692: Defining Zero Energy Buildings - A life cycle perspective

Patxi Hernandez[1]*, Paul Kenny[1]
**patxi.hernandez@ucd.ie*
[1] University College Dublin

Abstract
A simple definition of a zero energy building (ZEB) is a stand-alone building which does not use any off-site energy source for its operation. The definition is easily extended to buildings with a net-zero annual on-site energy balance, where a building is connected to the electricity grid and annual energy use is the same as energy exported to the grid. In this paper we expand the ZEB definition adding a life cycle perspective including the embodied energy (cradle to site) of materials, which is considered as an additional off-site supply. The consideration of embodied energy adds a level that will help discern the life cycle benefits of different demand or supply side building design strategies to achieve ZEBs.
Calculations of operational energy use and embodied energy for different house design options are presented, analyzing what options would move closer to this ZEB definition. Results show how the achievement of extreme reductions on energy demand by using high quantities of energy intensive materials are not an optimum solution over the life cycle of a building, active technologies becoming a better option after certain limits.

Keywords: zero energy, life cycle, embodied energy

1. Introduction

The concept of zero energy buildings (ZEB) has been around for a long time. A literal interpretation of zero-energy could be that of a building that operates without any external sources of energy, and we will assume that also refers to achieving comfortable indoor environmental conditions.
The first obvious solution is that of an 'autonomous' house, with no connection to any off-site energy sources. Brenda and Robert Vale (Vale and Vale, 2002) reviewed the evolution of the term autonomous over the years and its significance and implications. After a thorough philosophical and practical examination of the implications of an 'autonomous' energy system, and thinking of a wider global context, their conclusion and approach were that connecting a domestic renewable system to the electricity grid and achieving a net-zero energy home can have the same (or even better) life cycle performance than an autonomous house as using electric storage systems is avoided and some flexibility on the use of appliances is gained.
With this in mind, the two most interesting definitions in the context of this paper are the Net Zero Site Energy and Net Zero Source Energy, discussed for example by Torcellini et all (P. Torcellini et al., 2006). Net Zero Site Energy means that a site produces at least the same energy as it uses in a year, independently of the type of energy produced or used. On the 'Net-Zero Energy Source' definition, imported and exported energy is multiplied by a primary energy conversion factor thus allowing for some flexibility in the use of heating fuels. For example, in Ireland some PV produced electricity exported during the summer would be converted to primary energy with a factor of 2.7 and that primary energy could be reverted back to the house in forms of heating fuel in winter, which has a lower primary energy factor (1.1) and could be converted into delivered heating efficiently.
This paper outlines an attempt to introduce a further element on the definition of ZEB: the embodied energy of the materials used on the construction of the building and its systems.

2. Consideration of embodied energy

Embodied energy has been traditionally overlooked on building energy analysis, as the embodied energy of the building materials only represented a small percentage when compared with the operational used over the life of the building. Most building regulations and directives such as the European Energy Performance of Building Directive (European Council, 2002) ignore this aspect of energy use in buildings.
There are a number of voluntary environmental assessment methods such as LEED (US Green Building Council) or BREEAM (Building Research Establishment) that consider embodied energy together with a wide range of environmental aspects of buildings. These methods, although promoting the use of low embodied energy materials, do not provide an assessment of the embodied energy importance and do not serve as design support. There are also detailed LCA tools such as SIMAPRO (PRé Consultants) or ATHENA (ATHENA Institute) that offer the possibility of analyzing in detail the range of environmental aspects of materials and buildings, including embodied energy. Despite the potential and capabilities of such tools to aid in the design of buildings to minimize the environmental impact they are still rarely used at early design stages. This is perhaps because of their relative complexity which makes them impractical for use by a design team, particularly at early stages of the building process.

