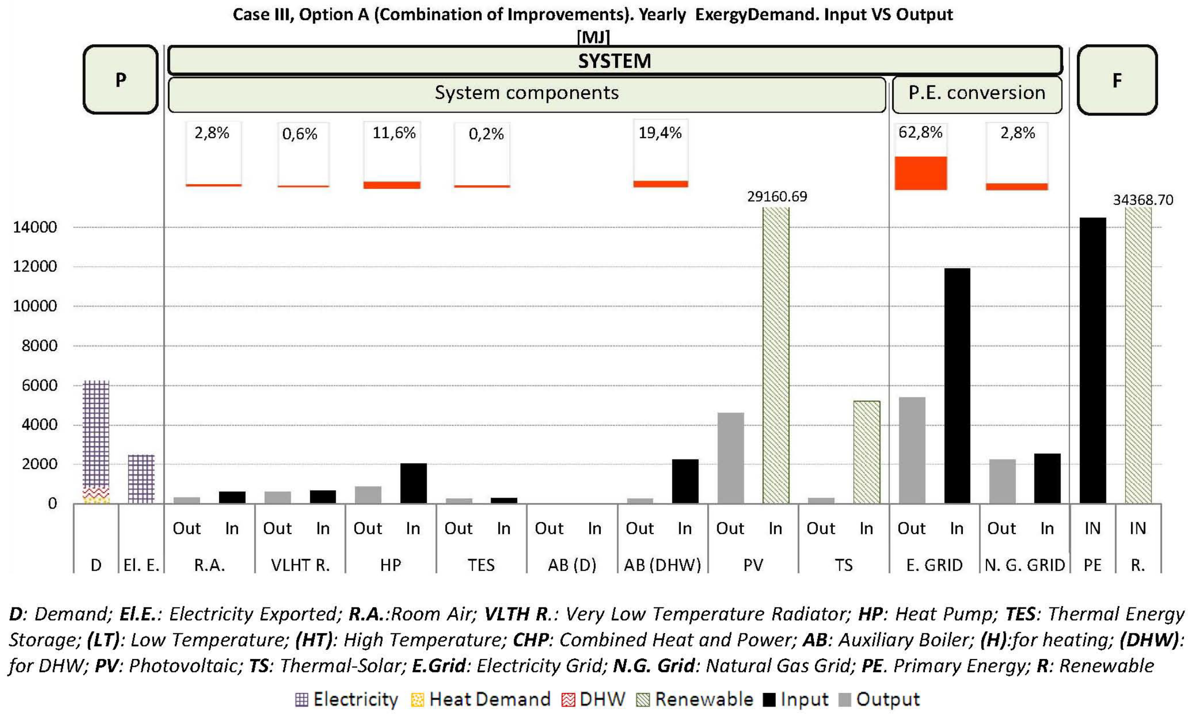


D: *Demand; **El.E.**: Electricity Exported; **R.A.**:Room Air; **VLTH R.**: Very Low Temperature Radiator; **HP**: Heat Pump; **TES**: Thermal Energy Storage; **(LT)**: Low Temperature; **(HT)**: High Temperature; **CHP**: Combined Heat and Power; **AB**: Auxiliary Boiler; **(H)**:for heating; **(DHW)**: for DHW; **PV**: Photovoltaic; **TS**: Thermal-Solar; **E.Grid**: Electricity Grid; **N.G. Grid**: Natural Gas Grid; **PE**. Primary Energy; **R**: Renewable*

Fig. 10. Detailed analysis of the input and output in each component of the improved system.

5.2.3 Combination of improvement 1 and 2

As a third option a combination of two improvements is evaluated, including an increased PV area on the roof as well as preheating the DHW by means of a heat pump, in order to reduce the use of the auxiliary boiler. The results from dynamic analysis show that this option could be considered the best of the evaluated ones according to its net primary energy input (8927 MJ/year), representing a reduction of required primary energy input of almost 15 % compared to the original Case III-option A. Obviously, the results of this option are very sensitive to the applied primary energy factor (PEF) as was studied previously in [18].



