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The exergy approach for evaluating and developing an energy system for a social dwelling

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Abstract

In this paper the energy and exergy performance of a social dwelling of a multi-family building from the 1960's in Bilbao (Spain) is presented and various improved energy concepts based on exergy principles are proposed and investigated. The aim of this paper is to explore and demonstrate the usefulness of the exergy approach in the assessment and development of an energy system for the dwelling under consideration. The total energy supply system is analysed, including the demand (space heating, domestic hot water and electricity), the system components (for conversion, storage and distribution) and the energy input from energy resources (primary energy and renewable resources). The study includes a comparison of the primary energy input of all cases considered and an analysis of the energy and exergy losses of each system component. The study has shown that the exergy analysis reveals thermodynamic losses that are not revealed using energy analysis and secondly, that taking into account the exergy principles in the development of an improved energy system has resulted in a significantly reduced primary energy input compared to the reference situation.

Keywords:* *exergy analysis, building simulation, exergy design principles, building retrofitting

1 Introduction

The energy demand for heating and cooling in the built environment is mainly a demand for 'low quality' energy, due to the associated temperatures required. Exergy is a thermodynamic concept which indicates the 'quality' of the energy, by expressing the thermodynamic ideal work potential of a certain form of energy. The

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first law of thermodynamics states that energy cannot be destroyed, but according to the second law exergy *can* be destroyed. Explanations of the exergy theory can be found in many textbooks on thermodynamics, such as [1-3].

Thermodynamic ideal processes are reversible, which means no exergy is destroyed and the original situation can be re-obtained. In real processes, however, exergy is always destroyed, often even in large amounts. The exergy destruction of a process indicates the ideal thermodynamic improvement potential of this process. This improvement potential is not shown in energy analysis; exergy analysis therefore has an added value for the evaluation of the performance and improvement potential of a system [4].

The 'low exergy' heating and cooling demands in the built environment are generally met with 'high exergy' energy sources, such as gas or electricity and usually a lot of exergy is being destroyed in these systems. This means there is much room for improvement. Exergy analysis of heating and cooling systems in the built environment is an emerging field of science in recent decades, as it is shown by a large number of publications and international research activities such as ([5-7].

In this paper the exergy performance of a social dwelling of a multi-family building from the 1960's in Bilbao (Spain) is presented and improved energy concepts based on smart exergy use are proposed and investigated. The aim of this paper is to explore and demonstrate the usefulness of the exergy approach in the assessment and development of an energy system for the dwelling under consideration.

The following cases are studied and presented:

- Case I) Original situation (no insulation, single glazing);
- Case II) Case study assuming the usual retrofitting works;
- Case III) Improved cases based on exergy principles.

For the improved cases (Case III) six options have been developed based on exergy principles. These options are evaluated using steady state analysis, but based on a dynamic energy and exergy demand calculation. In part 2 of this paper [8] three of the improved energy system options are evaluated using dynamic simulations, in order to assess the performance and improvement potential in more detail.

2 Methodology

This study aims at demonstrating the usefulness of applying the exergy approach for the development of an efficient energy system for a dwelling of a social multi-family building located in Bilbao (Spain). In this first part the reference cases are presented, the development of improved cases applying exergy principles is described and the energy and exergy performance - based on steady state analysis - of all cases is discussed. A detailed dynamic analysis of three improved options can be found in [8].

The following relevant methodology aspects for this study are described in this chapter: (1) the analysis framework according to the input-output approach; (2) the energy calculation method used; (3) the exergy calculation approach and (4) the exergy principles used for the development of exergetically improved options.

2.1 Analysis framework

In this study the total energy chain is analysed, which is composed of the energy demand, the energy system components (conversion, distribution and storage) and the energy resources. These are analysed according to the input-output approach described in [9] and [10]: The demand is the start of the analysis and for all subsequent energy system components the required input of the component equals the output of the next component. This way all energy and exergy losses are assigned to a component. In this study the demand for space heating and cooling as well as domestic hot water (DHW) and electricity for lighting and appliances is also considered. A scheme of the framework is shown in Fig. 1:

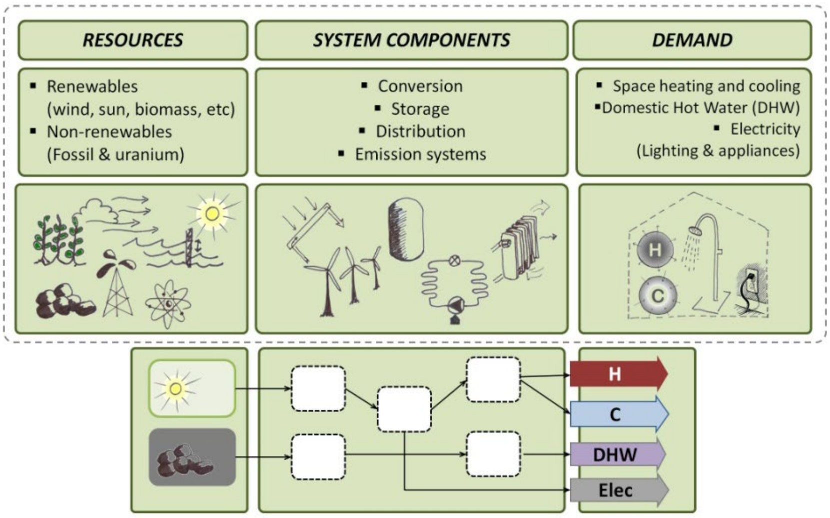

Fig. 1. Analysis framework consisting of demand, energy system components and energy resources

2.2 Calculation method

The analysis of the cases has been performed using dynamic simulations for the calculation of the energy and exergy demand of the building and using a simplified steady state approach for the energy performance of system components, as described below.

2.2.1 Dynamic energy and exergy demand calculation

The energy and exergy demands calculations are performed using the internationally well-known transient energy simulation software TRNSYS (V 17). An annual simulation has been carried out using a 1-h time-step. The energy demand for space heating for the different scenarios studied here are modelled using TRNSYS type 56. Only sensible heat is taken into account, in accordance with [11]. Cooling is not treated in this study as it does not usually exist in residential buildings in this area. The exergy demand is not a standard output of the TRNSYS software and is calculated for each time step according to the method explained in section 2.3.1. The demands for domestic hot water (DHW) and electricity for lighting and appliances are included as a schedule based on literature, as is further explained in the next chapter. The detailed building properties and operation schedules can be found in the appendix.

