FACULDADE DE ENGENHARIA
UNIVERSIDADE DO PORTO
Portugal

ECONOMIC-EFFICIENT DESIGN OF RESIDENTIAL NET ZERO ENERGY BUILDINGS WITH RESPECT TO LOCAL CONTEXT

Maria Kapsalaki

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Faculdade de Engenharia da Universidade do Porto
Rua Dr. Roberto Frias
4200-465 Porto, Portugal
Maria Kapsalaki, 2012

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ABSTRACT

The identification of the economical-optimal design solutions for Net Zero Energy Buildings (NZEBs) is a complex engineering problem with societal relevance. This work developed a methodology for this purpose which was then implemented in a software tool intended to be used in order to identify the combination of design variables that have optimal lowest life cycle costs, or a good compromise between initial cost and life-cycle cost for different climate contexts and electricity price scenarios. The following fourteen major design variables were identified that grossly determine the energy demand and supply of the building: 1) thermal insulation level; 2) thermal inertia level; 3) air leakage level; 4) window type; 5) shading type; 6) glazed area; 7) orientation; 8)type of ventilation; 9) heating system; 10) type of cooling system; 11) type of water heating system; 12) efficiency of lighting; 13) efficiency of appliances and 14) type of microgeneration system. Each design variable considered was discretised in a number of alternatives reasonably representing the range of possible options.

Calculation methodologies were implemented for the characterization of the energy demand, considering space heating & cooling, water heating, lighting, cooking, refrigeration and appliances as well as the amount of onsite microgeneration needed to offset the yearly demand. The most challenging part of the methodology was the characterization of the yearly heating and cooling needs, which was achieved through a quasi-steady state model based on the EN ISO 13790 and the Portuguese thermal building code (RCCTE).

An algorithm was implemented as a computational tool developed in Matlab, which goes through all possible combinations of envelope characteristics, building services equipment and renewable on-site production systems and for each computes the following results: 1) useful heating needs; 2) useful cooling needs; 3) final heating needs; 4) final cooling needs; 5) total final energy; 6) area of photovoltaic (PV) panels or number of wind turbines; 7) annual electricity and/or gas bill; 8) life cycle cost and 9) initial cost of the elements that influence the energy performance.

Two case studies, a detached house and a high rise building for three climates each (Stockholm, Lisbon and Iraklion), were analysed with the tool developed. This allowed to gain insights on the following: 1) economic space of NZEB solutions; 2) influence of the climatic context; 3) influence of fuel and electricity buy and sell prices; 4) influence of the level of compensation; 5) hierarchy of influence of design variables; 6) influence of limitations on the area available for PV installation; 7) impacts of considering wind turbines as a reliable microgeneration design option; 8) feasibility of high-rise NZEBs and 9) sensitivity to the costs of PV.

As main achievement it should be highlighted that a methodology for assisting in the choice of economically- efficient NZEB solutions, right from the early design stage is now available. The results have shown that its use in practice may be of great relevance as the results of the case studies have shown that the differences between an economically efficient and economically inefficient NZEB can be over three times both in terms of initial cost as in terms of life cycle cost.

RESUMO

A identificação das soluções eficientes ou mesmo ótimas no projecto de "NZEB" (Net Zero Energy Buildings na sua forma em inglês) é um problema de engenharia complexo com relevância para a sociedade. Neste trabalho foi desenvolvido um método , o qual foi depois implementado numa ferramenta de software, com o intuito de ser usado para identificar as combinações das variáveis de projecto que têm custos de ciclo de vida ou custo inicial mais baixos, ou ainda um bom compromisso entre o custo inicial e o custo de ciclo de vida para diferentes contextos climáticos e cenários de preços de energia. Catorze variáveis foram identificadas como as mais determinantes na energia no edifício: 1) nível de isolamento térmico; 2) nível de inércia térmica; 3) nível de infiltração de ar; 4) tipo de janela; 5) tipo de sombreamento; 6) área de envolvente envidraçada; 7) orientação; 8) tipo de ventilação; 9) tipo de sistema de aquecimento; 10) tipo de sistema de arrefecimento; 11) tipo de sistema de aquecimento de água; 12) eficiência do sistema de iluminação; 13) eficiência de equipamentos e 14) tipo de sistema de microgeração. Cada variável de projeto considerada foi discretizada de forma a criar uma série de alternativas representando o leque de opções possíveis.

