Thermal And Environmental Performance Of A Residential Building: A Portuguese Case Study

J. V. Ferreira, I. Domingos

Abstract: This work presents the results of the thermal and environmental performance of a new residential building, as a function of the heating system used, designed to Viseu, a moderate climate zone in Portugal. A case study has been conducted on a conventional residential building, modeled according to Portuguese Thermal Building Regulation (that is complying with EN ISO 13790 and EN 15603) and Life Cycle Assessment methodologies. Two scenarios were studied: the scenario ´VIS-HP´ where a heat pump is used as the heating system and the scenario ´VIS-WH´ using a wood heater as the heating system. In terms of energy, the results show that the scenario ´VIS-WH´ is about 2.4 times more efficient than scenario ´VIS-HP´. According to Portuguese Energy System Certification, the scenario VIS-WH is labeled as class (A^+) and the scenario VIS-HP as class (A). From an environmental point of view the ´VIS-WH´ scenario has a lower environmental load than the ´VIS-HP´ scenario if a very high weight is given to ´Resources´ while a very low weight is given to ´Human Health´ and ´Ecosystem Quality´. Otherwise, the opposite is true

KEYWORDS: Building Certification, Energy Performance, Environmental Performance, Life Cycle Assessment

1 INTRODUCTION

Energy and environment drive modern economies and are the keys to the sustainable development of our society. An analysis of Statistical Pocket Book 2012 [1] shows the following data in 2010: the final energy consumption in 2010 in the European Union, EU27 was 1153.3 Mtoe and in Portugal was 18.2 Mtoe representing an import dependency of 52.7% and 75.4% respectively; the households represent 26.6 % of energy consumption in EU27 and 16.5% in Portugal; the overall Renewable Energy Sources (RES) share of the gross final energy was 11.7% in EU27 and 24.5% in Portugal; the energy consumption per capita was 3507 kgoe/cap in EU27 and 2291 kgoe/cap in Portugal; the CO_2 emissions per capita were 8105 Kg CO_2/cap in EU27 and 5669 Kg CO_2/cap in Portugal. EU headline targets for 2020 highlighted in Europe 2020 Strategy [2] are: reduce greenhouse gas emissions by at least 20% compared to 1990 levels or by 30%, if the conditions are right; increase the share of renewable energy sources in our final energy consumption to 20%; and a 20% increase in energy efficiency. According to the Low Carbon Economy Roadmap 2050 [3] the achievement of the 20% Energy Efficiency and RES targets enables a 25% greenhouse gas emission reduction by 2020 and a crucial role of the building sector where the emissions could be reduced by 90 % by 2050. According to the Energy Efficiency Plan 2011 [4] two thirds of the energy consumption in residential homes goes to space heating so the greatest energy saving potential lies in the renovation process in public and private buildings and in the improvement of the energy performance of the components and appliances used in them.

The Directive 2012/27/EU [5] that EU Member States shall transpose by 5 June 2014 requires that each EU Member State set an indicative national energy efficiency target, based on either primary or final energy consumption, primary or final energy savings, or energy intensity, taking into account that the Union's 2020 energy consumption has to be no more than 1 474 Mtoe of primary energy or no more than 1 078 Mtoe of final energy. Considering the statistics mentioned above, the final energy consumption in EU27 in 2010 exceeded by about 7% the target for 2020. By properly transposing and implementing Directive 2010/31/EU [6], EU Member States can achieve a significant amount of cost effective energy savings and avoid related greenhouse gas emissions. The directive requires Member States to ensure that by 2021 all new buildings are so-called nearly zero-energy buildings. The directive should be transposed into national law by 9 July 2012, but until now (Jun 2013), Portugal had not yet done it although the revision process of the current legislation has been launched in 2010, as mentioned in an overview report of the current status of EPBD implementation in Portugal [7]. Following the cost-optimality principle of the directive, "nearly net zero energy" building definition was proposed by REHVA Task Force [8], as "national cost optimal energy use of > 0 KWh/(m².year) primary energy". The Portuguese Building Regulations complies with Directive 2002/91/EC (EPDB) [9]. The energy building certification is based on the Energy System Certification (SCE) [10] and Thermal Building Regulation (RCCTE) [11]. The purpose of the SCE is to certify the energy performance and indoor air quality in buildings and its management was entrusted to the Energy Agency (ADENE), which approved the energy performance and indoor air quality in buildings certificate model, wherein the energy performance label, for new buildings, is divided into four classes (from A+ to B^-) [12] as shown in Fig.1.