2.2.2 Steady state energy system analysis

The energy inputs and outputs of the subsequent energy system components for conversion and storage are calculated in a simplified way using a steady state approach. The analysis has been performed for the heating season (October until March) and the summer season (April until September). For this steady-state analysis the total demands resulting from dynamic simulation have been used. The exergy calculations are based on the energy values and the seasonal average temperatures, where the outdoor temperature is considered as the reference temperature as recommended by [10]. For this aim the average outdoor temperature is weighted by the heat demand per one hour time step; in this way the exergy calculations are more correct then when using the straight average outdoor temperature [12].

2.3 Exergy analysis approach

The exergy of an amount of energy can be calculated by multiplying this amount of energy with its exergy factor (F), which is defined as the exergy to energy ratio. This approach is used for calculating the exergy of the inputs and outputs of all energy system components as well as of the resources. The exergy factor of the fuels used is given in the Appendix. The exergy factor of heat at constant temperature can be calculated using eq. 1, while the exergy factor of sensible heat of an amount of matter ($m \cdot cp \cdot (T_2 - T_1)$) can be calculated using eq. 2. [9, 10, 13, 14]. Eq 1 is thus used to calculate the exergy of heat transfers across a system boundary, while eq. 2 is used to calculate the exergy of the sensible heat transferred by a flow of matter such as ventilation air or water.

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

2.3.1 The exergy demand for heating

The exergy demand for heating is calculated using the simplified approach as described in [9, 10, 12, 14]. In this approach the heat required is supposed to be delivered at the indoor temperature T_i. The exergy demand is therefore calculated using eq. 3.

$Ex_{dem,H} = Q_{dem,H} \cdot F_{dem} = Q_{dem,H} \cdot \left(1 - \frac{T_0}{T_i}\right)$	**eq. 3**

2.3.2 Room air

Between the demand for heating (required at T_i) and the emission system (e.g. a radiator) the fictive component 'room air' , as introduced by [9], is used to account for the exergy losses between emission system and demand which are a result of the temperature drop. No energy is lost in this step, but the exergy losses in the 'room air' component are a direct result of the mismatch between demand temperature and supply temperature.

2.4 Guidelines for exergy efficient energy systems for the built environment

The different options for improved energy and exergy performance have been developed using guidelines that are based on the exergy principle. Guidelines from the fields of mechanical engineering can be found in thermodynamic textbooks such as [3, 15]. Guidelines that are applicable to the built environment can be found in for example [10, 16, 17]. Based on literature as well as on previous studies [12, 18] the following guidelines are developed for and used in the study presented in this paper:

Principle 1: Use renewables and other flows of free or waste energy

This principle is in fact not an exergy based principle, but one of the most important strategies towards sustainability and is therefore also explicitly mentioned. It is important to make an inventory of all the free and renewable energy potential in order to make - exergetic- optimal use of it.

Principle 2: Match the quality levels of demand and supply (or in other words: use the lowest quality energy input as possible). This principle can be further elaborated into the following guidelines:

a) **Use low temperature heating (LTH) and high temperature cooling (HTC)**;

   This way exergy of the demand for heating and cooling, which represents a very low exergy demand, is still low at the emission system (i.e. radiator or floor heating) and a minimum exergy destruction between emission system and the thermal zones of the building takes place**;**

b) **Minimize temperature differences when exchanging heat;**

c) **Use low temperature energy flows existing in or around the building;**

   These energy flows include for example the heat from exhaust ventilation air or domestic hot water return, possible nearby surface water or waste water from industry.

d) **Use cascading principle (at building or district level);**

   When demands at multiple temperature levels are to be met, the principle of cascading can be applied, meaning high temperature heat flows are used for high temperature demands, and the return flow of this first demand is used to meet demands at lower temperatures. At building level cascading can theoretically be applied between the demand for domestic hot water (DHW) at 60 °C and space heating at ca. 30 °C. [10, 16]

Principle 3: Optimize storage strategies

Especially renewables and free energy sources are not always available at the time they are required, so when using renewable energy or waste flows storage becomes more important in the design of a system. Storage should also be optimised using the exergy principle by organizing storage at different temperature levels if present [17];

Principle 4: Use high quality energy sources as smart as possible

Also some components that make use of high quality energy input can be exergy efficient for heating purposes. In general the exergy efficiency of the system components should be considered rather than the energy efficiency. For the built environment the following conversion devices make smart use of the high quality input:

- **A heat pump (which generates more heat or cold than the electricity input)**

  For optimal use the temperature lift should be minimized [19];

- **A cogeneration system (combining the production of heat and power)**

  This option is only profitable if both outputs can be used. The electricity production should be large in order to have high exergy efficiency.

Principle 5: Avoid processes known to cause exergy losses

Exergy destructive processes include: Combustion, resistance heating, mixing, throttling, large driving forces (i.e. large temperature differences).

3 Description of the reference cases

The dwelling studied is a social sector dwelling located in a multi-family building built in 1960. This dwelling is selected since it is a representative apartment of the social sector housing stock in Bilbao. A plan of the dwelling is shown in Fig. 2. The net floor area is 52.52 m^2 and the floor to ceiling height is 2,47 m. The specific dwelling considered has 3 external façades, orientated East, West and South, but only two of them (E and W) have windows.

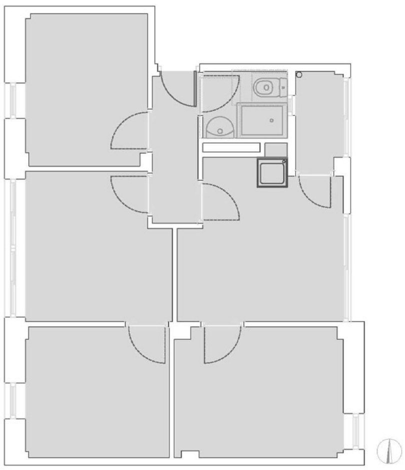

Fig. 2. Plan of the dwelling.

The total building consists of six storeys with six dwellings per floor, which means there is a total of 36 dwellings in the whole building. For the analysis only one dwelling is used and the results are also presented on a dwelling level (and not for the 36 dwellings). However, for the development of improved energy the whole building is taken into account with regards to the characteristics of certain technologies (such as combined heat and power (CHP) devices) or the use of renewables (i.e. 1/36th of the roof surface can be used by each dwelling).