Foram implementadas metodologias de cálculo para a caracterização da procura de energia, considerando aquecimento e arrefecimento, aquecimento de água, iluminação, cozinha, refrigeração e equipamentos, bem como a quantidade de microgeração local necessária para compensar a procura anual. A parte mais complexa da metodologia foi a caracterização das necessidades anuais de aquecimento e arrefecimento, que foi efetuada através de um modelo quase-estacionário, baseado na EN ISO 13790 e no Regulamento das Características de Comportamento Térmico dos Edifícios (RCCTE) de Portugal.

Foi desenvolvido e implementado em Matlab um algoritmo / ferramenta computacional que contabiliza todas as possíveis combinações de características das envolventes dos edifícios, equipamentos e sistemas de produção local a partir de renováveis. Para cada "solução" a ferramenta determina os seguintes resultados: 1) necessidades de energia útil para aquecimento; 2) necessidades de energia útil para arrefecimento; 3) necessidades de energia final para aquecimento; 4) necessidades de energia final para arrefecimento; 5) energia final anual; 6) área de FV (fotovoltaico) ou o número de turbinas eólicas necessárias para a compensação; 7) custos e proveitos anuais de eletricidade e/ou de gás; 8) custo do ciclo de vida e 9) custo inicial dos elementos relacionados com o desempenho energético.

Dois estudos de caso, uma moradia unifamiliar e um edifício multifamiliar foram analisados com a ferramenta desenvolvida, para três tipos de clima (Estocolmo, Lisboa e Iraklion). Isto permitiu, além de exemplificar o uso da metodologia, obter indicações sobre: 1) o espaço económico (custo de ciclo de vida vs custo inicial) de soluções para NZEB; 2) a influência do contexto climático; 3) a influência de preços (compra e venda) de combustíveis e eletricidade; 4) a influência do nível de compensação; 5) a hierarquia da influência das variáveis de projecto; 6) a influência das limitações da área disponível para instalação de FV; 7) os impactos de considerar as turbinas eólica como uma opção fiável para microgeração; 8) a viabilidade de edifícios multifamiliares em altura como edifícios NZEB e 9) a sensibilidade aos custos dos painéis FV.

Como principal contribuição prática deve-se destacar a disponibilização de uma metodologia para auxiliar na escolha de soluções NZEB economicamente eficientes, para aplicação na fase inicial de projeto. Os resultados dos casos de estudo demonstraram que a sua utilização na prática pode ser de grande relevância, dado que as diferenças entre um NZEB economicamente eficiente e um economicamente ineficiente podem ser de mais do triplo, tanto em termos de custo inicial quanto em termos de custo de ciclo de vida.

Contents

LIST OF SYMBOLS & ABBREVIATIONS

List of Abbreviations

AS1	Alternative scenario 1
AS2	Alternative scenario 2
BP	Price of electricity bought from the grid
CS	Central scenario
Dbl_Glz_Clr (Al)	Double glazed clear window with aluminum frame
Dbl_Glz_Clr (Al+TB)	Double glazed clear window with aluminum frame and thermal break
Dbl_Glz_low-e (Al+TB)	Double glazed low-e window with aluminum frame and thermal break
DHW	Domestic hot water
HP	Heat pump
HR	Heat recovery
IC	Initial cost
LCC	Life cycle cost
LIC	Lowest initial cost
LLCC	Lowest life cycle cost
MV	Mechanical ventilation
MVHR	Mechanical ventilation with heat recovery
NZEB	Net zero energy building
PV	Photovoltaic
RCHP	Reversible cycle heat pump
RCHP class A	Reversible cycle heat pump class A
SC	Solar collector
Sngl_Glz_Clr (Al)	Single glazed clear window with aluminum frame
SP	Price of electricity sold to the grid
Trpl_Glz_Clr (Al)	Triple glazed clear window with aluminum frame
Trpl_Glz_Clr (Al+TB)	Triple glazed clear window with aluminum frame and thermal break
Trpl_Glz_low-e (Al)	Triple glazed low-e window with aluminum frame
Trpl_Glz_low-e (Al+TB)	Triple glazed low-e window with aluminum frame and thermal break
TFE	Total final energy
WT	Wind turbine

