DESIGN ISSUES FOR NET ZERO-ENERGY BUILDINGS

Laura Aelenei[1], Daniel Aelenei[2], Helder Gonçalves[1], Roberto Lollini[3], Eike Musall[4], Alessandra Scognamiglio[5], Eduard Cubi[6], Massa Noguchi[7]

[1]National Energy and Geology Laboratory, Lisbon, Portugal, laura.aelenei@lneg.pt, helder.goncalves@lneg.pt
[2] Faculty of Science and Technology, Universidade Nova de Lisboa, Caparica, Portugal, aelenei@fct.unl.pt
[3] Institute for Renewable Energy of EURAC research, Bolzano, Italy, roberto.lollini@eurac.edu
[4] Bergische Universität Wuppertal, Wuppertal, Germany, emusall@uni-wuppertal.de
[5] ENEA CR Portici P.le E. Fermi, Napoli, Italy, alessandra.scognamiglio@enea.it
[6] IREC- Institut de Recerca en Energia de Catalunya, Barcelona, Spain, ecubi@irec.cat
[7] MEARU, Mackintosh School of Architecture, Glasgow, United Kingdom, m.noguchi@gsa.ac.uk

Abstract
Net Zero-Energy Buildings (NZEBs) have received increased attention in recent years as a result of constant concerns for energy supply constraints, decreasing energy resources, increasing energy costs and rising impact of greenhouse gases on world climate. Promoting whole, building strategies that employ passive measures with energy efficient systems and technologies using renewable energy, became a European political strategy since the publication of the Energy Performance of Buildings Directive recast in May 2010 by the European Parliament and Council. Designing successful NZEBs however, represents a challenge since the definitions are yet generic assessment method and monitoring approach are under development and the literature is relatively scarce about the best sets of solutions for different typologies and climates likely to deliver an actual and reliable performance in terms of energy balance (consumed vs generated) on a cost-effective basis. Beside this, the lessons learned from already built NZEBs examples are relatively scarce. The authors of this paper, who are participants in the IEA SHC Task 40-ECBCS Annex 52, “Towards Net Zero Energy Solar Buildings”, are willing to share insights from on-going research work on some best practice leading NZEBs residential buildings. Although there is no standard approach for designing a Net Zero-Energy Building (there are many different possible combinations of passive and efficient active measures, utility equipment and on-site energy generation technologies able to achieve the net-zero energy performance), a close examination of the chosen strategies and the relative performance indicators of the selected case studies reveal that it is possible to achieve zero-energy performance using well known strategies adjusted accordingly to balance climate driven-demand for space heating/cooling, lighting, ventilation and others energy uses with climate-driven supply from renewable energy resources.

Keywords: *zero energy building, residential building, passive measures, energy efficiency, renewable energy generation.*

Introduction
Zero-energy buildings have gained more attention since the publication in 2010 of the EPBD recast (EPBD 2010). According to Directive, by 31 December 2020, all new buildings should meet higher levels of performance than before by exploring more the alternative energy supply systems available locally on a cost-efficiency basis and without compromising the comfort in order to ensure that they are nearly zero-energy buildings. A “nearly zero-energy building” refers to a high energy performance building of which annual primary energy consumption is covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby. Since the Directive does not specify minimum or maximum harmonized

requirements as well as details of 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 net zero-energy concept which in 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/(m² 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 various studies in recent years as various countries have set this performance as long-term goal of their energy policies (Ayoub 2009, Aelenei et al. 2011, Sartori et al. 2012). The International 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 approximate 55 National Experts, among which can be found the authors of this work, together with other 25 regular participants and contributors, are currently researching net-zero, plus energy and near net-zero energy buildings and in order to develop a common understanding, a harmonized international definitions framework, tools, innovative solutions and industry guidelines for 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 has to be offset by the overall energy feed in to the grid. In the Net Zero Source Energy definition, which is the one that matches the currently used by EPBD recast in a nearly zero-energy context (EPBD 2010), the energy (delivered from and feed into the grid) has to take into account primary energy conversion factors. Net Zero Energy Cost buildings definition is based on a 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) whereas in the Net Zero Energy Emissions case, buildings produce and export at least as much emissions-free renewable energy as they import and use from emission-producing sources on an annual basis (Torcellini 2006). Although there is no standard approach for designing and realizing a Net Zero Energy Building (there are many different possible combinations of building envelope, utility equipment and on-site energy production equipment able to achieve net-zero energy performance and also the balance boundary, which defines which consumers are included in the balance differs in known approaches) there is some consensus that zero energy buildings design should start from passive sustainable design as this level of performance is achieved as a result of executing two fundamental steps: (a) reduce building energy demand and (b) generate electricity or other energy carriers to get enough credits to achieve the desired energy balance (Fig. 1) from 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 put on the buildings 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 it can be seen from Table 1, buildings are characterised according to location, conditioned floor area, climate challenge and primary energy performance (consumption versus supply).