This paper is an attempt to simplify the consideration of embodied energy, eliminating the need of a full inventory of building materials, and integrating the calculations with commonly used energy assessment tools, in this case with the national tool for building regulation compliance and building energy rating in Ireland.
For this simplified method, we propose to use a differential comparison of various building options from an initial base case and to only consider those changes in construction elements that are directly related to the energy performance such as the insulation of the building envelope and the energy production and delivery systems. The differential embodied energy of construction elements and systems over the 'base case' scenario, annualized to the lifetime of the particular component, will be added to the annual operational energy use figures. In this way we can compare the influence of the different building options, including the embodied energy, in the same indicator that is used for regulations and building energy rating, simplifying its understanding and application by architects and other design team members.
A building which would achieve zero energy status not increasing the 'base case' embodied energy or producing (exporting) enough energy to compensate the embodied energy increase will be defined as a life-cycle-zero-energy-building (LC-ZEB).
The buildings that will get closer to this LC-ZEB will be those that have the lowest sum of operational and embodied energy.
The consideration of embodied energy of materials will be in all cases from "cradle to site" which will consider all the energy used from the extraction of raw materials to manufacturing and transport to the building site.

3. Case Study Assumptions

3.1 Energy Balances

This paper analyzes how to reduce the heating and hot water energy demand in a sample house in Ireland to a net-zero level with an optimum life-cycle analysis. The analysis is based on a building design that minimizes heating demand and the use solar energy with solar thermal and photovoltaic (PV) systems. Observations on wind driven on-site electricity production have not been included despite its high viability in many situations, and in particular in Ireland, and because it is highly dependent on site location and conditions.
To find optimum solutions of LC-ZEB, the balance between electricity and thermal energy becomes very important. It is relatively easy and very effective to use solar thermal (both active and passive) for short-term heat storage (e.g. south facing windows or solar thermal collectors with water storage tank) to achieve a greater reduction in thermal energy use in a house. A greater use of solar thermal energy to achieve zero-heating demand status, on the contrary, would require large areas of solar collection and a larger storage medium. For the electricity an off-grid situation would present a similar situation with batteries or fuel cells needed. Here, the net-zero definition is adopted and the electricity grid being considered as a hypothetical energy sink with no penalization on energy exported to imported and with no associated embodied energy. The net-zero energy source definition is also adopted where the electricity exported is multiplied by a factor of 2.7 to convert to primary energy.
The rest of the electricity demand in the house, used for ventilation, lighting and rest of appliances, is not considered in the analysis as all the options are assumed with the same consumption for these end-uses. Performance of grid connected renewable electricity producing systems has a proven life cycle benefit and to offset the demand is only a matter of installing enough renewable energy capacity to match the annual electricity demand with the consumption. The key to achieve a LC-ZEB including these electricity aspects is to minimize the demand for those energy end uses and using the best electricity generation systems which, over their life cycle, not only offset the energy use of the building but export enough energy to account for the system embodied energy.

3.2 Building envelope, system options and reference values.

For this study the house size and type was selected from examples in the Irish Building Regulations Technical Guidance Document L (Minister for the Environment Heritage and Local Government 2006; Minister for the Environment Heritage and Local Government 2007). These details of the house correspond to a semi-detached two storey house, which is the most common domestic type in Ireland. For this example the house has been placed with a north-south orientation, and a larger area of glazing in the south façade (16.5m^2) compared to the north side (11.0m^2) so as to incorporate some passive design principles.