List of Symbols

a	Thermal inertia index (-)
a_c	Absorption coefficient for solar radiation (-)
a_r	Terrain roughness coefficient (-)
a_1	1st order heat loss coefficient (W/^{0}C)
a_2	2nd order heat loss coefficient (W/^{0}C^2)

β	Optimum inclination-slope of a photovoltaic module (º)
γ_c	Numerical parameter that depends on the building inertia (-)
γ_h	Numerical parameter that depends on the building inertia (-)
δ	Declination (º)
ΔT_1	Temperature difference between the indoor design temperature and the dry bulb temperature corresponding to 99.6% annual cumulative frequency of occurrence in the heating season (ºC)
ΔT_2	Temperature difference between the dry bulb temperature corresponding to 99.6% annual cumulative frequency of occurrence (cooling season) and the inside design temperature (^{0}C)
ΔT_{DHW}	Temperature difference between hot water furnished and the water entering the system to be heated (^{0}C)
ΔU	Default surcharge of U- Value considering the effect of thermal bridges (W/m^2.^{0}C)
ρ	Air density (kg/m^3)
ρ_0	Albedo (-)
τ	Coefficient of thermal loss reduction (-)
φ	Latitude (º)
ω_{ss}	Sunset hour angle (º)
$\omega_{ss}^{\prime}$	Sunset hour angle for a tilted surface (º)
A	Useful-heated area of a buildings´ (m^2)
A_{adj}	Wall area in contact with adjacent buildings (m^2)
A_{ef}	Collective effective area glazed elements (m^2)
A_{glz}	External glazed area (m^2)
A_{int}	Wall area in contact with non-heated spaces (m^2)
A_{roof}	Roof area (m^2)
A_{walls}	External wall area (m^2)
$A_{W(i,k)}$	Window area of element *i* for each *k* orientation (-)
A_{PV}	Photovoltaic panel area (m^2)
A_{SC}	Thermal solar collectors area (m^2)
$AESC$	Annual energy collected by the thermal solar collector (kWh)
b	Percent turbulence coefficient (%)
B_j	Benefits (positive cash flows) in year j for a system being evaluated (€)
C_j	Cost in year j for a system being evaluated (€)
C_p	Specific heat of air (J/kg.^{0}C)
C_{pw}	Specific heat of the water (J/kg.K)
C_0	Initial cost for a system being evaluated (€)
CDD	Cooling degree days per year (-)
CN_{final}	Final energy needs for space cooling (kWh/year)
CN_{usf}	Annual useful energy need for space cooling (kWh/m^2.year)