*D: Demand; **El.E.**: Electricity Exported; **R.A.**:Room Air; **VLTH R.**: Very Low Temperature Radiator; **HP**: Heat Pump; **TES**: Thermal Energy Storage; **(LT)**: Low Temperature; **(HT)**: High Temperature; **CHP**: Combined Heat and Power; **AB**: Auxiliary Boiler; **(H)**:for heating; **(DHW)**: for DHW; **PV**: Photovoltaic; **TS**: Thermal-Solar; **E.Grid**: Electricity Grid; **N.G. Grid**: Natural Gas Grid; **PE**. Primary Energy; **R**: Renewable*

Fig. 11. Detailed analysis of the input and output in each component of the system with the combination of improvements.

5.2.4 Overview of the tested improvements

The results of all improved options are presented in Table 5. Concluding it can be stated that the insight from the exergy losses has in this case contributed to the further reduction of required net primary energy input. The influences of envisioned improvements however have to be tested using dynamic analysis in order to tackle possible negative side effects, as is the case with improvement 1.

Table 5. Values of the Case A without improvements, with Improvement 2 (HP for DHW) and with the combination of 2 improvements (Net P.E. calculated according to procedure described in section 2.3)

6 Conclusions

Five different energy scenarios for a social dwelling in a multi-family building in Bilbao from the 1960's have been analysed, using the exergy approach under dynamic conditions. Two reference cases (the original situation and the situation after standard renovation works) and three improved cases based on previous studies have been analysed. Possible further reduction of the required primary energy input of the improved options has been investigated using a detailed analysis of the exergy losses.

Significant differences between energy and exergy performance of the systems and components are shown in this paper. As has been shown in other studies, the exergy approach complements and gives a more rational analysis than an analysis solely based on the energy approach. For all cases evaluated in this study several exergy losses have been revealed that cannot be identified using energy analyses. These losses represent the ideal thermodynamic improvement potential and indicate a direction for further improvement of the system.

The most important exergy losses revealed in this study which are not revealed using energy analysis are: exergy losses of heating systems using combustion or resistance heating (Annual energy losses in the electric heater system are negligible, but annual exergy losses are 17455 MJ/Year of the total losses of 71140 MJ/year, including losses in the P.E. transformation), exergy losses between the energy demand and the energy supplied by the emission system where the exergetic efficiency varies from 0.12 (using an electric heater) to 0.52 (using very low temperature floor heating); exergy losses of the combined heat and power (CHP) unit (21419 MJ/year of the total of 35111 MJ/year, including losses in the P.E. transformation), which are much bigger than its energy losses (3435 MJ/year), and the exergy losses in a heat pump (893 MJ/year and 1885 MJ/year, in Case III option A and C respectively), which are nonexistent in an energy approach. The quantification of the exergy losses as has been performed in this study directly shows which components are most responsible for the losses and thus are most responsible for the required input of resources.

The analysis of the exergy losses has been used to develop further improvement of one exemplary case (Case III-Option A). The study has shown that this analysis of exergy losses can support the development of improved systems with reduced exergy losses and thus reduced high quality energy input. For the exemplary case studied in this paper the improved configuration has further reduced net primary energy input by almost 15 %. It is however noted that these results are very sensitive to the primary energy factors of the electricity production and it is therefore recommended to further investigate the calculation of the exergy of primary energy and to the implication of using national primary energy factors (PEF's).

According to this study the exergy approach has shown to be useful to improve energy system configurations, by quantifying the exergy losses at each energy system component. It is recommended to further investigate how exergy analysis can contribute to the improvement of energy systems for the built environment, also taking other requirements into account.

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Appendix A. Building characteristics.

In this appendix the building characteristics of the case study and the operational aspects relevant to its energy performance are presented. The data are based on reference values given by TRNSYS, CTE (Spanish Technical Building Code) and The Institute for Energy Diversification and Saving [28]

A.1 Construction data

The heat demand of the social housing unit has been calculated by means of TRNSYS simulation, with TYPE 56. A dwelling on the 4th floor of a multifamily building of 6 floors has been chosen, so the ceiling and floor of the study case have been considered adiabatic in the TRNSYS simulation. The physical properties of the building envelope components are presented in Table A. 1.

Table A. 1. Physical properties of the building envelope components

A.2 Dwelling operation

A.3.1 Overview

Table A.2 summarizes the different schedules for all relevant dwelling operation aspects. It is noted that in the original situation there is a large infiltration rate but no controlled ventilation system is present; for this case it is assumed that the windows are one hour per day for fresh air (see ventilation column).