The two reference situations (Case I, without any renovation works and Case II, with the usual renovation works) are described in 3.1 and 3.2 respectively; the development and description of the improved options can be found in section 4. In the appendix the characteristics of the dwelling are described in detail.

3.1 Case I. Base Case

Case I corresponds to the original situation of the dwelling, which represents the dwellings without any renovations since it was built in 1960: the façades have no insulation and for all windows single glazing is assumed. The space heating system is based on 3 electric heaters and domestic hot water (DHW) is provided with a natural gas boiler. Electricity (for lighting and appliances) is provided by the national grid. In the original situation there is no controlled ventilation system but ventilation through open windows is assumed.

3.2 Case II. After Usual Renovation Works

Bilbao Social Housing renovates about 100 dwellings per year. The majority of these renovations are "dwelling scale" renovations. The measures adopted in these renovations are usually similar in every case. Case II represents this situation with the usual renovation works, which include placement of insulation (4cm of rock wool installation), replacement of the windows (clear double glazing), central heating using high temperature radiators and a natural gas combi-boiler (for both space heating and DHW). Air tightness is improved to decrease the infiltration rate, and fixed ventilation rates are assumed according to the Spanish Technical Building Code [20].

4 Case III. New proposals based on exergy guidelines.

To develop new exergy efficient proposals, several options have been considered, based on the guidelines mentioned in section 2.4. Three options requiring rather radical interventions have been considered as well as three options needing less radical renovation works. All options considered are assessed using steady state energy and exergy analyses, and a selection is made for further analysis in [8]. In this chapter the important features of the developed cases are described. All detailed characteristics can be found in the Appendix.

4.1 Considerations

The development of improved cases considers the total system as shown in figure 1 according to the exergy principles, aiming at an optimal solution combining a reduction of the demand, more efficient system components and increased use of renewable resources.

Firstly, for all cases the energy demand is further reduced by increasing the insulation value of the external façades (increased insulation thickness to 8 cm). Secondly, for options 1 until 3 a ventilation heat recovery system has been assumed, in order to further reduction of the heat to be delivered by the emission system.

Regarding the emission system the first three options are considered to have a floor heating system, which can operate at very low temperatures (35-30 ^{o}C). The required heating capacity for these options is 75 W/m^2 which means floor heating is feasible [21], even though attention still has to be paid to comfort issues [22]. The options 4 until 6, which should have less radical improvements, are considered to have low temperature radiators (40-35 ^{o}C).

The use of available energy flows is also taken into account in the development of the options. The heat from exhaust ventilation air is used for heat recovery in the first three cases. Option 4 considers the use of ventilation exhaust air as a source for a heat pump, which means only mechanical exhaust is required and no mechanical air supply has to be designed. In options 5 and 6 exhaust ventilation air is not used, which means the ventilation system can be natural. Return flows of domestic hot water are not considered.

Furthermore an inventory of the potential of available renewable resources has been made. The solar irradiation on 80% of the total roof surface of the building (360 m^2, covering a total of 36 dwellings) is determined and the potential supply of heat using solar thermal collectors (ST, assuming 44% energy efficiency) or electricity using photovoltaic panels (PV, assuming 15% energy efficiency) is investigated.

Solar thermal collectors are considered more suitable for meeting the Domestic Hot Water demand and less for meeting the space heating demand, since the seasons of space heating demand and solar supply do not match. For this aim a surface area of 110 m^2 has been considered most favourable. According to calculations carried out with TRNSYS, this area can supply the total DHW demand from May until August, and significant parts (>80%) can be met in April and September. When opting for larger surface area's the overproduction of energy in summer becomes very high, while only increasing the supply in winter to a smaller extent. This is illustrated in the Fig. 3.

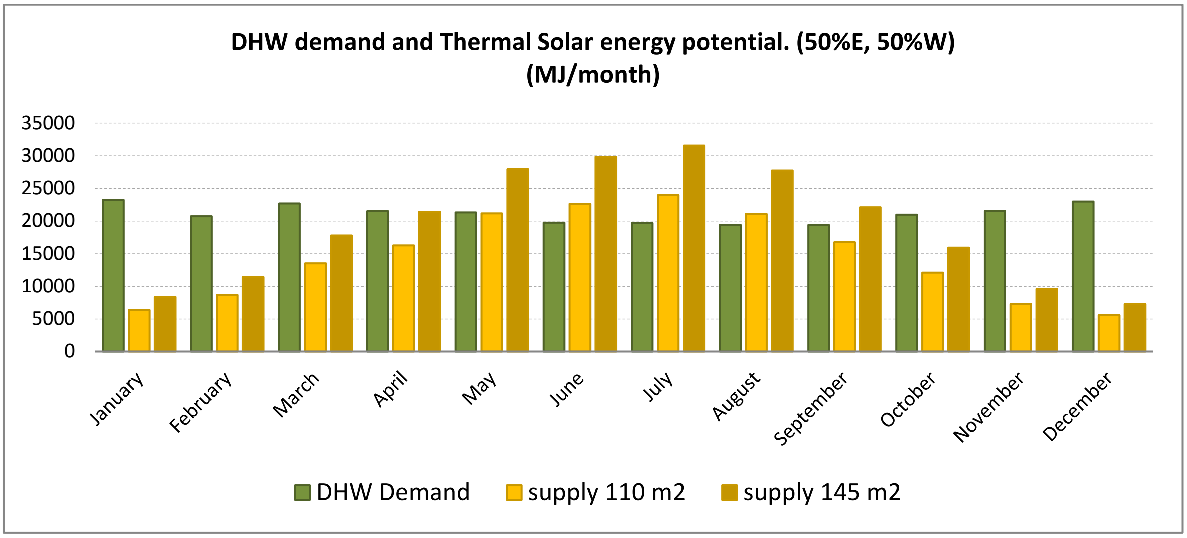

Fig. 3. DHW demand and Thermal Solar energy potential (It represents the DHW demand for the whole building of 36 dwellings)

Photovoltaic energy is considered in all options, the available surface area depending on the use of solar thermal energy, which depends on the total system configuration considered. When considering PV to be placed on the total roof surface, the total annual electricity demand (for lighting and appliances) can be met, though be it with a shortage in winter season and an overproduction in summer.

Wind energy (small urban turbines on the roof) has been investigated assuming small urban wind turbines (1 meter diameter wind turbines). The resulting annual electricity production is estimated about 40 kWh/year (1.5 kWh/year per dwelling), which is rather insignificant compared to the solar energy potential. Wind energy is therefore not further considered in this study.