d	Discount rate (%)
D_H	Diffuse horizontal radiation (Wh/m^2)
G_H	Global horizontal radiation (Wh/m^2)
DHW_{final}	Final energy needs for DHW (kWh/year)
DHW_{usf}	Useful energy needs for DHW (kWh/m^2.year)
E_{PV}	Daily energy produced by the photovoltaic module (Wh)
E_{sc}	Solar irradiation (Wh/m^2.day)
F_g	Ratio of the overall projected area of the glazed element to the projected frame area (-)
F_s	Obstruction factor or shading reduction factor (-)
F_w	Correction factor representing the reduction of the solar energy caused by variations on the glass properties with the angle of incidence of the direct solar radiation (-)
g	Solar factor of the glazing (g-value) (-)
g_c	Solar factor of the window (average of 30% of the g-value of the glazing plus 70% of the g-value of the window considering the blinds closed (-)
h	Height at which the wind velocity v is being computed (m)
h_0	Height at which the wind velocity v_0 is being computed (m)
H_0'	Actual sunset sunrise hour angle (º)
HDD	Heating degree days per year (-)
HN_{usf}	Annual useful energy need for space heating (kWh/m^2.year)
HN_{final}	Final energy needs for heating (kWh/year)
HW_N	Needs for domestic hot water (lt/day.person)
KWp_h	Peak design heating load (kW)
KWp_c	Peak design cooling load (kW)
LCC	Life cycle cost (€)
M	Duration of the heating season (months)
MV_{final}	Final energy needs for mechanical ventilation (kWh/year)
n_c	Gain utilization factor for cooling (-)
n_h	Gain utilization factor for heating (-)
n_v	Number of hours per year in which the velocity has approximately the value v (-)
n_0	Zero loss efficiency (-)
n_{CS}	Efficiency of the cooling system (-)
n_{DHWS}	Efficiency of the DHW system (-)
n_{HR}	Efficiency of the heat recovery system (-)
n_{HS}	Efficiency of the heating system (-)
n_{SC}	Efficiency of the solar system (-)
n_{PV}	Photovoltaic panel efficiency (-)
$P(v)$	Power output of the wind turbine when the velocity has the value v (W)

P_{MV}	Power consumption of the mechanical ventilation system (W)
PB	Payback Period (years)
q_i	Average thermal internal gains (W/m^2)
Q_{adj}	Heat loss through the walls in contact with non-heated areas and/or adjacent buildings (kWh/year)
Q_{air}	Heat loss resulting from the air renewal (heating season) (kWh/year)
Q_{env}	Heat loss through the envelope due to conduction (heating season) (kWh/year)
Q_g	Total heat gain due to lighting, equipment and occupants, plus the solar gains through the glazed elements (heating season) (kWh/year)
Q_{glz}	Heat loss through the glazed areas (kWh/year)
$Q_{gn,c}$	Internal and solar heat gains (kWh/year)
Q_i	Internal heat gains caused by occupants, equipment and lighting (kWh)
$Q_{o,e,l}$	Heat gains from lighting, equipment & occupants (kWh/year)
Q_{opq}	Solar gains of the opaque surfaces(kWh)
Q_{roof}	Heat loss through the roof (kWh/year)
Q_s	Solar gains of the transparent surfaces-glazed areas (kWh)
Q_{sol}	Solar gain through glazed areas (kWh/year)
Q_{walls}	Heat loss through the walls (kWh/year)
R_b	Ratio of the average daily beam radiation on a tilted surface to that on a horizontal surface(-)
R_k	Integrated solar radiation (cooling season) for each *k* orientation (kWh/m^2)
R_{ph}	Rate of mechanical ventilation and infiltration (ach^{-1})
R_{sol}	Average solar energy impinging on a vertical surface facing the south during the heating season (kWh/m^2 .month)
S_r	Maximum solar insolation (W/m^2)
T_a	Average ambient air temperature (^{0}C)
T_{in}	Indoor air temperature (^{0}C)
T_m	Thermal collectors mean fluid temperature (^{0}C)
T_{out}	Average outdoor temperature during the cooling season (^{0}C)
TPO	Total annual power output of wind turbine (kWh)
U	Thermal transmittance (U- Value) of the wall area (W/m^2.^{0}C)
U_{gl}	U- value of the glazed area (W/m^2. ^{0}C)
v	Wind velocity (m/sec)
v_0	Wind velocity at 10m height (m/sec)
v_1	Corrected wind speed (m/sec)
V	Volume of the building (m^3)
$\dot{V}_{MV}$	Air flow rate due to mechanical ventilation (m^3/h)
$\dot{V}_{NV}$	Air flow rate due to natural ventilation (m^3/h)
X_k	Orientation factor for each *k* orientation (-)

1 Introduction

1.1 Context

Buildings are seen as a key-part of the needed transition towards Sustainability in its energy dimension. This derives from the fact that the buildings sector represents between 30% and 40% of the demand of final energy in most developed countries. Given that in buildings there is a high use of electricity, these figures often convert to about or more than 40% in primary energy and energy-related CO_2 emissions. Complementarily, the Intergovernmental Panel on Climate Change (IPCC) fourth assessment report states that about 30 percent of the projected global greenhouse gas emissions in the building sector can be avoided by 2030 with net economic benefit (Bernstein, et al. 2010).