Table A. 2. Schedules and operation values assumed in TRNSYS model

A.3.2.2 Set point Temperatures. Operative Temperature.

The TRNSYS software is programmed in such a way that the ideal heating demand calculation in principle reacts to the *air temperature* of a thermal zone, while for a more correct evaluation of comfort the *operative zone temperature* (T_{op}) should be controlled. This control is in TRNSYS obtained using eq. A. 1 and eq. A. 2, where T_{mean_surf} is the average surface temperature of all surrounding (wall and window) surfaces in the zone. T_{mean_surf} is result of the TRNSYS simulation. (The set-point temperature is for this reason modelled as an input from the TRNSYS studio instead of a direct value in the TRNBUILD program).

$T_{op} = \frac{T_{air} + T_{mean\_surface}}{2}$	**eq. A. 1**
$T_{air,sp} = \left(T_{op,sp} - 0.5 \cdot T_{mean\_surf}\right) \cdot 2$	**eq. A. 2**

A.3.2.4 Domestic Heating Water Demand (DHW)

A daily demand of 101 litres of warm water is assumed, according to the schedule shown in Table A. 3, with a desired (output) temperature of 60 ºC. The water supply temperature is calculated using eq. A. 3, with an annual average supply temperature assumed at 15,4 ºC. The heat losses through the piping system are neglected.

- If $T_{out} < -5^{o}C \rightarrow T_{sup\_DHW} = 1.8$ - If $T_{out} \geq -5^{o}C \rightarrow T_{sup\_DHW} = \left(2 \cdot T_{out} + 15.4\right)/3$	**eq. A. 3**

A.4 Energy system components

In table A.3 the assumed properties of the energy systems components are presented: Energy Efficiency η (if it is a fixed value), Inlet Exergy Factor, Outlet exergy Factor, and temperatures used for calculating the exergy factor when applicable. Equation 1 and 2 used for the calculation of the exergy factor are explained in section 2 of this paper.

Table A.3: Properties of the energy system component for each case

A.5 Assumptions and calculations

The calculations are based on the input-output approach. The simulation of several components has been developed in a simplified way, based in their energy efficiency in each time steep of the simulation. However, in some specific components dynamic assumptions have been considered, as it is described below.

7.1.1 Heat Recovery. (Type 91)

An Efficiency of 60% is assumed in the Heat Recovery Unit. According to ventilation criteria shown in [18] ventilation air temperature is ruled by eq. A 4:

- $\text{If } \mathrm{T_{in}} < 23^{\circ} C \rightarrow T_{vent} = T_{HR}$
- $\text{If } \mathrm{T_{in}} \geq 23^{\circ} C \rightarrow T_{vent} = T_{out}$

eq. A 4

7.1.2 Heat Pump

For simulating the Heat Pump performance, Type 42 of the standard TRNSYS component library has been used. The COP is calculated assuming a performance of 50% of the Carnot COP [29]. The thermodynamic equivalent temperatures of T_H (load side) and T_L (source side) are used for the calculation of COP_{Carnot}, assuming a load temperature according to the required input of the emission system (in case of floor heating 35-30 degrees and in case of low temperature radiators 40-35 degrees) and a source temperature of the outdoor temperature with 5 degrees temperature drop as a result of the heat intake by the heat pump. A maximum electricity input in the Heat Pump of 0.8 kW is assumed and an auxiliary boiler is assumed to cover the remaining demand if present.

7.1.3 Thermal Energy Storage (TES)

For simulating the TES tank in principle a simplified approach is taken. In this simplified approach in fact no storage effect is taken into account; the losses caused by the storage are simply included in a steady state manner. This simplified approach means the component delivering the thermal energy to the storage device is thus supposed to deliver the energy at the time step it is demanded by the system taking energy from the storage tank (i.e. the emission system for space heating or DWH demand profile). This simplification is considered acceptable since the aim is to the study the energy and exergy losses and not the optimization of the storage strategy.

For the analysis of option A and C however, where solar thermal energy is used to deliver the DHW demand the storage has to be taken into account more dynamically since the profiles of supply (the solar radiation) and demand (DHW profile) do not match. For these cases TRNSYS type 4a has been used, with the following assumptions:

- The tank volume is considered is 0.23 m^3 (230 litres)

  It is calculated according to $Q_{stored}=V \cdot \rho \cdot c_p \cdot \Delta T$, where Q_{stored}= the daily heat demand for DHW (Q_{DHW}= 7,031 MJ/year = 19263 kJ/day), ΔT is based on a supply inlet temperature from the solar collectors of 80 °C and a return temperature of 60 °C.