For meeting the remainder of the demand several configurations of a heat pump based system and a CHP based options have been considered, as well as one option including both. A heat pump is considered optimal for meeting the low quality space heating demand, while the heat output from the CHP can also be used for domestic hot water. An air source heat pump is considered, using the outside air as a heat source (only option 4 also uses ventilation exhaust air as a heat source, as far as available).

4.2 Options considered.

All considerations have led to six options described in Table 1, of which schemes are shown in Fig. 4:

Option 1: Drastic / HP	Using heat recovery, low temperature floor heating, a heat pump to meet the space heating demand, solar thermal (110 m2) and PV (250 m²).
Option 2: Drastic / HP+CHP	Using heat recovery, low temperature floor heating, a heat pump to meet the space heating demand and CHP for domestic hot water and electricity, and PV (360 m²).
Option 3: Drastic / CHP	Using heat recovery, medium temperature radiators, a CHP for space heating, domestic hot water and electricity, and PV (360 m²).
Option 4: Moderate / HP(+)	Medium temperature radiators, space heating supplied by a heat pump (also using ventilation exhaust air as heat source), solar thermal (110 m2) and PV (250 m²).
Option 5: Moderate / CHP	Medium temperature radiators, a CHP for space heating, domestic hot water and electricity, and PV (360 m²). (similar to option 3 but without heat recovery)
Option 6: Moderate / HP	Medium temperature radiators, space heating supplied by a heat pump, solar thermal (110 m2) and PV (250 m²).

Drastic = options with very low temperature heating (floor heating) (35-30 °C) and ventilation heat recovery;
Moderate = options with low temperature radiator (40-35 °C)
HP = heat pump; HP(+)= heat pump making use of ventilation exhaust air; CHP = combined heat and power

Table 1: overview of the improved options developed

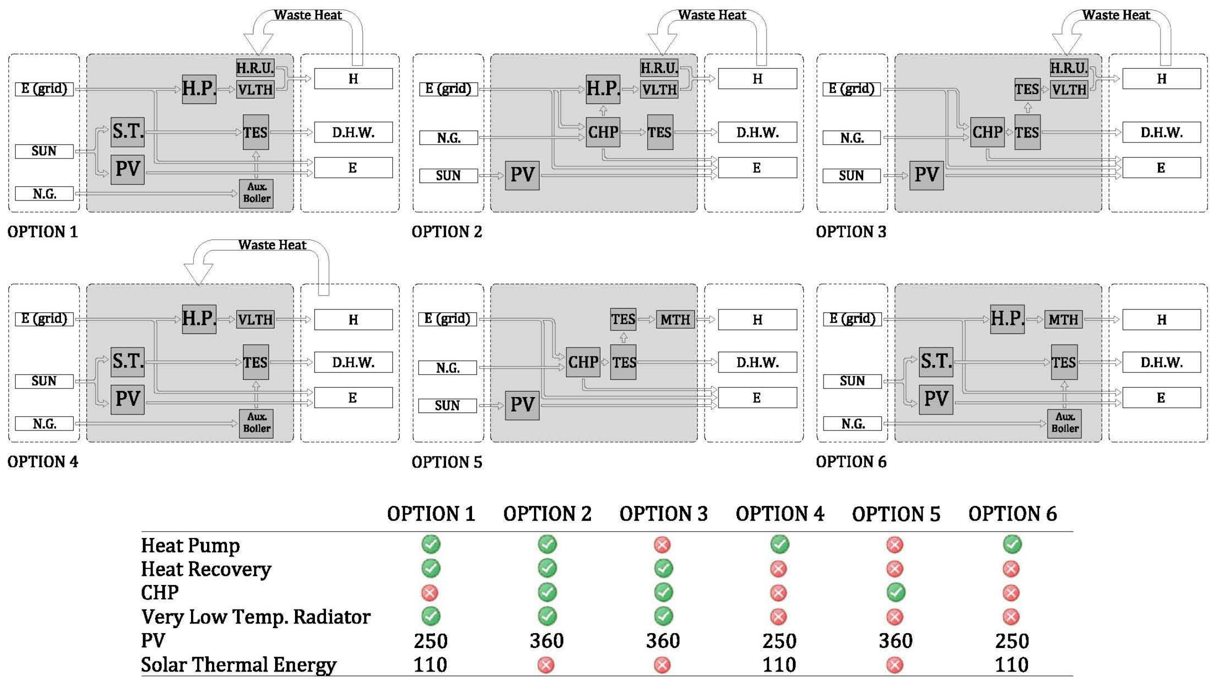

Fig. 4. Schemes of the improved options developed.

5 Results and discussion

5.1 Resulting energy and exergy demands

The annual energy and exergy demands for all cases are listed in the Table 2. As explained in the methodology section the demands for space heating are calculated using the dynamic simulation software TRNSYS. The demands for DHW and electricity are considered equal for all cases.

demand	Case I		Case II		Case III, option 1,2,3		Case III, option 4,5,6	
	Energy	Exergy	Energy	Exergy	Energy	Exergy	Energy	Exergy
Space heating	26,166	1,035	16,044	613	7,800	305	14,688	555

DHW	7,031	524	7,031	524	7,031	524	7,031	524
Electricity	5,466	5,466	5,466	5,466	5,466	5,466	5,466	5,466

Table 2: Annual energy and exergy demands for all cases studied [MJ/year]

It can be seen that the measures taken in Case II reduce the energy demand for space heating by ca. 40%. All options of Case III have further reduced demand for space heating as a result of higher insulation values; options 1 until 3 realize an even larger reduction of the heat demand due to the use of ventilation heat recovery. As could be expected the exergy demand for space heating and domestic hot water is much lower than the energy demand for these outputs due to the low exergy factor of these demands: In energy terms the demand for space heating is the largest demand; in exergy terms however the electricity demand is the largest.

5.2 Energy system results and discussion

5.2.1 Case I and Case II

In Fig. 5 the (steady state) annual results of the energy systems of Case I and Case II is presented. It shows the energy and exergy demand, the energy and exergy losses in the system components and the total primary energy input. For primary energy the exergy content equals the energy content, since an exergy factor of 1 is assumed for the primary energy, as explained in the appendix.