Significant policy action towards the promotion of energy-efficiency and on-site renewable energy in the building sector has been developed all around the world, with different levels of intensity and structure. The fundamentals of this action go back at least to the 1970's, when demand-side management started to be recognized as a viable – besides rational - energy policy option. It then comprised actions such as the development of thermal regulations for buildings or the promotion of passive solar architecture, and kept gaining momentum until nowadays. For instance, the first French regulation on thermal requirements for buildings approved in 1974 (French Government 1974), Balcomb's demonstration Passive Solar Building became operational in 1975 (Nichols 1976), the book "Solar energy—fundamentals in building design" was published in 1977 (Kreider 2003) and the Passive and Low Energy Architecture first congress was held in 1981 (Cook 2008).

In the European Union (EU), the Energy Performance of Buildings Directive (EPBD) approved in 2002 (EU 2003) called for the assessment and publicity of the energy performance of all new buildings as well as of those undergoing major refurbishments or entering the market for rental or selling. This directive is now at the stage of concrete implementation, while at the same time in October 2010 the Directive was replaced by a recast Directive approved in May 2010 (EU 2010). Other tools to enhance energy-efficiency and integration of renewable energy technologies have also been developing in several parts of the world, such as the PassivHaus design standard in Germany (Feist 1988), the BREEAM in the United Kingdom (BRE Group 1990) or the LEED certification in the United States (U.S Green Building Council, 2000).

A radical approach for the mitigation of the energy usage as regards the buildings sector is the concept of the net zero energy building (NZEB). This concept started to appear in the literature as an evolution of very energy-efficient buildings, and it requires that the building that has zero energy balance on an annual basis (Figure 1.1). Even if it may receive energy from the electric or gas grids at some times, it has local systems that produce and export energy carriers into the grids at other times so that the annual balance is about null. Conceptually the exportation of energy could be made with various energy carriers, although for its easiness of transport electricity has been the obvious choice so far.

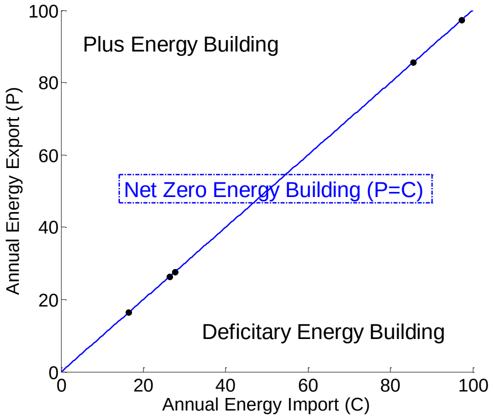


Figure 1.1: The Net Zero Energy Building Concept

The first country to require NZEBs in a large scale was the United Kingdom (UK), which in its Energy Efficiency Action Plan of 2007 stated*: 'In the household sector we will continue to raise energy performance standards for new homes in England and Wales through Part L of the Building Regulations with the aim of delivering zero-carbon homes by 2016. The Code for Sustainable Homes will support this ambition and drive wider environmental improvements in new homes…'* (DEFRA 2007). By the same time, the Welsh Assembly Government adopted the target that all new buildings, not just housing, must be zero carbon in relation to space heating, hot water and lighting by 2011 (DEFRA 2007). The UK government has meanwhile announced to be conducting feasibility studies to enforce the NZEB target also for non-residential buildings (Department for Communities and Local Government 2009).

