...he literature is relatively scarce about
... actual and reliable performance in
...onally the lessons learned from exist-
...pants in the IEA SHC Task 40-ECBCS
...olar Buildings ... willing to share ...nts from on-going research work on
...ential buildings. Although there is no standard approach for designing a Net
... different possible combinations of passive and efficient active measures, utility
...ration technologies able to achieve the net-zero energy performance), a close
...s and the relative performance indicators of the selected case studies reveal that it
... performance using well known strategies adjusted so as to balance climate driven-
...g, lighting, ventilation and other energy uses with climate-driven supply from renew-

...ing, Residential Building, Passive Measures, Energy Efficiency, Renewable Energy

...have gained more attention ...n 2010 of the recast Energy ...ings Directive (EPBD 2010). ...s that by 31 December 2020 ...ould meet higher levels of per- ...ore in order to ensure that they ...ergy buildings. Building design- ... achieve this outcome by explor- ... alternative energy supply systems ... using a cost-efficiency assessment ...ompromising the comfort for the ...

...early zero-energy building" refers to a ... performance building where annual ...rgy consumption is provided to a very ... extent by energy from renewable ...eing energy from renewable sources pro- ...n-site, or nearby or both. Since the Directive does not specify minimum or maximum harmonized requirements nor details of the energy performance calculation framework, it is up to the Member States to define the exact meaning of "high energy performance" and "amount of energy from renewable sources" according to their own local conditions and strategic interests. Nearly zero-energy performance derives from the net zero-energy concept which, in the case of buildings, is usually defined as a high energy performance building that over a year is energy neutral (i.e. net balance of primary energy is 0 kWh/(m^2 y)). Therefore, a possible way to assess the nearly zero-energy performance is by analysing the annual energy balance in Net Zero-Energy Buildings.

Net Zero-Energy Buildings have been the object of numerous studies in recent years as various countries have set this performance as a long-term goal of their energy policies (Ayoub 2009, Aelenei et al. 2011, Sartori et al. 2012). The

International Energy Agency collaborative research initiative between the Solar Heating and Cooling (SHC) and the Energy Conservation in Buildings and Community Systems (ECBCS) through Task 40/Annex 52 - "Towards Net-Zero Energy Solar Buildings", summarises most of the recent developments in the field (IEA 2008).The Task members, including approximately 55 National Experts, among which can be found the authors of this work, together with another 25 regular participants and contributors, are currently researching examples of; net-zero, plus energy and near net-zero energy buildings in order to develop:

- a common understanding of NZEBs,
- a framework of harmonized international definitions,analysis tools,
- examples of innovative solutions and
- industry guidelines for the design of NZEBs.

NZEB performance

In the international context, there are four main types of NZEBs:

- Net Zero Site Energy,
- Net Zero Source Energy,
- Net Zero Energy Cost and
- Net Zero Energy Emissions.

Net Zero Site Energy means that the annual balance is based on the grid interaction at the boundary of the building site, i.e. the overall energy delivered to the building from the utility grid is offset by the overall energy fed back into the grid.

The Net Zero Source Energy definition is the one that most closely matches the EPBD recast in a nearly zero-energy context (EPBD 2010). IN this definition the energy (delivered from and feed into the grid) has to take into account primary energy conversion factors.

The Net Zero Energy Cost definition is based on an economic balance (the energy bills of a building are equivalent the amount of money the utility pays the owner for renewable energy the building feeds to the grid).

In the case of Net Zero Energy Emissions buildings on an annualised basis these produce and export at least enough emissions-free renewable energy to equal the total emissions that were caused in the importation and use of emission-producing sources on an annual basis (Torcellini 2006).

As with all buildings the design and realisation of a Net Zero Energy Building includes many different possible combinations of building envelope, utility equipment and on-site energy production equipment able to achieve net-zero energy performance. Further influencing the design is a need to consider the balance boundary, which defines which consumers are included in the balance. Despite these variables there is some consensus that zero energy building design should start from passive sustainable design as this NZEB level of performance is achieved as a result of executing two fundamental approaches; (a) reducing building energy demand and (b) generating electricity or other energy sources to get enough off-sets to achieve the desired energy balance (Fig. 1) from renewable energy systems (RES). As one can easily imagine passive approaches play a crucial role in addressing NZEB design as they directly affect the heating, cooling, ventilation and lighting loads of the building's mechanical and electrical systems and, indirectly, the strive for renewable energy generation.