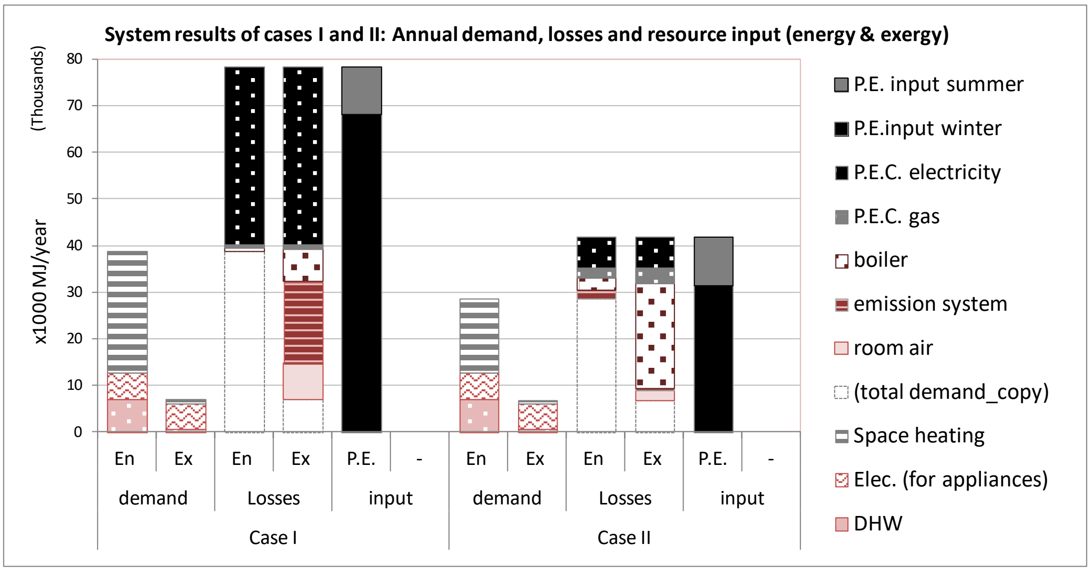

Fig. 5. Annual results of Case I and Case II: energy and energy demand, energy and exergy losses of the various system components and primary energy input (energy equals exergy in this case)

The results of the two reference cases show that in case I a total system energy efficiency of ca 50% is obtained, while for Case II a total system energy efficiency is ca 70%. The total system exergy efficiency is around 10% and 16% respectively. According to an energy analysis the losses in the system are almost solely caused by the primary energy conversion for grid electricity (P.E.C. electricity, see Appendix) in case I, and some by the boiler and the primary energy conversion for gas supply from the grid for Case II. The exergy losses however reveal significant additional losses that are not shown with the energy approach:

- Exergy losses of the 'room air' component, due to the difference in required indoor temperature Ti and the temperature supplied by the emission system (electrical heater and radiator respectively);
- Exergy losses of the emission system of Case I (electrical boiler) due to conversion of electricity into heat;
- Exergy losses in the boiler due to the conversion of gas into heat.

In line with the guidelines mentioned previously it has been tried to avoid these losses in the development of the improved options, which are discussed in the next paragraph.

5.2.2 Case III options 1 until 6.

The results of the improved options (Case III) are slightly more complex to clearly illustrate, since they include the input of renewable energy and 'free' outdoor energy. For correctly understanding the results of the improved options the following aspects have to be taken into account:

- The steady state approach involves the inability to take into account daily and hourly profiles. This means the demand and input of solar gains are not evaluated hourly and thus the total energy need from the grid and total energy returned to the grid is not obtained; only the net monthly electricity demand from the grid is calculated.
- However, a possible monthly surplus of thermal heat from the solar collectors is considered as 'unused' heat and thus not included in the results;
- In case of the use of a CHP and the total roof covered with PV (cases 2, 3 and 5) the results for the summer season show a large surplus of electricity production. In reality this means the output of the energy system in these cases (2,3, and 5) is different from the output of the other cases (1, 4 and 6). For comparison between the cases, however, it is desired to compare the input required for the same output. Since a CHP by definition provides two useful outputs for the same input, it is not possible to subtract a part of the input responsible for the electricity overproduction. In order to make the cases comparable it has therefore been chosen to reduce the primary energy input with the amount of

primary energy that - due to the electricity overproduction - does not need to be spent by the national grid. This method of making the cases comparable to each other increases the sensitivity of the results to the primary energy factor (PEF), as will be further shown in the next paragraph.

The resulting energy and exergy demands according to the assumptions described above can be seen shown in Fig. 6 and Fig. 7. For all cases the primary energy or exergy input for the summer season is very small relative to the annual input. This is mainly caused by the fact that in summer there is no demand for space heating and there is a lot of electricity overproduction (especially in cases with a CHP, being 2,3 and 5).

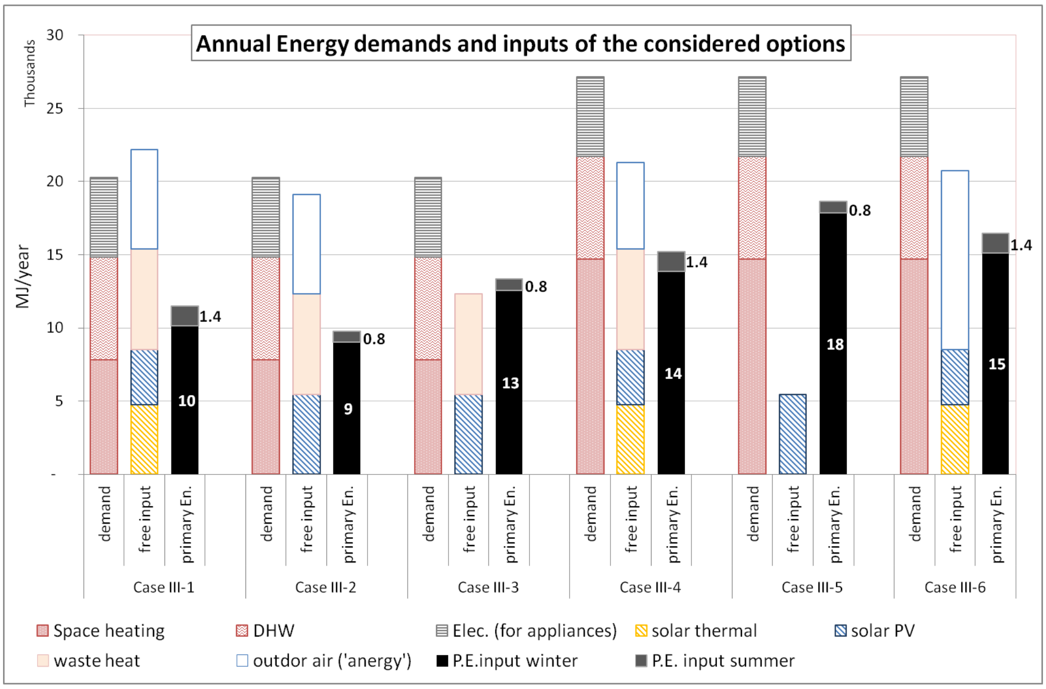

Fig. 6: Results Case III options 1-6: Annual energy demands (=system output) and energy inputs.