  N.B. In reality probably a larger tank will be used to provide DHW for the whole building. This means transmission losses will be less but some distribution losses will increase.
- The Tank Loss Coefficient is considered 0.35 W/m^2K, considering 10 cm insulation material (λ=0.035 W/mK)
- The demand side flowrate is resulting from the DHW demand profile described in Table A.2.
- The load (or supply side) flowrate is equal to the flowrate assumed for the solar collector (see also Fig 10 for this configuration). It is calculated using eq. A 5, where Q_{coll} = the thermal heat available from the collector, $T_{out,coll}$ is the desired output temperature of the collector of 80 °C and $T_{return,TES}$, is the temperature of the load side return flow from the TES, resulting from type 4a. Practical limitations to maximum and minimum flowrate are neglected.

$$\dot{m} = \frac{Q_{coll}}{(T_{out,coll} - T_{return,TES}) \cdot c_p} \quad \textbf{eq. A 5}$$

7.1.4 CHP

CHP supplies a maximum thermal power of 3 kW per dwelling (108kW unit) When the TES of High Temperature (TESHT input) demand is higher than that value, the rest of the demand is supply by an auxiliary Boiler. Moreover, it is assumed that the CHP is running in function to the demand (In a real case it could be running for a continued period and storage the energy in the TES)

According to these assumptions, the equations which rule the working of CHP in the model are defined in eq. A 6, eq. A 7 and eq. A 8.:

$Q_{CHP,output}$

$$\begin{aligned} &\text{If } \mathrm{Q}_{\mathrm{TESHT,inp}} < 10800kJ \rightarrow Q_{CHP,outp} = Q_{TESHT,inp} \\ &\text{If } \mathrm{Q}_{\mathrm{TESHT,inp}} \geq 10800kJ \rightarrow Q_{CHP,outp} = 10800kJ \end{aligned}$$

eq. A 6

$$\mathrm{Q}_{\mathrm{CHP,\ inp}} = \mathrm{Q}_{\mathrm{CHP,\ outp}} \Big/ \eta_{CHP,Q}$$

eq. A 7

$$\mathrm{E}_{\mathrm{CHP,\ outp}} = \mathrm{Q}_{\mathrm{CHP,inp}} \Big/ \eta_{CHP,E}$$

eq. A 8

Where the electric η of the CHP is assumed as a constant value of 0.28 and the thermal η of the CHP is assumed as a constant value of 0.63.

7.1.5 Transformation to Primary Energy

The Total Primary energy is obtained from the sum of the different primary energy supplied to Auxiliary Boiler and CHP (By means of Natural Gas) and electricity supply. The conversion factors assumed has been taken from [30]. These factors are F_{NG}=1.07 and F_{Elect}= 2.21.

P. Ex. of electricity could be calculated more in detail based on the electricity mix, by calculating the exergy value of each source (Nuclear, wind, solar…) and weighting them according to the electricity mix of the country. In this paper, however, a simplification has been done, assuming that Primary energy equals Primary Exergy.

8 Nomenclature

A	[m^2]	Area	PE		Primary Energy
c_p	[J kg^{-1} K^{-1}]	Isobaric heat capacity	PEF	[-]	Primary Energy Factor
D	[MJ/y]	Annual exergy destruction	Q	[MJ/y]	Heat and sensible heat
E	[MJ/y]	Electricity	T	[ºC]	Air Temperature
F	[-]	Exergy Factor	U	[W m^{-2} K^{-1}]	Heat transfer coefficient
L	[MJ$_{ex}$/y]	Annual exergy losses	V	[m^3]	Volume
m	[kg]	Mass	x	[MJ$_{ex}$/y]	Exergy
$\dot{m}$	[kg/s]	Mass flow rate			