- *J. V. Ferreira is currently a Professor in Technology School in Viseu Polythecnic Institute, Portugal, PH-+351232480567. E-mail: jvf@estv.ipv.pt*
- *Domingos is currently a Professor in Technology School in Viseu Polythecnic Institute, Portugal, PH-+351232480567. E-mail: ijd@estv.ipv.pt*

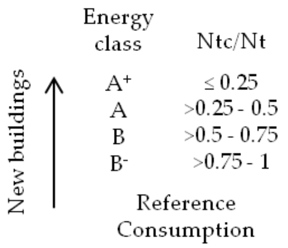

Fig. 1. Portuguese new buildings energy certification scheme. Adapted from [12] (Ntc = nominal needs of global primary energy; Nt = maximum allowable primary energy)

According to the energy classification adopted by the SCE the energy consumed in the most efficient building (class A$^+$) is < ¼ of the energy consumed by a ´reference building´[1] and the energy consumed in a building (class A) is >1/4 and ≤1/2 of the energy consumed by a ´reference building´. The energy label is based on calculations in terms of primary energy and nominal CO_2 emissions are also listed in the front page of the Energy Performance Certificate (EPC). With this study the authors intend to help building owners and public authorities in making decision as to the best choice of the heating system in order to accommodate the requirements of the EPBD recast.

2 Case Study

The new residential building which we intended to study is located in a central (north) region of Portugal in the municipality of Viseu. The main geographical and climatic data, as well as some relevant building features are reported in Table 1.

TABLE 1 Main features and climatic data of the Building in Viseu

Building features		Geographical and climate data	
Typology	T2	Altitude	330 m
Occupants (conventional)	2	Latitude	40º 21' 0" North
[illegible]	[illegible]	[illegible]	7º 52' 00" West
External walls area (A)	300.42 m^2	Degree Days (GD)	1940
Gross volume (V)	306.5 m^3	Climatic area	I2; V2
Shape factor (FF=A/V)	0.98	Conventional heating period	7.3 months
Cooling system	electrically driven heat pump (ηv = 3)		
DHW system	solar collector + natural gas wall boiler with accumulation and 50mm insulation (ηa = 0.82)		
Heating system	electrically driven heat pump (ηi = 4) - scenario VIS-HP		
Heating system	wood heater (ηi = 0.6) - scenario VIS-WH		

Two scenarios were studied: the scenario ´VIS-HP´ where a heat pump is used as the heating system and the scenario ´VIS-WH´ using a wood heater as the heating system, which ensure the same indoor conditions required by the building regulation (RCCTE): indoor air temperature of 20 ºC for the heating season and 25 °C and 50% relative humidity for the cooling season; consumption of 40 liters of hot water at 60 ºC per person per day for 365 days/year. In the absence of more accurate data, we adopted de reference values recommended by legislation (RCCTE) for nominal efficiency of equipment for heating (ηi), cooling (ηv) and DHW (ηa). A sensitivity analysis has be done to test the influence of the heating system efficiency. Solar thermal collector system for DHW was considered because it is mandatory for new residential buildings producing 1249 KWh/year (SOLTERM, [13]).