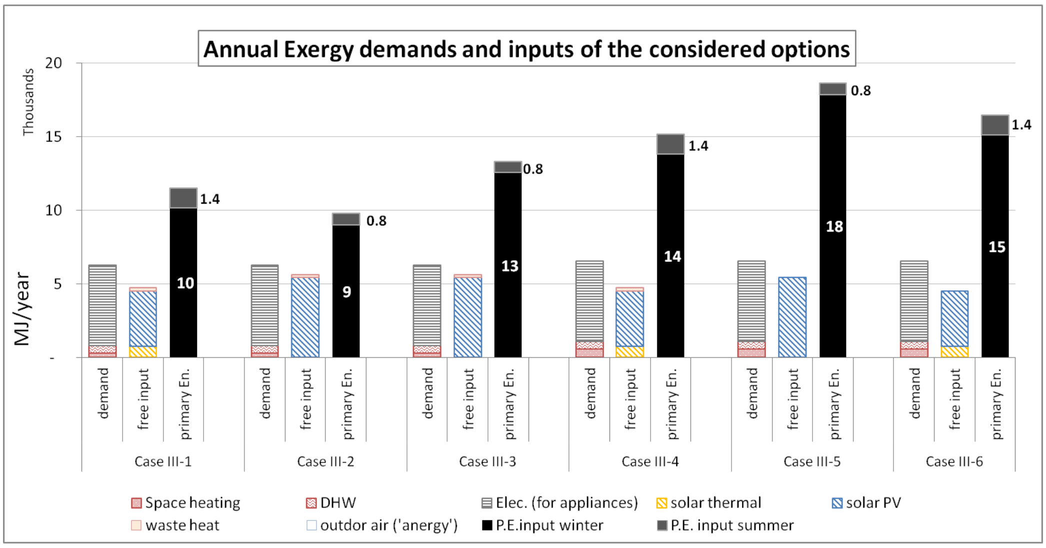

Fig. 7: Results Case III options 1-6: Annual exergy demands (= output) and exergy inputs.

The results show that the improved options perform significantly better than both reference cases with respect to primary energy input. This is caused by a further reduction of the demand for space heating, the use of renewable energy sources and the more exergy efficient system components and configuration.

Of the 'drastic' first 3 cases, the results show that Option 2 (with both a heat pump and a CHP) results in the lowest primary energy input, since it combines the advantages of the HP and the CHP; The second best case is Option 1 using mainly a heat pump. The performance however depends greatly on the actual component characteristics assumed as well as on the primary energy factors, as will be shown in the next paragraph.

Of cases 4 until 6 the heat pump cases also show the best performance. Option 4 performs a little better than option 6, since it makes use of the ventilation waste heat.

An analysis of the losses of case III 1 until III-6 during the heating season is shown in Fig. 8. For each option the energy losses and exergy losses per component are shown.

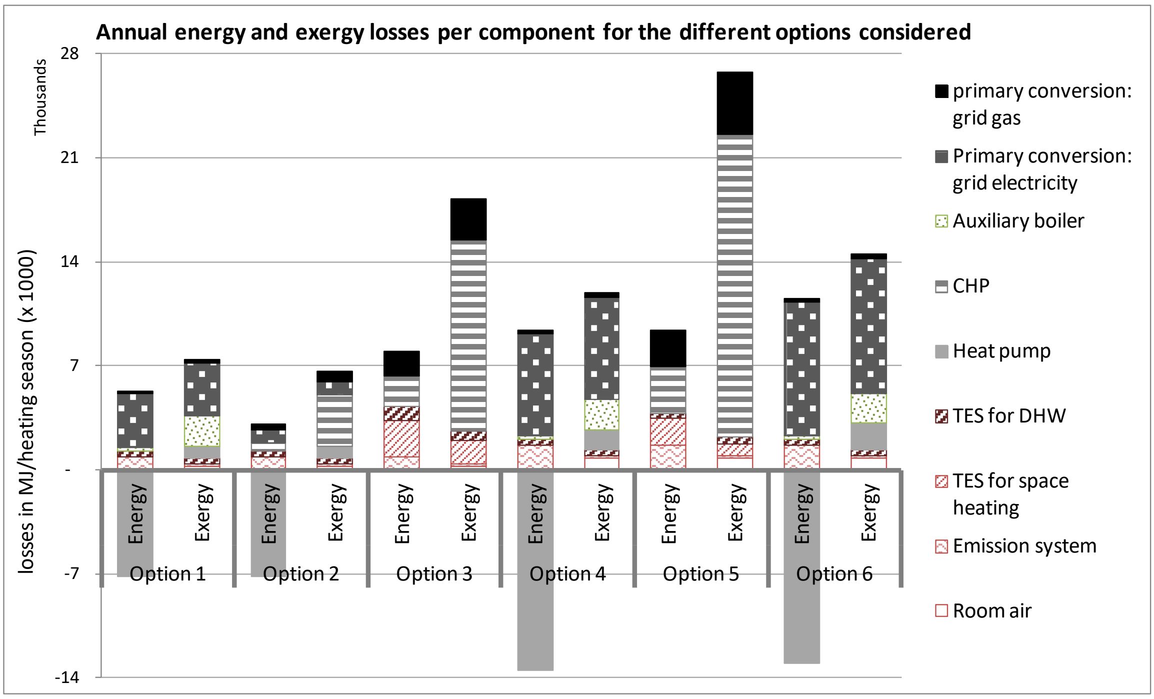

Fig. 8 Energy and exergy losses per energy system component, for each of the improved options considered (according to steady state evaluation of the heating season).