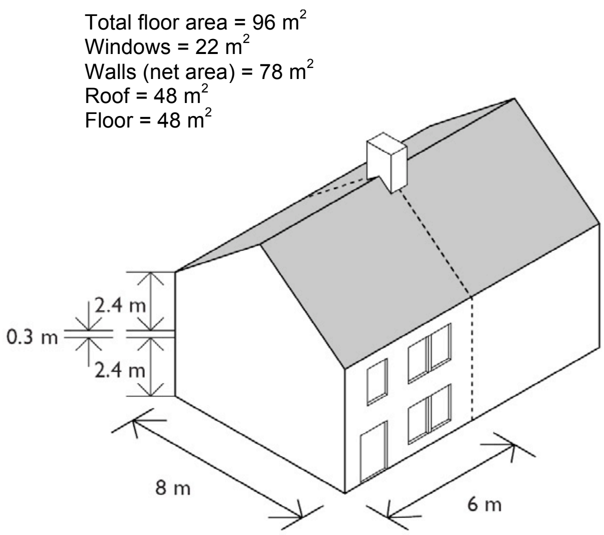

Figure 1. Case study semi-detached dwelling characteristics

The Irish climate is a maritime temperate climate with solar radiation levels similar to those in Central and Northern Europe. This together with the mild temperature means that it should be possible to greatly reduce the heating demand by passive strategies. With respect to hot water usage, it is also possible to use domestic solar water heating systems to contribute to a high proportion of the annual energy hot water use and in case of using a solar 'combisystem' also contributing to some extent to cover the space heating demand. The use of mechanical ventilation systems with heat recovery in an air-tight structure and the minimization of thermal bridging are also well proven strategies that are accepted as best practice to reduce demand.

For these reasons the BASE CASE scenario for the case study corresponds to a house complying with the insulation levels from the 2006 Building Regulations but including some additional energy efficient features such as:

- High reduction of thermal bridging to a value of 13 W/K for the whole house (compared to 23 W/K for the same house with typical construction details).
- Limitation of infiltration and ventilation heat losses by air tightening the house (up to 0.60 ach at 50 Pa) and including mechanical heat recovery ventilation (MVHR) with an efficiency of 85% and an specific fan power of 1.0 W/ l /s.
- Use of triple glazed argon filled windows with a U value of 1.1 W/m^2 K.

A range of improved U values for this BASE CASE have been considered with the maximum upgrade achieving levels of 0.1 W/m^2 K, which is a value already reached in some Irish Passive House constructions. A solar 'combisystem' and a solar PV system will be included in the analysis. Table 1 shows the different upgrades and U values considered:

Table 1. U values of construction elements for the five building envelope insulation options studied [W/m^2 K]

	BASE CASE	UP 1	UP 2	UP 3	UP 4
Walls	0.27	0.21	0.15	0.12	0.1
Floor	0.25	0.2	0.15	0.12	0.1
Roof	0.16	0.14	0.12	0.11	0.1

Table 2 shows the thickness of the insulation layer needed to achieve the U values for each construction element. Calculations were carried according to the EN ISO 6946 (CEN 1997).

The additional insulation material selected to lower U values was polystyrene, which is still one of the most widely used insulation materials in Irish construction. Physical properties of the polystyrene used in this case study are 20 kg/m^3 density and 0.034 W/mK thermal conductivity.

Table 2. Thickness of insulation layer [mm]

	BASE CASE	UP 1	UP 2	UP 3	UP 4
Walls	115	150	210	265	315
Floor	85	120	170	215	270
Roof	255	285	325	365	425

4. Calculation Methodology

4.1 Heating and Hot Water Demand

Heating demand for each of the insulation options from Table 2 was calculated with the DEAP Irish calculation methodology (Sustainable Energy Ireland, 2007).

The calculation gives a monthly heating demand result calculated according to EN ISO 13790 (CEN, 2004).

An example of the monthly heating energy demand calculated for four of the options is displayed on Figure 2:

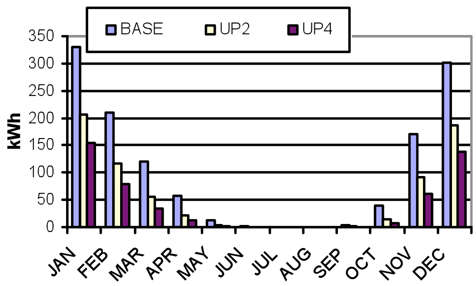

Figure 2. Comparison of monthly heating demand for three of the options

As we can observe on the figure, our BASE CASE, which included the MVHR and triple glazing, together with good air tightness and low thermal bridging, already has a low heating demand, a total of 1243 kWh per year, which equates to 13 kWh per square meter per year. Upgrading the insulation to the highest level (UP4), the annual total heating demand would reduce to 489 kWh/year, or just 5 kWh/m^2/year.

Hot water demand is set to 3200 kWh as calculated in the DEAP methodology. A uniform daily hot water demand through the year is assumed.

We can observe that this hot water demand is much larger than the heating demand, even for our BASE CASE option, so renewable energy supply to fulfil this demand becomes a key issue towards the zero energy goals.