3 Methodology

To compare the two building scenarios from the energy consumption perspective, we used the models proposed in the Portuguese legislation, SCE [10] and RCCTE [11] where energy performance sustains the building energy classification and, therefore, the energy rating of a building is a function of the ratio Ntc (nominal needs of global primary energy)/Nt (maximum allowable primary energy) as shown in Fig.1. The energy produced by renewable systems (solar, wood, etc..) is subtracted from the energy required by conventional systems not contributing to the nominal needs of global primary energy. The energy needs are calculated based on EN ISO 13790 and EN 15603. For this case study the models used to calculate the energy limit for heating (Ni), energy needs for heating (Nic),energy limit for cooling (Nv), energy needs for cooling (Nvc), energy limit for DHW (Na), energy needs for DHW (Nac), the maximum allowable primary energy (Nt) and the nominal needs of global primary energy (Ntc) were:

$$Ni = 4.5 + (0.021 + 0.03 \, x \, FF) \, x \, GD \quad \text{(KWh/m}^2\text{.year)} \qquad (1)$$

$$Nic = (Qt + Qv - Qgu)/Ap \quad \text{(KWh/m}^2\text{.year)} \qquad (2)$$

$$Nv = 18 \quad \text{(KWh/m}^2\text{.year), for Zone I2; V2} \qquad (3)$$

$$Nvc = Qg \, x \, (1-\eta)/Ap \quad \text{(KWh/m}^2\text{.year)} \qquad (4)$$

$$Na = (0.081 \, x \, M_{AQS} \, x \, n_d)/Ap \quad \text{(KWh/m}^2\text{.year)} \qquad (5)$$

$$Nac = ((M_{AQS} \, x \, 4187 \, x \, \Delta T \, x \, n_d \, / \, 3\,600\,000 \, x \, \eta_a) - Esolar) \, / \, Ap \quad \text{(KWh/m}^2\text{.year)} \qquad (6)$$

$$Nt = 0.9 \, x \, (0.01 \, x \, Ni + 0.01 \, x \, Nv + 0.15 \, x \, Na) \quad \text{(Kgoe/m}^2\text{.year)} \qquad (7)$$

$$Ntc = 0.1 \, x \, (Nic/\eta i) x \, Fpui + 0.1 \, x \, (Nvc/\eta v) x \, Fpuv + Nac \, x \, Fpua \quad \text{(Kgoe/m}^2\text{.year)} \qquad (8)$$

Where: FF=0.98 (see Table 1); GD=1940 ºC.day (see Table 1); Qt (heat losses by conduction through the envelope) = 12496.7 KWh/year (calculated); Qv (heat losses resulting from air renewal) = 4124.3 KWh/year (calculated); Qgu (useful thermal gains in the heating season) = 5735.02 KWh/year (calculated); Ap = 94.3 m^2 (Table 1); Qg (gross total gains of building) = 3259.02 KWh/year (calculated); η (use factor of gains) = 0.92; M_{AQS} = 2 occupants x 40 l water/occupant =80 l of water; n_d=365 days/year; ΔT= 45ºC (reference value); ηa =