Case Studies

Table 1 presents a summary of the main technical features of the 9 projects selected from the IEA Task 40 project data base for analysis (Musall 2012). As can be seen from Table 1 buildings are characterised according to location, conditioned floor area, climate challenge and primary energy performance (consumption versus supply). In the case of the climate challenge it should be noted that these case studies correspond to only two different categories of climate challenges; heating dominated and heating & cooling dominated.

These nine projects were selected as case studies based on criteria such as; access to technical documentation regarding physical characteristics, availability of monitored and/or simulated energy performance data, as well as the authors access to lessons learned about designing, operating, and post-evaluation processes.

Reference to Figure 1 below shows that, in terms of Net Zero Energy performance, of these nine buildings six are plus-energy buildings and three are nearly zero-energy buildings (Fig.1).

Two of the three projects exhibiting a near zero-energy performance, *Leaf*, was initially designed to meet net zero-carbon performance (Musall 2012) whereas *Lima* and *Écoterra*, were designed to be energy efficient to minimise negative impacts on the environment (Noguchi et al. 2008). One should be mindful that *Lighthouse*, which is a demonstration building, was also designed as net zero-carbon, being the UK's first house that also meets Level 6 (the highest level) of the Code for Sustainable Homes (Department for Communities

Building Name and Location	Conditioned floor area [m²]	Climate challenge	Annual Energy consumption [kWh/m².y]	Annual Energy Supply [kWh/m².y]	Annual Energy Balance [kWh/m².y]
Écoterra Québec, Canada	234	Heating	50.80	16.35	-34.45
Energy FlexHouse Denmark	216	Heating	90.3	108.3	18.0
Leaf House Italy	477	Heating & Cooling	151.24	128	-23.24
Lima Spain	45	Heating & Cooling	79.8	61.56	-18.24
Riehen, Switzerland	315	Heating	62.86	85.08	22.22
Riverdale Canada	234	Heating	38.50	42.40	3.90
Lighthouse UK	79	Heating	166.92	191.54	24.62
Plus Energy Houses Austria	855,9	Heating	129.50	150.4	20.9
Plus Energy Germany	7890	Heating	70.65	113.95	43.3

Table1. Case studies - common parameters consider.

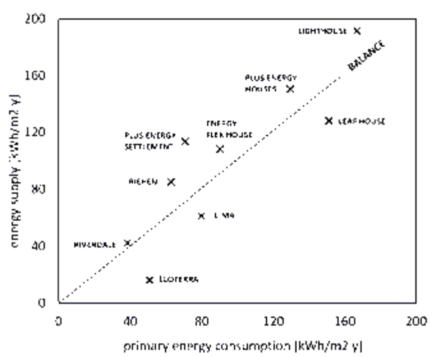

Figure 1. Annual primary energy performance in terms of NZEB performance for case studies.

and Local Government 2009).

NZEB Design Features

Although the main principles applied in passive sustainable design are well known, the fundamental issue here is to find if the same principles can also be applied in NZEB design given the other RES imperatives. To discover the answer, an analysis of the nine case studies was performed according to the scheme shown in Figure 2. Figure 2 illustrates that the first principle in the NZEB design focuses on reducing the amount of energy needed through passive approaches, (inner circle of the chart). Given the inherent needs of artificial lighting and possible heating and/or cooling, the second principle aims at implementing energy efficient systems, (second circle of the chart). The renewable energy systems are needed to offset in large measure the energy demand required for lighting, heating and cooling (the third principle). However, rather than performing a detailed analysis of each of the projects, a cross examination was performed instead. This procedure is expected to allow for the identification of the set of relevant NZEB design issues (combination of passive approaches (PA), energy efficient systems (EES) and renewable energy systems (RES)) which are more likely to succeed in reaching the desired energy performance.

In the sections to follow an overview of the key components arising from these principles and which affect NZEB energy performance will be presented for each of the three research components, passive approaches, energy efficient systems and renewable energy systems.

First Principle: Passive Design

As noted above, passive approaches play a fundamental role in NZEB design as they directly affect the loads put on the building's mechanical and electrical systems, and indirectly, the strive for renewable energy generation. In this context it is understandable why zero energy building design should start from passive sustainable design thinking and approaches. In this respect, and even though the buildings were designed to meet different energy performance levels (according to national specific strategic needs), the first characterisation focuses on envelope thermo-physical characteristics and compactness (Table 2).