Regarding the climate challenge, one can observe that case studies correspond to only two different categories of climate challenges: heating dominated and heating and cooling dominated. With regard to energy balance, which takes heating, cooling, DHW and appliances into account, the Net Zero Site Energy definition applies to all cases.

Table 1: Case studies - common parameters consider

Picture	*Name/ Location*	*Conditioned floor area* [m^2]	*Climate challenge*	*Annual Energy consumption* [kWh/m^2.y]	*Annual Energy Supply* [kWh/m^2.y]	*Annual Energy Balance* [kWh/m^2.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

As for the energy net zero-energy performance, 6 projects are plus-energy buildings and 3 are nearly zero-energy buildings (Fig.1).

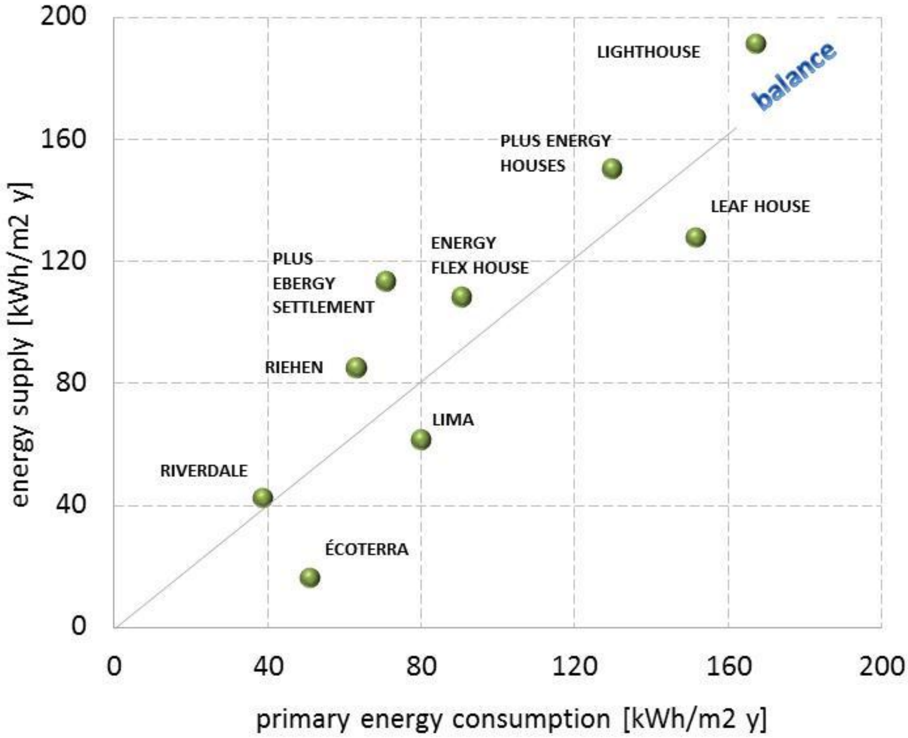

Figure 1: Annual primary energy performance in terms of NZEB performance for case studies

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 impact in environment (Noguchi et al. 2008). One should be mindful that *Lighthouse*, which is a demonstration building was also designed as net zero-carbon house, being the UK's first that also meets Level 6 (the highest level) of the Code for Sustainable Homes (Department for Communities and Local Government 2009).

One should remark that the selection of the 9 projects was based on criteria such as access to technical documentation regarding physical characteristics, monitored and/or simulated energy performance data, as well as lessons learned about designing, operating, and post-evaluating processes.

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 can be applied in NZEB design as well. To find out the answer, the analysis of the 9 project buildings was performed according to the scheme shown in figure 2. As it can be seen in the scheme from figure 2, 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.