0.82 (Table 1); Esolar (energy from solar thermal collector system) = 1249 KWh/year (calculated by SOLTERM program [13]); ηi and ηv represent the nominal efficiency of the equipment used respectively for heating and cooling (see Table 1); Fpu represent the conversion factors between net energy and primary energy (Fpu=0,29 kgoe/kwh for electricity and Fpu=0,086 kgoe/kwh for gas/liquid/solid fuels). An eligible solution should verify legislation requirements for the heating energy index (Nic/Ni ≤ 1), the cooling energy index (Nvc/Nv ≤ 1), the DHW energy index (Nac/Na ≤ 1) and the primary energy index (Ntc/Nt ≤ 1). To compare the environmental aspects and potential impacts associated with the two building scenarios a Life Cycle Assessment (LCA) study was performed based on ISO 14040:2006 [14] and ISO 14044:2006 [15] recommendation. LCA provides better understanding and better estimation of energy (and other environmental) aspects in the life cycle of any sort of good and can help decision makers in the selection of products or processes that result in a lesser impact on the environment [16, 17]. LCA is divided into four phases [14]: 1) goal definition – which defines the aim and scope of the study as well as the functional unit; 2) inventory analysis – which lists emissions of pollutants into air, water and soil, solid wastes and consumption of resources per functional unit; 3) impact assessment – which assesses the environmental impact of the pollutants emitted throughout the life cycle; 4) interpretation of results. *Goal and scope of the study* – The main aim of this LCA study is to compare the environmental impacts of the two scenarios of the building which fulfill the same indoor reference conditions required by RCCTE mentioned above. *Description of product* – scenario VIS-HP is the single-family house with a heat pump for heating. Scenario VIS-WH is the same building with a wood heater for heating. According RCCTE [11] the efficiency (reference values) for heat pump (heating) is (ηi = 4) and for wood heater is (ηi = 0.6). *Boundaries* –The system boundaries for both scenarios are represented in a simplified way in Fig. 2. Though this figure does not show full details, it contains the main processes studied. The transports between processes are presented in a generic way, considering these processes are associated with a lot of other processes.

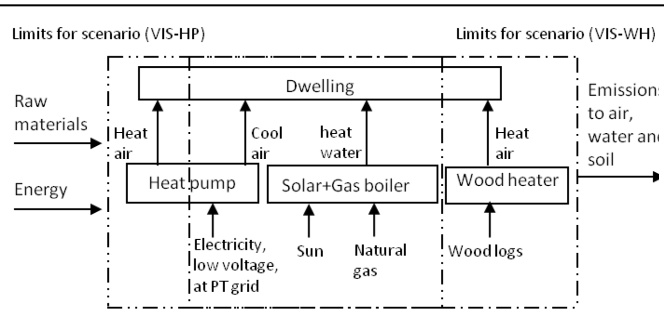

Fig. 2. System boundaries of the dwelling scenarios: VIS-HP and VIS-WH

The system boundaries for the scenario VIS-HP include the following main sub-systems: low voltage electricity (production + import) from the Portuguese grid; heat from heat pump (heating); cool from heat pump (cooling); and heat water from gas boiler burning natural gas. The system boundaries for the scenario VIS-WH include: low voltage electricity (production + import) from the Portuguese grid; cool from heat pump (cooling); heat water from gas boiler burning natural gas; and heat from wood heater. *Data type/Data collection* – To access the necessary data set, literature and a specialized database such as Ecoinvent 2.2 [18] were used. We used the data from the same database. The unitary processes and their correspondents in the Ecoinvent database are described in Table2. These are average values of European manufacturers, or European-based average values of processes having similar outputs, using the average technology or a mix of technologies.

TABLE 2 UNITARY PROCESSES AND ITS CORRESPONDENTS IN THE ECOINVENT DATABASE

Unitary process	Ecoinvent process
Electricity, low voltage, at Portuguese (PT) grid	Electricity, low voltage, at grid/PT U
Heat from heat pump (heating)	Heat, at air-water heat pump 10KW/CH U – adapted (ηi=4)
Cool from heat pump (cooling)	Heat, at air-water heat pump 10KW/CH U – adapted (ηv=3)
Heat water from solar + gas boiler burning natural gas	Heat, at hot water tank, solar+gas, flat plate, one-family house/CH U – adapted
Heat from wood heater	Heat, mixed logs, at wood heater 6KW/CH U – adapted (ηi=0.6)

Data from heating distribution systems in the house are not included. According to Vigon *et al* [19] data from manufacturing of capital goods are, generally, not included in the limits of the system because they have been shown to have a negligible effect on results.

Functional unit – According to ISO 14040:2006 [14], ´the functional unit is a measure of the function of the studied system´. The functional unit should be defined so that the different building scenarios being compared provide the same indoor reference conditions required by RCCTE mentioned above. Consequently, the functional unit is 1 m^2/year, similar to that proposed in Sartori [16].