In general, passive solar energy concepts fall into three main categories/challenges depending of the solar energy exploitation (heating, cooling, lighting/appliances) and the relative strategies used (prevention, modulation, rejection/collection,

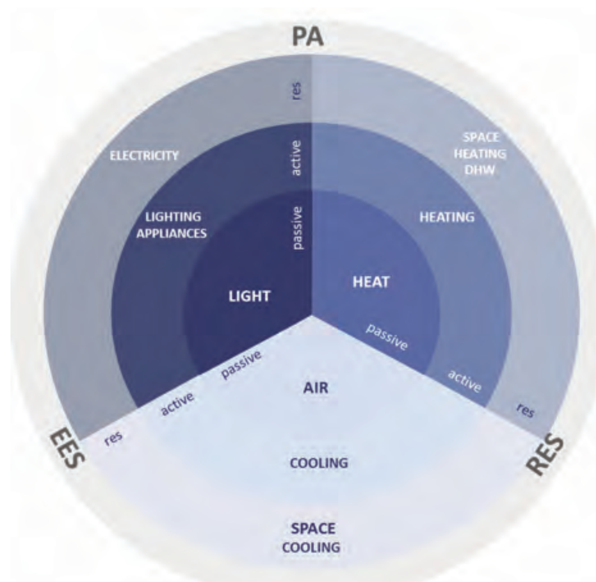

Figure 2. NZEB design approach.

control). However, taking into account that all of the case study buildings are dealing with heating challenges, it is natural that the passive strategies are oriented towards solar heating maximization and prevention of heat loss strategies.

Thermo characteristics (U-values and g-values)

In order to have a clearer picture of the values shown in Table 2, and using Passive House standard as reference, one can represent graphically the physical thermo-characteristics of building envelopes (Fig.3, Fig.4 and Fig.5). Figure 3 shows the range of thermal transmittances (U-values) found in the opaque envelope of selected case studies. Most projects under analysis present values as low as the Passive House example included as a reference for comparison purposes. One interesting feature shown in Figure 3 is that all buildings dealing with heating and cooling challenges are characterised by U-values greater than the one indicated by the Passive House standard.

With respect to windows, the Case Study U-values vary between 0.70W/m^2 K and 1.35W/m^2 K, which suggests low values that are very close to Passive House standard. An interesting feature regarding U-value of windows is that the projects with best net zero-energy performance (i.e. *Plus Energy Settlement*, *Plus Energy Houses*, *Riehen* and *Lighthouse*) are characterised by lower U-value of windows compared with the rest of the buildings.

As for the g-values, all buildings, with the exception of *Lima* and *EnergyFlexHouse,* are characterised by values higher than the 50% minimum stipulated by the Passive House standard that we have used as reference. Considering a combination of the U-value and g-value of windows, it is well known that they must be balanced according with the building's climate challenge. Low U-values in conjunction with high g-values are appropriate for a cold climate given that this arrangement promotes high heating performance. Bearing this in mind it is no surprise that the U-values and g-values of *Lima* are, respectively, higher and lower, than the rest of the case study projects given that *Lima* faces combined heating and cooling challenges.

Compactness

An important role in a building's heat modulation and distribution is played by ratio of thermal heat loss surface area of envelope (A) to heated volume (V) or, in other words, compactness. Typically, a high compactness (for small residential buildings

Project	U value wall [W/m^2.K]	U value roof [W/m^2.K]	U value ground [W/m^2.K]	Solar energy transmittance (g)	Compactness
Ecoterra	0.16	0.16	0.16	0.53	0.46
Energy Flex House	0.08	0.09	0.08	0.47	0.41
Leaf House	0.15	0.25	0.15	0.61	0.52
LIMA	0.19	0.17	0.19	0.42	1.07
Plus energy Houses Weiz	0.09	0.11	0.09	0.55	0.47
Plus Energy Settlement Freiburg	0.12	0.12	0.16	0.55	0.56
Riehen	0.13	0.11	0.13	0.52	0.59
Riverdale	0.10	0.06	0.10	0.55	0.74
Lighthouse	0.11	0.11	0.12	0.55	0.87

Table 2. . *Envelope physical characteristics.*

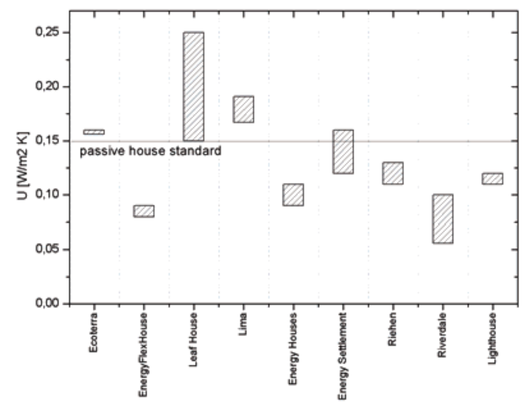

Figure 3. *U-values of opaque envelope of the case studies.*

A/V ≤ 0.7 m^2/m^3) is recommended for heating dominated climates due to the fact that a low exposed surface area limits the heat losses, whereas medium-high compactness is more appropriate for heating and cooling dominated climates because the cooling demand is reduced (Wimmers 2012). A high compactness could be sacrificed sometimes in favour of a higher surface oriented to the sun (Passive On 2007). According to table 2 and figure 5, the A/V ratio values of buildings varies between 0.41 and 1.07 m^2/m^3, indicating high to medium-high compactness.