4.2 Solar thermal and solar PV

Calculation of energy delivered by the solar thermal system has been calculated according to the CEN standard(CEN, 2007a).

Solar panels were assumed to have a southern orientation and inclined of 45 degrees.

The solar thermal collectors chosen for this analysis are flat plate collectors with an efficiency factor of 0.8 and a linear heat loss coefficient factor of 3.5, standard typical values from (CEN, 2007a).

Storage, pumps and rest of the systems are sized with relation to the collection areas. The type of installation calculated in this paper is a

'combisystem', which uses solar input to provide both solar water and space heating. The electricity use of the pumps is also calculated according the same standard.
The solar PV panels used are multi crystalline silicon with a peak power coefficient of 0.15 kW/m^2 and its output has been calculated according to the CEN standard (CEN, 2007b).

4.3 Embodied Energy

4.3.1 Insulation.

The embodied energy of polystyrene was taken from the Inventory of Carbon and Energy ICE v1.5 (Geoff Hammond and Craig Jones, 2006) . For polystyrene insulation, a value of 88 MJ/kg was used. A lifetime of 50 years has been considered.

4.3.2 Solar thermal systems

The embodied energy values of solar thermal panel and corresponding systems have also been approximated from various references (Ardente et al., 2005, Crawford and Treloar, 2004, Kalogirou, 2004).
For this paper, two options of solar thermal installations are considered, one of $5m^2$ and one of $10m^2$. The embodied energy for the $5m^2$ installation is set to 5500 MJ and for the $10m^2$ installation to 9200MJ. The lifetime of the systems has been set to 20 years.

4.3.3. Photovoltaic system

There is a wide variation in the range of embodied energy values published for PV panels and installations. The values used in this paper are approximated from various references as (Battisti and Corrado, 2005, Pacca et al., 2007, Raugei et al., 2007, Fthenakis and Alsema, 2006). The embodied energy of the PV installation is set for this paper to 6000 MJ/m^2 of installation. A lifetime of 25 years has been considered.

5. Results

5.1 Space heating demand and insulation levels

Analyzing heating demand without the integration of any renewable energy we can already get some interesting conclusions. Figure 3 shows the different options, and we can observe that as we increase insulation levels, the additional energy savings we achieve diminish. In this case, which uses an energy intensive material such as polystyrene, the energy saved by the final upgrade (UP4) is lower than the annualized embodied energy added by the insulation.

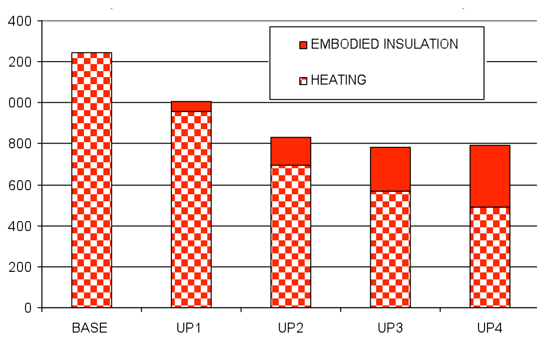

Figure 3. Annual heating energy use and annualized embodied energy (differential with base case)

5.2 Space heating and hot water demand and solar thermal systems

With a solar 'combisystem' installation, some of the solar input will be used to provide hot water and some to contribute to the space heating. As we increase the collector area of a solar system it produces a higher input of hot water than required during the summer months so the annual energy delivered per square meter of installation is reduced. There is also a higher electricity use for the pumps in larger solar systems which is an important factor as electricity has a primary energy factor of 2.7 in Ireland. As we can see in Figure 4, while the first $5m^2$ has an impressive effect on the reduction of heating demand the addition of an additional $5m^2$ does not have much added value from a life-cycle perspective, particularly in cases with insulation upgrades. The addition of larger collection areas above $10m^2$ for this case study would result in a negative impact over the life cycle.