Life cycle impact assessment (LCIA) – The inventory analysis and, subsequently, the impact analysis has been performed using the LCA software SimaPro7.3.3 [20] and associated databases and methods. The method chosen for impact assessment was the Eco-Indicator (99) H/A [21] since it is commonly used and provides similar results to several other methods. This method is based on the so-called damage oriented (end-point) approach. Its aim is to evaluate the environmental consequences with reference to wider areas of concern, such as "Human Health", "Ecosystem Quality" and "Resources". We have avoided using the aggregation method because there is currently no unanimity for the weighting factors used; furthermore, the comparison of impact classes' results allows one to have a more transparent vision on the effect of each impact class.

4 Results and Interpretation

4.1 Energetic Assessment

Applying the models proposed in the methodology to the building scenarios under study, the Nic (energy needs for heating), Ni (energy limit for heating), Nvc (energy needs for cooling), Nv (energy limit for cooling), Nac (energy needs for DHW), Na (energy limit for DHW), Ntc (the nominal needs of global primary energy), Nt (the maximum allowable primary energy), Ntc/Nt (the primary energy index) and energy class (according Fig.1) are recorded in Table 3.

TABLE 3 Energy performance of the building scenarios

Energy \ Scenario	Scenario VIS-HP	Scenario VIS-WH
Nic (KWh/m^2.yr)	115.43	
Ni (KWh/m^2.yr)	115.60	
Nvc (KWh/m^2.yr)	2.93	
Nv (KWh/m^2.yr)	18	
Nac (KWh/m^2.yr)	6.52	
Na (KWh/m^2.yr)	25.08	
Nt (Kgoe/m^2.year)	4.59	
Ntc (Kgoe/m^2.year)	1.43	0.59
Ntc/Nt	0.31	0.13
Energy Class	A	A$^+$

Both building scenarios, (VIS-HP) and (VIS-WH), are eligible solutions because they verify legislation requirements for heating energy index (Nic/Ni = 0.99 ≤ 1), cooling energy index (Nvc/Nv = 0.16 ≤ 1), DHW energy index (Nac/Na = 0.26 ≤ 1) and primary energy index (Ntc/Nt ≤ 1). The energy needs for DHW through conventional systems are decreased from 13.64 KWh/m^2.year with the installation of solar collectors. The scenario VIS-HP presenting a primary energy index Ntc/Nt = 0.31 is labelled (A) according to the Portuguese energy certification system (SCE). The nominal needs of global primary energy, (Ntc) is 1.43 Kgoe/m^2.year: the heating system represents 59% of that primary energy, the DHW 39%, and the cooling system only 2%. The scenario VIS-WH presenting a primary energy index Ntc/Nt = 0.13 is labelled (A$^+$). The nominal needs of global primary energy, (Ntc) is 0.59 Kgoe/m^2.year: the heating system, using a renewable energy, does not contribute for that primary energy; the cooling system represents 5% and the DHW 95%. In both scenarios, DHW is very significant being the system that most contributes to nominal global primary energy needs (Ntc), in the scenario VIS-WH. This helps us understand the obligation imposed by RCCTE and required by the new EPBD (recast) to use solar thermal collector systems (or other forms of renewable energy) for DHW in buildings where there is adequate sun exposure, in addition to the use of conventional systems. The energy efficiency of the building scenario VIS-WH is about 2.4 times higher than the efficiency of the scenario VIS-HP.

4.2 Life Cycle Assessment

The potential environmental impacts associated with the functional unit (1 m^2/year) of building scenarios were made with the help of SimaPro7.3.3 software and using the Eco-Indicator method. The results on eleven different environmental impacts are plotted in the following Figures. The environmental profile of the 'VIS-HP' scenario is represented in Fig. 3 and, as we can observe, the ´Heating´ system is the one that most contributes for the environmental impacts, except for radiation, where domestic heat water ´DHW´ is the most representative. The contribution of the ´Cooling´ system is almost residual.