Figure 5 reveals that, with the exception of *Lima* (which is a very small, single story building dealing with heating & cooling challenges) and *Lighthouse*, all buildings exhibit A/V ratios very close or lower than 0.7 m^2/m^3.

Cooling Loads

In the quest for reduced seasonal cooling loads, passive approaches are divided into three functional component sets: overheating prevention, heat

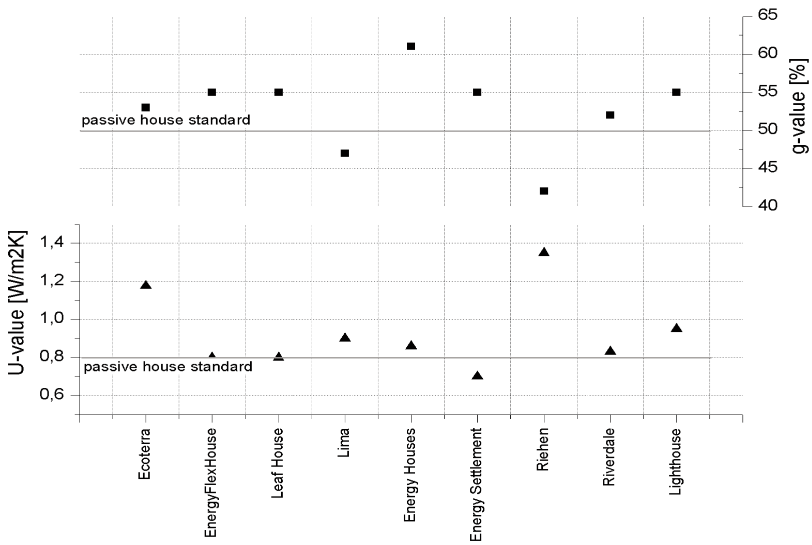

Figure 4. *U-values and g-values of windows of the case studies.*

rejection, and control.

From the prevention point of view, Sunshading, which is critical in preventing overheating in passively heated buildings, is present in all case studies in the form of fixed and/or movable overhangs and/or external screens.

As for heat rejection natural (cross) ventilation is one of the most commonly used strategies to deal with heat rejection by reducing the internal loads in buildings adopting passive design approaches. It is sometimes more effective during the night (night cooling) when outdoor temperatures are lower than indoor temperatures. When coupled to an earth tube system that uses the earth as the cold source, ventilation may also prove useful in reducing the building's internal loads by precooling ventilation air. The so called 'stack effect' is sometimes used to supplement natural (cross) ventilation (by providing building openings and windows at different heights) to increase the passive cooling impact (e.g. *Lighthouse*).

Information on the use of these various passive strategies in the case studies is summarised in Figure 6.

Second Principle: Energy Efficiency Systems

In order to lower a building´s energy demand, in addition to implementing passive approach strategies, buildings should also rely on improving the energy efficiency of the various incorporated building systems. In the residential sector, most energy consumption is due to systems used to provide district hot water (DHW) and ambient heating and cooling (although in the case study buildings the cooling demand is much smaller than heating in terms of annual energy used).. Lighting together with other occupant related electric use, despite not

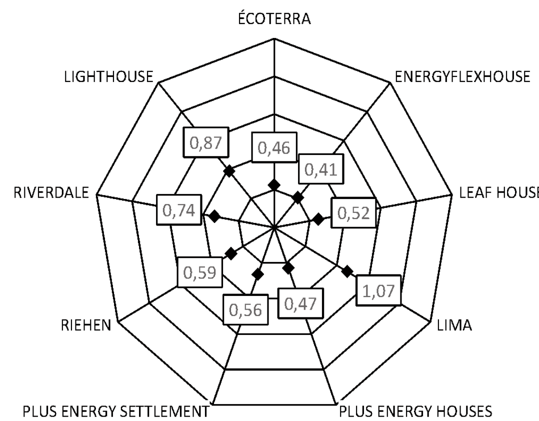

Figure 5. *Compactness values of case studies.*

being considered in most building codes, may also play represent a significant amount of the total energy use and it's demand should not be ignored in NZEB design.