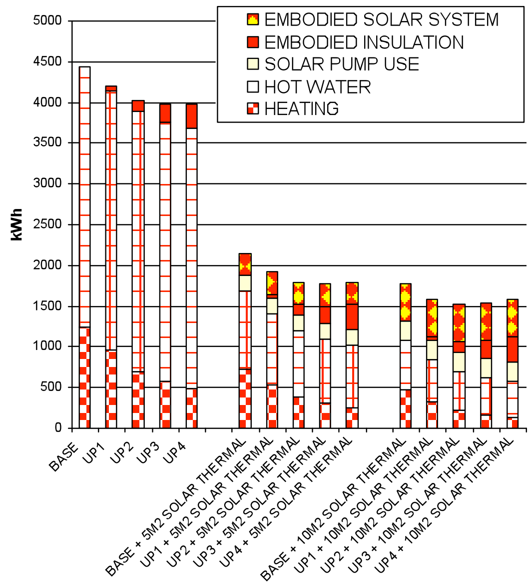

Figure 4. Annual space & water heating embodied energy for insulation and solar systems, and electricity use for the solar pump.

We can also observe that even with the first $5m^2$ of solar collectors going beyond the insulation upgrade UP2 does not have additional benefits.

We can also observe an interesting comparison between active and passive approaches to zero energy housing. The annual primary energy (including embodied) used on the BASE case with 10m^2 of solar is practically the same as for the case study house with insulation upgrades above UP2 but with only 5m^2 of solar collection area.

5.3 Photovoltaic production to offset space and hot water demand.

The analysis of the PV systems differs from the previous two analyses in that the efficiency can be considered practically constant and independent of the size of the system, when electricity is exported to the grid. As we consider the net-zero source energy definition we will multiply the exported energy by the primary factor.

A way to compare a PV system with the upgrade of insulation levels or the solar thermal systems in a life-cycle perspective is to calculate the annualized embodied energy of an equivalent PV system that would produce enough energy to compensate for the energy savings achieved by those levels of insulation or the solar thermal systems. With the assumptions and calculation methods mentioned in previous sections the Net Energy Ratio of the PV system, defined as the ration between primary energy produced over the life cycle and embodied energy, equals 4.9. That translates to around 0.2 kWh embodied energy per kWh primary energy produced. When we compare this factor to the results presented in Figure 4, we can observe that for this case study it compares favourably in many cases. A PV system would have less embodied energy to produce the energy saved by any insulation option above UP1 or by a solar system bigger than 5m^2. This suggests that above those limits, the best option with a life-cycle energy perspective would be a PV system.

We have to note that this calculation also assumes that the use of the electricity to cover the heating demand would be delivered with at least a factor of 2.5 to 1 from electricity to thermal, a value easily achievable with equipment such as compact air-to-water heat pump compact units. If directly electric heating is used (an electric resistance), the PV would still be favourable for the options above UP2, and its application becomes similar to a life-cycle energy performance such as the inclusion of 10m^2 of solar thermal collectors instead of 5m^2.

6. Conclusions

This paper has defined a new concept of life-cycle zero energy building (LC-ZEB). It has also presented a simplified methodology to account for embodied energy of building materials and energy systems to be used at early stages of the design process.

This methodology has been applied to a case study, which has been used as an example to choose between options that achieve a best life-cycle energy performance and become closer to a LC-ZEB.

The authors acknowledge that the annualized embodied energy calculations used as a basis for this paper are only approximations from published work and do not represent the specific life-cycle characteristics of those systems in Ireland. The material used in this study as additional insulation (polystyrene), although widely used in construction in Ireland, is one of the most energy intensive insulation materials. Repeating the same analysis with a less energy intensive insulation material would yield different results more favourable to higher insulation levels. However, the authors believe an interesting conclusion can be drawn from the study.

As we approach zero-energy a particular focus has to be placed on the embodied energy of materials and systems used in buildings. This aspect, which is not directly linked to the costs, should be considered on the definition and evaluation of zero-energy, within a new definition for LC-ZEB, and building regulations and building energy certification methods should, in time, evolve towards this definition.

7. Acknowledgements

The authors would like to acknowledge the support of the Irish Research Council for Science, Engineering and Technology, funded by the National Development Plan.

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