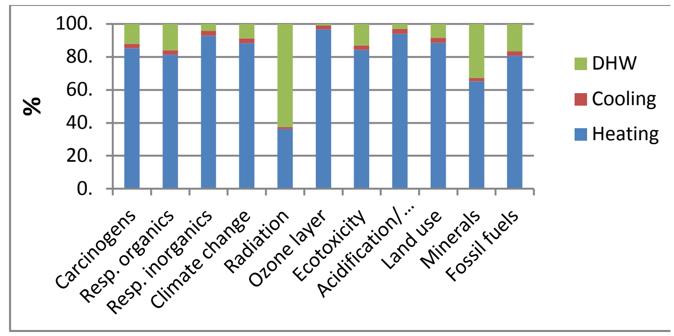

Fig. 3. Environmental profile of building scenario 'VIS-HP'

Fig. 4 shows the normalized environmental profile results of the 'VIS-HP' scenario and through that we can see that ´fossil fuels´ is the most significant category followed by ´resp. inorganics´ and ´carcinogens´, all of them almost exclusively due to the ´heating´ system.

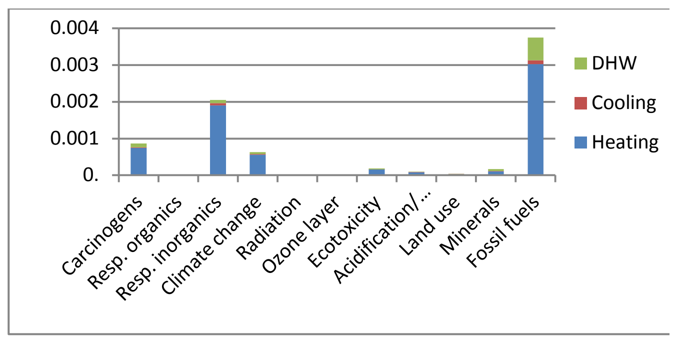

Fig. 4. Normalized environmental profile of 'VIS-HP' scenario (in European equivalents per year)

The environmental profile of the 'VIS-WH' scenario is represented in Fig. 5. The heating system is the one that most contributes for the majority of the impact categories but in this scenario ´DHW´ is the one that most contributes for ´Fossil fuels´, ´Minerals´, and ´Radiation´ and has a significant importance for ´Climate change´ and ´Ozone layer´. The ´cooling´ system is the most accountable for the ´Ozone layer´.

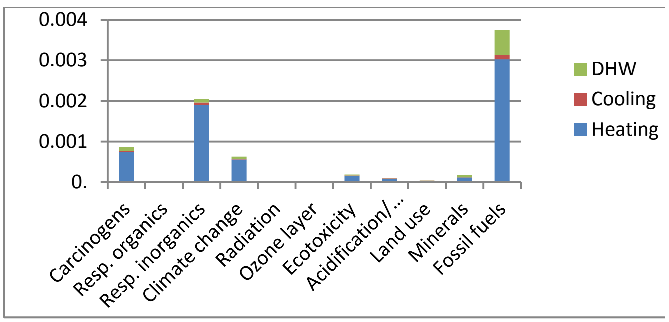

Fig. 5. Environmental profile of building scenario 'VIS-WH'

The results of normalized damage categories of the 'VIS-WH' scenario are plotted in Fig. 6 through which we can see that the category ´Resp. inorganics´ is the most meaningful and is almost exclusively due to particulates (< 2μm) and nitrogen oxides from the ´heating´ system.