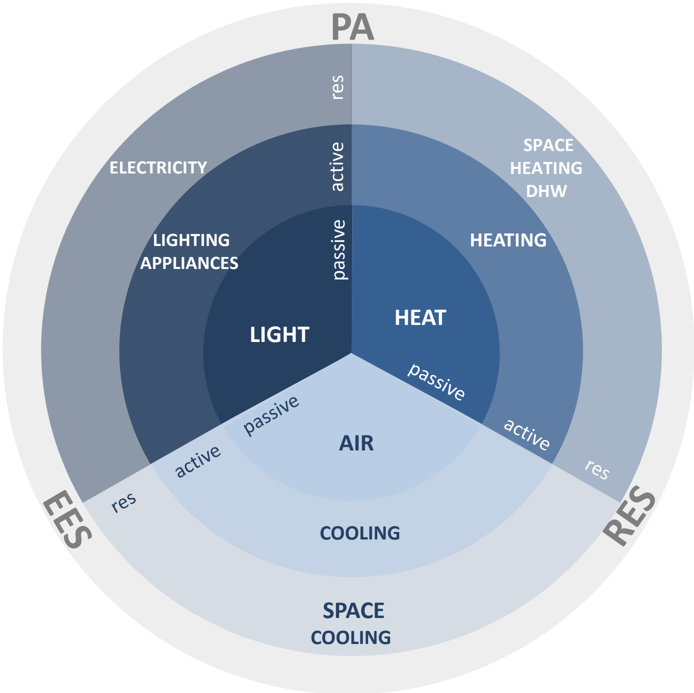

Figure 2: NZEB design approach

In the following, an overview of the key components that affect NZEB energy performance will be presented for each of the three research components, passive approaches, energy efficient systems and renewable energy systems.

Passive Approaches Findings

As noted above, passive approaches play a fundamental role in NZEB design as they directly affect the loads put on the buildings mechanical and electrical systems, and indirectly, the strive for renewable energy generation. In this context it is understandable why zero energy buildings design should start from passive sustainable design. With this respect, and even though the buildings were designed to meet different energy performance levels (according to national specific strategic needs), the first characterization 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, control). However, taking into account that all 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. 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 buildings envelope (Fig.3, Fig.4 and Fig.5). As it can be seen from figure 3, which 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 one of Passive House standard used here as reference for comparison. 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.

Table 2: Envelope physical characteristics

Project	*U value wall* [W/m^2.K]	*U value roof* [W/m².K]	*U value ground* [W/m².K]	*Solar energy transmittance (g)*	*Compactness*
Écoterra	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

With respect of windows, U-value varies 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.

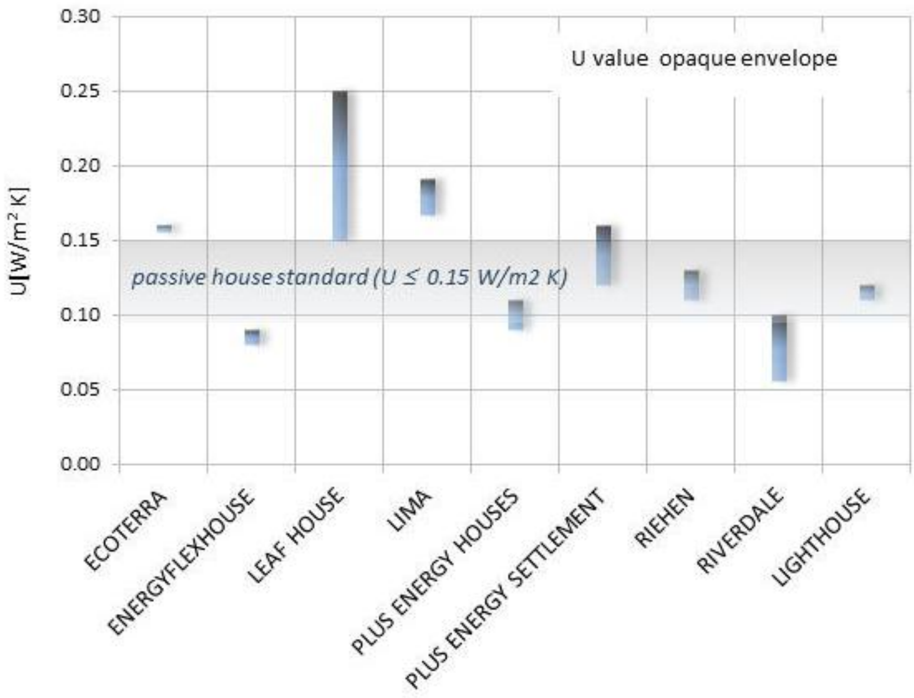

Figure 3: U-values of opaque envelope of the case studies

As for the g-values, all buildings with the exception of *Lima* and *EnergyFlexHouse* are characterised by values higher than 50% used as reference. With consideration of U-value and g-value of windows, it is well known that they must be balanced according with the climate building challenge. Low U-values in conjunction with high g-values, for instance, are appropriate for a cold climate given that in this way is promoted heating performance. Bearing this in mind, it is no surprise that U-values and g-values of Lima that face heating and cooling challenges are, respectively, higher and lower, than the rest.