In the analysis of the losses again large differences between the energy and exergy analysis are present. These are especially important in the evaluation of the heat pump and the CHP. The energy performance of the heat pump is very positive since the heat output is larger than the electricity input (free energy input is disregarded, so negative losses are presented); the exergy of the heat output however is smaller than the exergy of the electricity input, which means there are exergy losses. The energy performance of the CHP is also more positive than its exergy performance, since the low value (i.e. low exergy content) of the heat produced by the CHP is not considered in the energy evaluation.

5.3 Sensitivity analysis

All results are naturally dependent on the input parameters as described in the appendix. Figure 8 shows that for all improved options the biggest losses occur in the primary energy conversion and in the CHP component, therefore a sensitivity check of the input parameters used for these components has been performed.

The sensitivity to the electrical efficiency of the CHP is shown in Fig. 9 a. For this sensitivity check the total energy efficiency (electrical efficiency plus thermal efficiency) is kept constant at 91 % (according to the CHP type chosen for the steady state analysis, from [23]) but the electrical efficiency is varied between 20% and 40%. The sensitivity of the resulting primary energy input for options 5 and 6 on the primary energy factor(PEF) for (national grid) electricity production is shown in Fig. 9 b. The PEF is varied between 2.00 and 2.80; the current PEF for Spain according to [24] is 2.21.

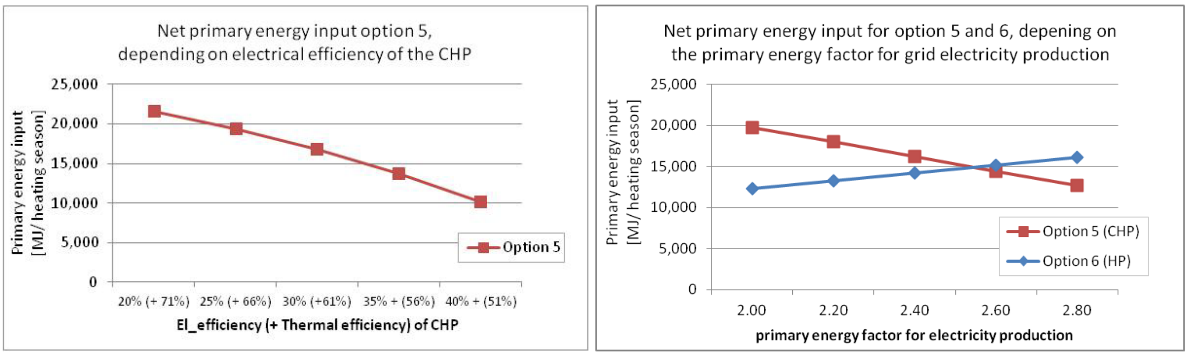

Fig. 9. (a): Sensitivity of the net primary energy input of option 5 to the electrical efficiency of the CHP (left graph), and (b): Sensitivity of the net primary energy input of options 5 and 6 to the primary energy factor for electricity from the national grid (right graph).

As could be expected from the analysis of the exergy losses, the results are very sensitive to the primary energy factor for electricity production as well as on the actual performance of the CHP. This means it is important to take these factors into account when selecting promising options. Also scenarios for future developments of these aspects could be considered.

5.4 Selected options

For further investigation in part II of this paper [8] Option 1, 5 and 6 have been chosen. Option 2 performs best but this is considered not a feasible option due to the high costs of using both a heat pump and a CHP. In a larger scale case study this configuration might be an option.

6 Conclusions and recommendations

This paper has demonstrated the added value of the exergy approach in the analysis and development of an energy system for the built environment, in this case a social dwelling in Bilbao, Spain. It has shown that an exergy analysis reveals thermodynamic losses that are not revealed using energy analysis. Additionally it has shown that taking into account the exergy approach and the exergy guidelines in the development of an energy system configuration for this dwelling resulted in significantly reduced primary energy input compared to both the original situation and the situation with usual retrofitting works. This reduction was caused by a further reduction of the demand, the use of renewable resources, the exergy efficiency of the energy system components and an exergy conscious design of the system as a whole.

It has been shown with the sensitivity analysis that the influence of specific component characteristics on the final results can be very large. The system is more sensitive to parameters of components causing the largest exergy losses. The results of this study have shown to be especially sensitive to the primary energy factor for electricity production and to the electrical efficiency of the CHP unit.

For further development of the energy system the exergy losses should be analysed into more detail and an optimization between exergy efficiency and other objectives, such as costs should be performed. A detailed analysis is performed in part 2 of this paper [8].

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Appendix

In this appendix the building characteristics of the dwelling shown in chapter 3 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 [25].

A.1 Geometrical and construction data

The dwelling has been modelled divided into two zones. Extensive research has been done in other simulations to investigate the influence on the results of the single zone model versus a model divided into more zones. Since the differences are relatively small and the final aim of the project is to investigate the added value of exergy analysis in the evaluation and development of the total systems, the choice to use a simplified model of 2 zones has been made.

A.2 Construction data

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.

No	Function (*1)	Or.	Area [m2]	CASE 1		CASE 2		CASE 3	
				U-Value [W/m²K]	g-Value	U-Value [W/m²K]	g-Value	U-Value [W/m²K]	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/m²K in all cases.

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

A.3 Schedules and 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 a day for fresh air (see ventilation column).

	Infiltration		Ventilation		Internal Gains			Heating Operation	Demands	
	[(m³/h)/m³]		[(m³/h)/m³]		[kJ/h]			[ºC]	[w/m²]	[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. 2. Schedules and operation values assumed in TRNSYS model

A.3.2 Notes and references

Alls schedules in this study are based on CTE and [25]. However, since no difference between weekdays and weekends is assumed in this paper some adaptations to the scheduled from these sources have been made. Additional information for some items is provided below.

A.3.2.1 Air infiltration and ventilation

In the original situation as it was built in the 1960's there is no controlled ventilation. Therefore manual ventilation (opening windows) is assumed for an hour with an air change rate of 4 $(m^3/h)/m^3$, whilst Infiltration airflow rate is assumed constant at 1,3 $(m^3/h)/m^3$ in the dwelling.

For study cases II and III the minimal requirements according to [20] and [25] are followed. This leads to a constant ventilation rate of 1,72$(m^3/h)/m^3$ and a constant infiltration rate of 0,2 $(m^3/h)/m^3$.

The reduced infiltration airflow rate of case II and III is mainly due to the better air tightness of window frames. The retrofitted case also will consider an extra air change rate of 0,24 $(m^3/h)/m^3$ in ventilation.