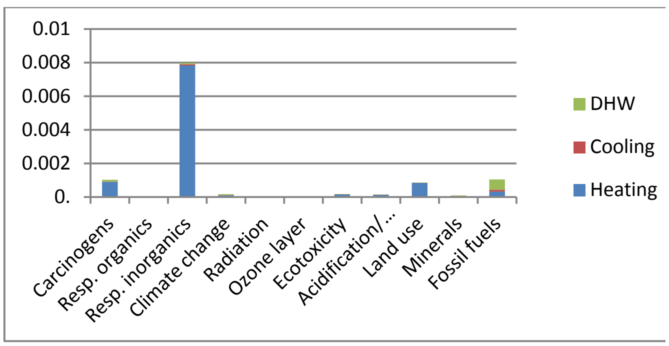

Fig.6. Normalized environmental profile of 'VIS-WH' scenario (in European equivalents per year)

The comparison of the potential environmental impacts associated with building scenarios per impact category are plotted in Fig. 7. The Figure shows that from the point of view of ´Carcinogens´, ´Resp. organics´, ´Resp. inorganics´, Acidification/Eutrophication´ and ´Land use´, the ´VIS-HP´ scenario is preferable to the ´VIS-WH´ scenario and that the opposite is true for remaining impact categories.

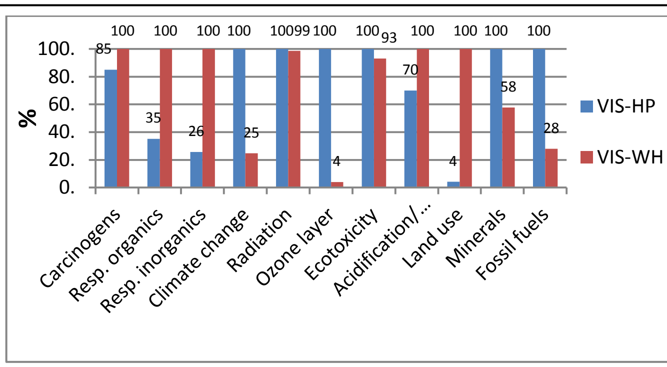

Fig. 7. The environmental impact comparison of building scenarios per impact category

The ´VIS-HP´ scenario contributes 4 times more for ´Climate change´ than the ´VIS-WH´ scenario and the opposite is true for ´Resp. inorganics´. However, as we can see from normalized results (Fig.s 4 and 6) the ´Resp. inorganics´ value is much more important than the value of ´Climate change´ or other impact category values. A comparison of the building scenarios in damage categories is given in Fig. 8. The VIS-WH scenario is seen to be more damaging than scenario VIS-HP on the ´Human health´ (2.6 times) and ´Ecosystem quality´ (3.7 times) and the scenario VIS- HP is more damaging (3.4 times) than scenario VIS- WH in ´Resources´.

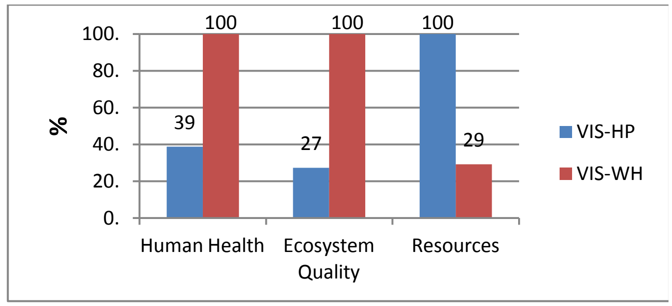

Fig. 8. The environmental impact comparison of building scenarios per damage category

The line of indifference in the weighting triangle and the sub areas with their specific ranking orders is presented in Fig. 9. In this study we can conclude the ´VIS-WH´ scenario has a lower environmental load than ´VIS-HP´ scenario if a very high weight is given to Resources while a very low weight is given to ´Human Health´ and ´Ecosystem Quality´. However, if a very high weight is given to ´Ecosystem quality´ and ´Human Health´ and a very low weight is given to ´Resources´, the ´VIS-HP´ scenario has a lower environmental load than ´VIS-WH´ scenario.