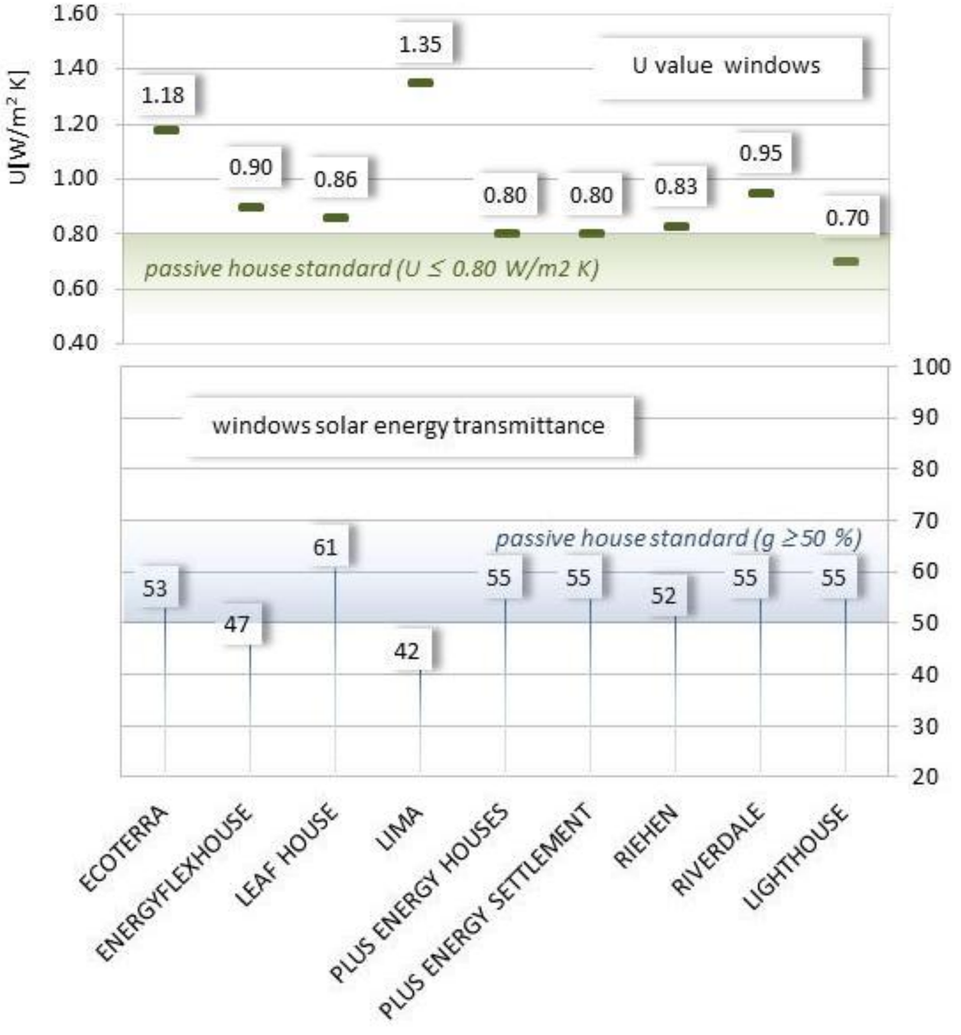

Figure 4: U-values and g-values of windows of the case studies

An important role in the buildings heat modulation and distribution is played by thermal heat loss surface area of envelope (A) - heated volume (V) ratio or, in other words, compactness. Typically, a high compactness (for small residential buildings A/V ≤ 0.7 m^2/m^3) is recommended for heating dominated climates due to the fact that a low exposed surface area is limiting the heat losses, whereas medium-high compactness is more adequate for heating and cooling dominated climates because the cooling demand will be reduced (Wimmers 2012). A high compactness could be sacrificed sometimes in in favour of higher surface oriented to the South (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, a fact which suggests high to medium-high compactness. As it can be seen from figure 5, 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.