With respect to the energy efficient systems for ambient heating and cooling, the case study buildings make use of low exergy systems in the form of radiant heating (*EnergyFlexHouse*, *Leafhouse* and *LIMA*) and cooling (*LIMA*), and efficient mechanical ventilation through air heat recovery (virtually all buildings) (see Figure 6). In addition the case study buildings all include some, or all, of low power lighting, energy efficient electrical equipment and load management systems as strategies for lowering energy demand notwithstanding that their clear advantages are yet to be proved (Musall and Voss 2012). Information on the use of these strategies in the case study buildings is summarised in Figure 6.

Figure 6. Matrix of design solutions.

Third Principle: Renewable Energy Systems

Having performed all necessary steps towards lowering a building´s energy demand, the last step to be carried out is the integration of renewable systems for energy generation. Since the objective is to reach a net zero energy performance, the lower the energy demand the lower the need for energy generation. In the case of residential buildings with their heating and cooling energy needs, renewable energy systems should either provide the heating and cooling or the fuel necessary to run the space heating and cooling systems together with lighting and other occupant related uses. Consequently the most common strategies make use of photovoltaic systems for electricity generation and solar thermal collectors for DHW production (of the case study buildings only three, Écoterra, Plus Energy Settlement and Plus Energy Houses are not equipped with solar thermal collectors). For space heating and cooling and DHW, geothermal (Écoterra, EnergyFlexHouse, Leafhouse and Riehen) and biomass (Lighthouse) energy sources may also be used depending on the feasibility and the development cost involved. Air source heat pumps, which are used to transfer ambient heat to a useful temperature level, are also appropriate if they meet certain energy-efficiency rating (Lima, Riverdale and Plus Energy Houses). In addition to this, a wide range of combined strategies can be employed. Case Study examples include:

• a building integrated photovoltaic thermal system BIPV/T system able to harvest a large amount of heat (Écoterra),
• geothermal and solar thermal combined with low exergy systems (radiant heating) for space heating (Leafhouse and Riehen);
• buildings equipped with transfer stations (hot water storage tanks) which are connected to a district heating grid fed by a combined heat and power plant fired by wood chips and natural gas (Plus Energy Settlement).

Matrix of design solutions

The main design strategies used in NZEB design have been addressed in the preceding sections in a systematic and goal directed way. Although the role played by each individual strategy remains to be demonstrated, the representation of the set of PA, EES and RES measures applied in each case in the form of the matrix at Figure 6 offers a more general perspective with several advantages.

Firstly, for each case study it is possible to identify all the sets of strategies applied to the building for each class of challenge (heating, cooling, lighting/appliances/equipment and each key component of the energy balance (PA, EES and RES). In this way Solution Sets can be established.

Taking the *Écoterra* building as an example, one can observe that heating challenges have been addressed with PA (high thermal insulation, passive solar gain, thermal mass and thermal storage - 2nd column from the left) combined with EES (heat recovery - 2nd column from the right). The RES applied to answer the same heating challenges are photovoltaic systems (heat recovered from building-in integrated photovoltaics) and a geothermal heat pump (represented in the matrix by the two light coloured boxes overlapping heating challenges).

Secondly, the matrix enables useful insights to be extracted to identify design issues that are more likely to succeed in achieving a true net zero-energy performance in heating and heating & cooling dominated climates. In the context of lowering a building's energy demand through the implementation of PA and EES Figure 6 reveals that the most frequent strategies rely on high thermal insulation and passive solar gains combined with radiant heating and air heat recovery in the case of heating, and on sunshading and natural cross ventilation combined with radiant cooling and displacement ventilation in the case of cooling.

An interesting aspect to consider in this analysis is the energy performance of the buildings given the respective energy efficiency measures adopted (PA and EES only) (Fig. 1). As it can be seen from figure 1, although neither *ÉcoTerra* nor *Lima* have reached net-zero energy performance, they´re both characterised by very low and medium-low annual primary energy consumption, respectively. At the same time, *Lighthouse*, which can be considered a successful project from the point of view of NZEB performance, exhibits the highest annual primary energy consumption.

Final Remarks

In order to present and discuss the design strategies used in NZEB design, nine projects have been selected from the IEA Task 40/Annex 52 ("Towards Net Zero Energy Solar Buildings") project database. Although the database indicates that there is no standard approach for designing a Net Zero-Energy Building (as there are many different possible combinations of passive and efficiency measures, utility equipment and on-site energy generation technologies able to achieve the net-zero energy performance), a close inspection of the strategies and indicators of the relative performance of the nine case studies revealed that it is possible to achieve zero-energy performance using well known strategies, a fact which provides evidence in the support of the theory that zero-energy buildings design is a progression of passive sustainable design.

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