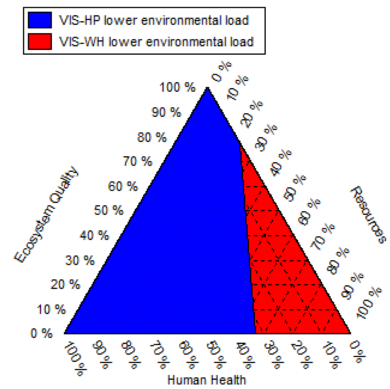

Fig. 9. The weighting triangle

4.2.1 Sensitivity analysis

As previously mentioned the nominal CO_2 emissions are listed in the front page of the ´Energy Performance Certificate´ of buildings so a sensitivity analysis was performed using the impact assessment method - the ´IPCC GWP 100a´. By using this method the CO_2 equivalent emissions per functional unit in the building scenarios are: scenario VIS-HP - 26.8 Kg CO_2eq/u.f.; and scenario VIS-WH - 6.44 Kg CO_2eq/u.f.. This means that the building with a heat pump for heating (scenario VIS-HP) is about 4 times worse than with a wood heater (scenario VIS-WH) confirming the result obtained by the Eco-Indicator method. The influence of the heating efficiency of chosen wood heater in energy and environmental performance of the building was tested by assuming a new net value for heating system of (ηi = 0.75) considered valid for boilers with nominal capacity up to about 20 KW and representing the average technology available on market [18]. The energy indicators didn´t change because as stated before the energy produced by renewable systems does not contribute to the nominal needs of global primary energy. However, the wood fuel needs are decreased in the same proportion that the heating system efficiency is increased (25 %) and a meaningful cost reduction during the use phase of building is reached. The environmental results showed a reduction in the environmental loads that ranged from a minimum of 3.1 % for ´Ozone layer´ and a maximum of 20 % for ´Land use´ and ´Resp. inorganics´ and with a meaning relevant to ´Resp. organics´ and ´Acidification/Eutrophication´ (19 %), ´Carcinogens´ (18 %), ´Ecotoxicity´ (17 %) and ´Climate change´ (10.9%).

5 Conclusions and Recommendations

The influence of the heating system in the energy and environmental efficiency of a new residential building designed for Viseu, a moderate climate zone in Portugal, was assessed by mean of a Portuguese thermal building legislation and LCA methodology. Two scenarios were studied: scenario VIS-HP is the building with a heat pump (ηi = 4) for heating and scenario VIS-WH is the same building with a wood heater (ηi = 0.6) for heating. The cooling and DHW systems were maintained in both scenarios. One of the main study outcomes is that, in terms of energy and according Portuguese thermal building legislation, the building with a wood heater for heating (scenario VIS-WH) is about 2.4 times more efficient than the building with a heat pump for heating (scenario, VIS-HP). In the scenario VIS-WH the building is labeled as class (A^+) and in the scenario VIS-HP as class (A). Another main study outcome is that from an environmental point of view we can´t say that one scenario is better than other but only that scenario VIS-HP is more environmentally friendly related to ´Carcinogens´, ´Resp. organics´, ´Resp. inorganics´, ‘Acidification/Eutrophication´ and ´Land use´ and that VIS-WH is preferable in terms of ´Climate change´, ´Radiation´, ´Ozone layer´, ´Ecotoxicity´, ´Minerals´ and ´Fossil fuels´. The equivalent CO_2 emissions per functional unit in building scenario VIS-HP are 26.8 Kg CO_2eq/u.f. and in scenario VIS-WH are 6.44 Kg CO_2eq/u.f. Through weighting triangle we can conclude that if a very high weight is given to ´Resources´ and a very low weight is given to ´Ecosystem quality´ and ´Human health´ the ´VIS-WH´ scenario has a lower environmental load than ´VIS-HP´ scenario. Otherwise, the opposite is true. Taking into account the main conclusions of the study and to achieve a significant amount of energy savings and avoid related greenhouse gas emissions as recommended by Directive 2010/31/EU, it is suggested that the future Thermal Building Regulation further promotes the use of modern wooden heating systems with a high efficiency.

Acknowledgments

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