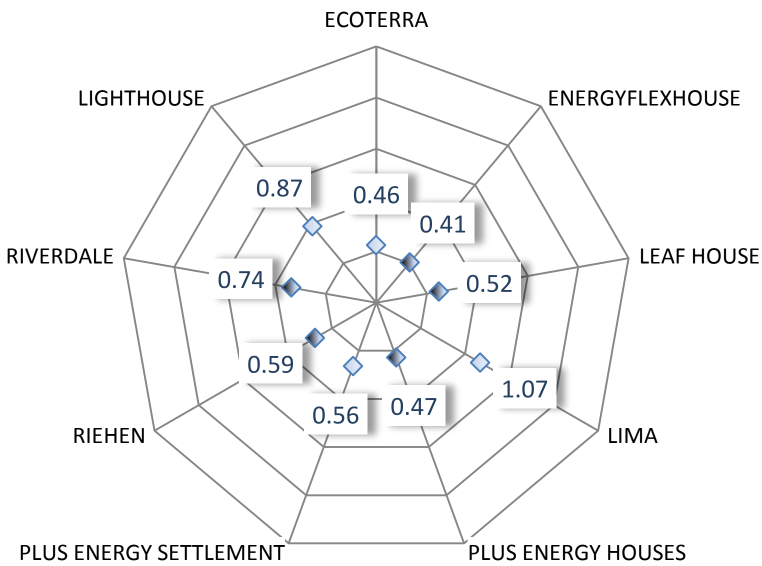

Figure 5: Compactness values of case studies

With respect of strive for reducing seasonal cooling loads, passive approaches are divided into three functional component sets: overheating prevention, heat rejection, and control. From the prevention point of view, sunshading, which is critical for passively heated buildings, is present in all cases under analysis under the form of fixed and movable overhangs and/or external screens. As for heat rejection, natural (cross) ventilation is one of the most commonly used strategies used to reduce the internal loads in passive design. 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 internal loads by pre-cooling ventilation air and evacuation, rejection. Partly the stack effect is used (by open spaces and windows in different heights) to increase the passive cooling (e.g. *Lighthouse*). Information on the use of these strategies in the buildings under analysis is synthetized in figure 6.

Energy Efficiency Systems Findings

To lower building´s energy demand, in addition to implementing passive approach strategies, buildings should also rely on improving energy efficiency of systems. In residential sector, most energy consumption is due to systems used for ambient heating and cooling (much smaller than heating in terms of annual energy used) and district hot water (DHW). Lighting together with other occupants related electric use, despite of not being considered in most building codes, may also play represent a significant amount of the total energy use. With respect to the energy efficient systems for ambient heating and cooling, the investigated projects 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) (Fig. 6). On the other hand, low power lighting, energy efficient electrical equipment and load management system are also used as strategies for lowering all building´s energy demand, despite of the fact that their clear advantages are yet to be proved (Musall and Voss 2012). Information on the use of these strategies in the buildings under analysis is synthetized in figure 6.

Renewable Energy Systems Findings

After having performed all necessary steps towards lowering 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 strive for energy generation. Given the residential buildings specific 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's related uses. With this respect, the most common strategies make use of photovoltaic systems for electricity generation and solar thermal collectors for DHW production (only *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 used to transfer ambient heat to a useful temperature level is also possible if they meet certain energy-efficiency rating (*Lima*, *Riverdale* and *Plus Energy Houses*). In addition to this, a wide range of mixing strategies can also be employed: a building integrated photovoltaic thermal system BIPV/T system is able to harvest a large amount of heat (*Écoterra*); geothermal and solar thermal may be 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 under the form of a matrix offers a more general perspective with several advantages (Fig. 6). Firstly, for each building under analysis it is possible to identify, for each class of challenge (heating, cooling, lighting/appliances/equipment - 1stcolumn from the left of figure 6) and each key component of the energy balance (PA, EES and RES) all sets of strategies applied. Taking *Écoterra* building as example, one can observe that heating challenges have been addressed with PA (high thermal insulation, passive solar gain, thermal mass and thermal storage - 2nd 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 figure by the two light coloured boxes overlapping heating challenges). Secondly, it allows extracting useful insights about design issues which are more likely to succeed in achieving a true net zero-energy performance in heating and heating and cooling dominated climates. In the perspective of lowering buildings energy demand through the implementation of PA and EES, the inspection of figure 6 reveals that 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 feature to observe is the energy performance of the buildings on the account of the adoption energy efficiency measures (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 consumptions, 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.

Figure 6: Matrix of design solutions

Final Remarks

In order to present and discuss the design strategies used in NZEB design, a number of 9 projects have been selected from IEA Task 40/Annex 52 (“Towards Net Zero Energy Solar Buildings”) project database. Although 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 9 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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