A.3.2.2 Set point Temperatures

The setpoint and setback temperature shown in table A.2 are based on the criteria given by IDAE [25] Annex III. However, 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).

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

A.3.2.3 Electricity Demand

The electricity demand schedule is based on the IDAE criteria for internal gains, assuming that all heat gains from lighting and appliances are a result of electricity consumption. The electricity Demand sums up to 14977,45 kJ/day, which equals 4,16 kWh/day and 1518,55 kWh/year

A.3.2.4 Domestic Heating Water Demand (DHW)

The schedule assumed for the DHW demand is based on profiles defined in [25], which is similar to the profiles as described in [26]. 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.

• $If\ T_{out} < -5ºC \xrightarrow{then} T_{Sup\_DHW} = 1{,}8$ • $If\ T_{out} \geq -5ºC \xrightarrow{then} T_{Sup\_DHW} = \frac{(2 \cdot T_{out} + 15.4)}{3}$	**eq. A. 3**

Thus, the DHW supply temperature follows the outdoor temperature in a tempered way. In addition the minimum temperature is 1,8 degrees and the maximum is 26 degrees (since the highest outdoor temperature in Bilbao in the EPW data files for a typical year is 30,6 ºC, 27th of July at 5.00 PM)

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>
<tr><th rowspan="2">Component</th><th rowspan="2">η</th><th colspan="3">INPUT</th><th colspan="3">OUTPUT</th></tr>
<tr><th>T_{inl}</th><th>T_{ret}</th><th>F</th><th>T_{inl}</th><th>T_{ret}</th><th>F</th></tr>
<tr><td colspan="8">Demands</td></tr>
<tr><td>Space heating</td><td>N/A</td><td colspan="2">Ti</td><td>1</td><td colspan="3" rowspan="3">N/A</td></tr>
<tr><td>DHW</td><td>N/A</td><td>60 ºC</td><td>eq. A. 3.</td><td>eq. 2</td></tr>
<tr><td>Electricity</td><td>N/A</td><td colspan="2">N/A</td><td>1</td></tr>
<tr><td colspan="8">Emission systems</td></tr>
<tr><td>Elect. heater</td><td>1</td><td colspan="2">N/A</td><td>1(Electricity)</td><td colspan="2">150 ºC</td><td>eq. 1</td></tr>
<tr><td>H.T. Rad.</td><td>0.9</td><td>70 ºC</td><td>55º C</td><td>eq. 2</td><td>70 ºC</td><td>55º C</td><td>eq. 2</td></tr>
<tr><td>M.T. Rad.</td><td>0.9</td><td>40 ºC</td><td>35 ºC</td><td>eq. 2</td><td>40 ºC</td><td>35 ºC</td><td>eq. 2</td></tr>
<tr><td>L.T. Rad / floor</td><td>0.9</td><td>35 ºC</td><td>30 ºC</td><td>eq. 2</td><td>35 ºC</td><td>30 ºC</td><td>eq. 2</td></tr>
<tr><td colspan="8">Conversion components</td></tr>
<tr><td>Boiler</td><td>0.9</td><td colspan="2">N/A</td><td>0.95 (NG)</td><td colspan="2">DHW or emission system</td><td>eq. 2</td></tr>
<tr><td>Heat Pump</td><td>(*1)</td><td colspan="2">N/A</td><td>1(Electricity)</td><td>35 ºC</td><td>30 ºC</td><td>eq. 2</td></tr>
<tr><td>CHP (elec/thermal)</td><td>0.28/ 0.63</td><td colspan="2">N/A</td><td>0.95 (NG)</td><td>80 ºC</td><td>60 ºC</td><td>1(Electricity) / eq. 2</td></tr>
<tr><td>Solar Thermal</td><td>0.44</td><td colspan="2">N/A</td><td>0.95 (Sol)</td><td>80 ºC</td><td>Type 4</td><td>eq. 2</td></tr>
<tr><td>PV</td><td>0.15</td><td colspan="2">N/A</td><td>0.95 (Sol)</td><td colspan="2">N/A</td><td>1(Electricity)</td></tr>
<tr><td colspan="8">Storage</td></tr>
<tr><td>H.T. TES</td><td>0.9</td><td>80 ºC</td><td>60 ºC</td><td>eq. 2</td><td colspan="3">(DHW)</td></tr>
<tr><td>M.T. TES</td><td>0.9</td><td>60 ºC</td><td>40º C</td><td>eq. 2</td><td>40 ºC</td><td>35 ºC</td><td>eq. 2</td></tr>
<tr><td colspan="8">Primary energy conversion (P.E.C.) of grid electricity and grid gas.</td></tr>
<tr><td>P.E.C. elec</td><td>0.45(*2)</td><td colspan="3" rowspan="2">Primary energy, F is assumed 1 (*3)</td><td colspan="3">1(Electricity)</td></tr>
<tr><td>P.E.C. gas</td><td>0.93 (*2)</td><td colspan="3">0.95 (NG)</td></tr>
</table>

(*1) The COP of the heat pump is calculated assuming a performance of 50% of the Carnot COP [19].
(*2) These values are the inverse of the following primary energy factors taken from [24]: 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.3: Properties of the energy system component for each case

Nomenclature

A	[m^2]	Area
c_p	[J kg^{-1} K^{-1}]	Isobaric heat capacity
E	[J]	Electricity
En	[J]	Energy
Ex	[J]	Exergy
F	[-]	Exergy Factor (Exergy to energy ratio)
H	[J]	(space) heating
Q	[J]	Heat
Q_{sens}	[J]	Sensible heat
T	[K]	Temperature (^{0}C if explicitly mentioned)
U	[W m^{-2} K^{-1}]	Heat transfer coefficient
V	[m^3]	Volume

Greek symbols

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

Subscripts

0	Reference
dem	Demand
i	indoor
inl	Inlet
op	Operative (Temperature)
outp	output
ret	return
sp	Set-point (Temperature)
sup	Supply

Abbreviations (also used as subscript)

CHP	Combined Heat and Power (Cogeneration)
DHW	Domestic hot water
H.R.U.	Heat recovery unit
H.T.	High temperature
L.T.	Low temperature
M.T.	Medium temperature
NG	Natural gas
P.E.C.	Primary energy Conversion
P.E.F.	Primary energy factor
PV	Photo Voltaic (energy)
S.T.	Solar thermal (energy)
TES	Thermal energy storage
V.L.T.	Very low temperature

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