Greek symbols

Ψ	[-]	Exergy Efficiency
η	[-]	Energy Efficiency

Subscripts

CHP	Related to co-generation system	*out*	Outdoor
DHW	Related to Domestic hot water	*outl*	Outlet
del	Delivered	*outp*	Output
dem	Demand	*ret*	return
E	Related to electricity	*sp*	Set-point (Temperature)
exp	Exported	*sol*	Solar gains
H	Related to heating system	*ST*	Related to Solar Thermal.
HR	Related to Heat Recovery	*sup*	Supply
i	Stream	*TES*	Related to Thermal Energy Storage system
in	Indoor	*TESHT*	Related to Thermal Energy Storage system (High Temp.)
inl	Inlet	*TESLT*	Related to Thermal Energy Storage system (Low Temp.)
inf	Infiltrations	*trans*	Transmission
Inp	Input	*vent*	Ventilation
int	Internal gains	*X*	Related to exergy
op	Operative (Temperature)	*0*	Reference

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10 Tables with captions

		U-Value (Façade)	U-Value (Windows)	Use of Exhaust air	Heating system	Electricity
CASE I		1.49	5.68	No	Electric resistance	Grid
CASE II		0.59	2.63	No	Gas Boiler with High Temp	Grid
CASE III	Option A	0.375	2.63	Heat Recovery	HP	Grid
	Option B			No	CHP	Grid + CHP
	OptionC			No	HP	Grid

Table 6. Highlights of the dwelling for each studied scenario.

Anual results	**CASE I**		**CASE II**		**CASE IIIa**		**CASE IIIb**		**CASE IIIc**	
MJ/year	**Energy**	**Exergy**	**Energy**	**Energy**	**Energy**	**Exergy**	**Energy**	**Exergy**	**Energy**	**Exergy**
DEMANDS										
Heat Demand	*26166*	*1035*	*16044*	*613*	*7560*	*308*	*14375*	*555*	*14375*	*555*
DHW	*7031*	*524*	*7031*	*524*	*7031*	*524*	*7031*	*524*	*7031*	*524*
Elect. App & Light.	*5466*	*5466*	*5466*	*5466*	*5466*	*5466*	*5466*	*5466*	*5466*	*5466*
Electricity exported	-	-	-	-	*1946*	*1946*	*12269*	*12269*	*1843*	*1843*
P.E. Inputs										
Total P.E. Input)	*78164*		*41634*		*14772*		*48441*		*18826*	
Net P.E. Input (see §2.3)	*78164*		*41634*		*10478*		*21351*		*14760*	
Renewable Energy	-	-	-	-	*8606*	*4275*	*5427*	*5427*	*8606*	*4275*

Table 7. Annual energy and exergy demands and P.E inputs [‡].

[‡] Authors’ note: The results presented in this paper are somewhat different than those presented in [18], showing slight differences in three energy demand values. This is caused by the fact that the results in [18]were obtained using a 0.25h-timestep, although it mistakenly stated that a 1 hour timestep was used. These minor differences do not influence any of the conclusions or relevance of either paper.

	CASE I				CASE II			
	Output En (*Ex*) [MJ/y]	Input EN (*Ex*) [MJ/y]	η (Ψ) [–]	L (D) [MJ/y]	Output En (*Ex*) [MJ/y]	Input EN (*Ex*) [MJ/y]	η (Ψ) [–]	L (D) [MJ/y]
Component								
Room Air	*26166* *(1035)*	*26166* *(8712)*	*-* *(0.12)*	*-* *(7677)*	*16044* *(613)*	*16044* *(2563)*	*-* *(0.24)*	*-* *(1950)*
Electric Heater	*26166* *(8712)*	*26166* *(26.166)*	*1.00* *(0.33)*	*0* *(17454)*	*N/A*			
H. Temp. Radiator	*N/A*				*16.044* *(2563)*	*17826* *(2848)*	*0.90* *(0.90)*	*1783* *(285)*
Boiler	*7031* *(524)*	*7813* *(7422)*	*0.90* *(0.07)*	*782* *(6899)*	*24857* *(3372)*	*27620* *(26239)*	*0.90* *(0.13)*	*2763* *(22867)*
P.E. Transf. (NG)	*7813* *(7422)*	*8360* *(8360)*	*0.93* *(0.89)*	*547* *(938)*	*27620* *(26239)*	*29553* *(29553)*	*0.93* *(0.89)*	*1933* *(3314)*
P.E. Transf. (Elec)	*31632* *(31632)*	*69804* *(69804)*	*0.45* *(0.45)*	*38172* *(38172)*	*5466* *(5466)*	*12081* *(12081)*	*0.45* *(0.45)*	*6615* *(6615)*

Table 8. Annual performance of the energy system components used in cases I and II. (η = energy efficiency; L = energy losses; ψ = exergy efficiency; D = exergy destruction)

	OPTION A				OPTION B				OPTION C			
	Outp En (*Ex*) [MJ/y]	Inp EN (*Ex*) [MJ/y]	η (Ψ) [–]	L (D) [MJ/y]	Outp EN (*Ex*) [MJ/y]	Inp EN (*Ex*) [MJ/y]	η (Ψ) [–]	L (D) [MJ/y]	Outp En (*Ex*) [MJ/y]	Inp EN (*Ex*) [MJ/y]	η [–]	L (D) [MJ/y]
Comp.												
Room Air	7560 (308)	7560 (598)	- (0.52)	- (290)	14375 (555)	14375 (1334)	- (0.42)	- (779)	14375 (555)	14375 (1334)	- (0.42)	- (779)
V.L.T. Heating	7560 (598)	8400 (664)	0.90 (0.90)	840 (66)	*N/A*				*N/A*			
L. T. Heating	*N/A*				14375 (1334)	15973 (1482)	0.90 (0.90)	1597 (148)	14375 (1334)	15973 (1482)	0.90 (0.90)	1597 (148)
Heat Pump	8400 (664)	1557 (1557)	5.40 (0.43)	-6843 (893)	*N/A*				15674 (1450)	3335 (3335)	4.70 (0.43)	-12339 (1885)
TES (LT)	*N/A*				15973 (1482)	17747 (2265)	0.90 (0.65)	1775 (783)	*N/A*			
TES (HT)	4158 (225)	4569 (435)	0.91 (0.52)	411 (210)	24778 (2789)	27532 (4801)	0.90 (0.58)	2754 (2012)	4158 (225)	4569 (435)	0.91 (0.52)	411 (210)
CHP	*N/A*				34729 (14837)	38164 (36256)	0.91 (0.41)	3435 (21419)				
Aux.Boiler (DHW)	2873 (299)	3193 (3033)	0.90 (0.10)	319 (2734)	3489 (650)	3876 (3682)	0.90 (0.18)	388 (3032)	2873 (299)	3193 (3033)	0.90 (0.10)	319 (2734)
Aux. Boiler (Heat)	*N/A*				*N/A*				298 (32)	332 (314)	0.90 (0.10)	34 (282)
P.E. Transf. (NG)	3193 (3033)	3418 (3418)	0.93 (0.89)	225 (385)	42040 (39938)	44983 (44983)	0.93 (0.89)	2943 (5045)	3525 (3347)	3771 (3771)	0.93 (0.89)	246 (424)
P.E. Transf. (Elect from the Grid)	5137 (5137)	11354 (11354)	0.45 (0.45)	6217 (6217)	1565 (1565)	3458 (3458)	0.45 (0.45)	1893 (1893)	6812 (6812)	15055 (15055)	0.45 (0.45)	8243 (8243)

Table 9. Annual performance of the energy system components used in case III, options A, B and C. (η = energy efficiency; L = energy losses; ψ = exergy efficiency; D = exergy destruction)

CASE	P.E. Input [MJ/year]	Elec. Exported [MJ/year]	Net P.E. [MJ/year]
Case III-A	14771	1946	**10470**
Case III-A Improvement1 (PV 85%-TS 15%)	16744	2636	**10918**
Case III-A Improvement2 (preheating by HP)	13421	1837	**9361**
Case III-A. Improvement 3 (Combination)	14472	2509	**8927**

Table 10. Values of the Case A without improvements, with Improvement 2 (HP for DHW) and with the combination of 2 improvements (Net P.E. calculated according to procedure described in section 2.3)

No	Function (*1)	Or.	Area [m2]	CASE 1		CASE 2		CASE 3	
				U-Value [W/m^{2}K]	g-Value	U-Value [W/m^{2}K]	g-Value	U-Value [W/m^{2}K]	g-Value
1-3	Façade	W,S,E	56.9	1.49	-	0.59	-	0.375	-
4-5	Internal partition	N	17.68	2.39	-	0.70	-	0.70	-
6-7	Ceiling and floor	Hor.	3.97	2.23	-	2.23	-	2.23	-
W	Windows (*1)	E, W.	10.55	5.68	0.855	2.83	0.755	2.83	0.755

(* 1) Values for Solar Absorbance, Convective heat Transfer coefficient and F_{sky} are according to the standard values provided by TRNSYS.

(*2) For windows only the U value of the glass is presented. The frame covers 15% of the total window surface and has a U-value of 2,15 W/m^{2}K in all cases.

Table A. 4. Physical properties of the building envelope components

	Infiltration		Ventilation		Internal Gains			Heating Operation	Demands	
	[(m^3/h)/m^3]		[(m^3/h)/m^3]		[kJ/h]			[ºC]	[w/m^2]	[l/h]
	CI	CII&III	CI	CII&III	Occup.	Lighting	Appl.	Set-Point Temp.	Elect Demand	DHW Demand
00.00-06.00h	1.3	0.24	0	1.72	12,64	1,58	1,58	17	0.88	0
06.00-07.00h	1.3	0.24	0	1.72	12,64	1,58	1,58	17	0.88	11
07.00-08.00h	1.3	0.24	4	1.72	3,17	4,75	4,75	20	2.64	11
08.00-09.00h	1.3	0.24	0	1.72	3,17	4,75	4,75	20	2.64	11
09.00-15.00h	1.3	0.24	0	1.72	3,17	4,75	4,75	20	2.64	4
15.00-18.00h	1.3	0.24	0	1.72	6,34	4,75	4,75	20	2.64	4
18.00-19.00h	1.3	0.24	0	1.72	6,34	7.92	7.92	20	4.4	4
19.00-21.00h	1.3	0.24	0	1.72	6,34	15,84	15,84	20	8.8	8
21.00-23.00h	1.3	0.24	0	1.72	6,34	15,84	15,84	20	8.8	4
23.00-00.00h	1.3	0.24	0	1.72	12,64	7.92	7.92	17	4.4	4

Table A. 5. Schedules and operation values assumed in TRNSYS model

Component	η	INPUT			OUTPUT		
		T_{inl}	T_{ret}	F	T_{inl}	T_{ret}	F
Demands							
Space heating	N/A	Ti		1	N/A		
DHW	N/A	60 ºC	eq. A. 3.	eq. 2			
Electricity	N/A	N/A		1			
Emission systems							
Elect. heater	1	N/A		1(Electricity)	150 ºC		eq. 1
H.T. Rad.	0.9	70 ºC	55º C	eq. 2	70 ºC	55º C	eq. 2
L.T. Rad.	0.9	40 ºC	35 ºC	eq. 2	40 ºC	35 ºC	eq. 2
V.L.T. floor	0.9	35 ºC	30 ºC	eq. 2	35 ºC	30 ºC	eq. 2
Conversion components							
Boiler	0.9	N/A		0.95 (NG)	DHW or emission system		eq. 2
Heat Pump	(*1)	N/A		1(Electricity)	35 ºC	30 ºC	eq. 2
CHP (elec/thermal)	0.28/ 0.63	N/A		0.95 (NG)	80 ºC	60 ºC	1(Electricity) / eq. 2
Solar Thermal	0.44	N/A		0.95 (Sol)	80 ºC	Type 4	eq. 2
PV	0.15	N/A		0.95 (Sol)	N/A		1(Electricity)
Storage							
H.T. TES	0.9	80 ºC	60 ºC	eq. 2	(DHW)		
M.T. TES	0.9	60 ºC	40º C	eq. 2	40 ºC	35 ºC	eq. 2
Primary energy conversion (P.E.C.) of grid electricity and grid gas.							
P.E.C. elec	0.45(*2)	Primary energy, F is assumed 1 (*3)			1(Electricity)		
P.E.C. gas	0.93 (*2)				0.95 (NG)		

(*1) The COP of the heat pump is calculated assuming a performance of 50% of the Carnot COP [8].

(*2) These values are the inverse of the following primary energy factors taken from [9]: PEF_{Elect}= 2.21 and PEF_{NG}=1.07, for electricity and gas respectively.

(*3) the exergy content of the primary energy is in fact dependent on the mix of resources used to obtain the energy output. But this calculation is out of the scope of this research.

Table A.6: Properties of the energy system component for each case