The movement to make NZEBs mandatory at least in the residential sector took another boost in 2009 when the European Parliament in its vote on 23 April 2009 voted: '*Member States shall ensure that all new buildings are at least net zero energy buildings by 31 December 2018 at the latest and that MS shall set targets for minimum percentage of buildings which shall be, by 2015 and by 2020 respectively, net zero energy buildings…'* (European Parliament 2010). This measure ended up being adopted by the EU in a softer way, since the final EPBD recast approved on the 19th of May, 2010 calls for all new buildings to be *nearly zero-energy buildings* by 31 December 2020 and new buildings occupied and owned by public authorities to be nearly zero-energy buildings, after 31 December 2018, with the quantitative performance targets of 'Nearly Zero Energy Buildings' yet to be defined (European Parliament 2010).

Other NZEB enforcement examples are France, where all new buildings should be energy positive by 2020 (European Commission 2009) and Hungary, which has set the target of achieving zero emissions for all new buildings by 2020 (Thomsen, Wittchen e EuroACE 2008). Ireland, is planning to have net zero energy buildings by 2013 and in the Netherlands there is a voluntary agreement with industry to have energy neutral buildings in 2020 (European Commission 2009).

Furthermore, Sweden has proposed a strategy for all public buildings to be zero energy by 2019, extending to all buildings by 2021 (Boermans, et al. 2011). Finally, in Norway zero energy buildings are expected by 2027 (Jagemar, et al. 2011).

In other parts of the World, South Korea has included residential NZEBs by 2025 as part of a Green Building Policy Package (United Nations Environment Programme 2010); to fulfill the objective of low carbon green growth, the Korean government unveiled ‘Measures to Develop Green Cities and Buildings’ on November 5, 2009 (Korean Government 2009).

Given the relevance that the concept of a Net-zero energy building is receiving from the policy makers in several geographical contexts, it is of outmost importance to develop technical tools that enable the quantification and analysis of their effective environmental and economic merits or defects. It is also important to develop tools that may assist the identification of the best design options for each type or buildings and location, as well as the identification of market failures or distortions of the regulatory framework that may need to be corrected in the adaptation to this new approach.

1.2 Design of NZEBs as an engineering problem

Reaching a null or even positive net yearly energy balance is, at least for low rise-buildings, not technically difficult. In the limiting case, it could be achieved even with a “conventional” design, complemented by the installation of sufficient on-site photovoltaic (PV) or other technologies able to produce exportable energy carriers. In practice, because of the cost of the photovoltaic systems, or because of other technical or non-technical reasons, in most cases the design strategy followed is to design the building with an energy-efficient way, and then incorporate PV systems to offset the yearly energy demand of the building. In fact the requirement of “energy efficiency” is even proposed by some authors as part of the definition of NZEB, as will be seen in chapter 2 (Torcellini, et al. 2006).

Yet, even if energy efficiency were to be accepted as a requirement, there are several levels of energy efficiency, and there are many ways of achieving a given performance target. E.g. there are many different combinations of design variables (shape, level of thermal insulation, glazed area, glazing orientation, type of glazing, type of ventilation, etc.) that could lead to about the same level of annual heating needs. This observation can be transposed to the whole annual energy demand for the building if the building systems (for heating, cooling, hot water) and the appliances are also considered.

On the supply side, too, there are several options that can be used to generate electricity and offset the yearly imports consisting of thermal solar collectors, photovoltaic modules, small wind turbines, efficient HVAC systems etc.

Combing the design variables that determine the energy demand with those that ensure the compensation, it becomes clear that there are many – potentially unlimited – combinations of them (building design solutions) that can result in an approximate annual net-zero energy balance. Yet, even if all resulting in a yearly zero balance, it is clear that they will achieve the balance at different levels of energy import-export equilibrium and that they have different initial costs and different expected life-cycle costs.

The ‘know how’ that has been established previous to this work takes the form of design guidelines which address, for some climatic contexts, the form, orientation, thermal mass and windows (Charon e Athienitis 2006). Despite its apparent logic, these guidelines are not a product of a rigorous systematic analysis covering all the range of possibilities, meaning that there has not been an analysis of the ‘optimal’ coupling point for the energy import and export level. However, the problem of producing and comparing the results of many different possible combinations of variables and identifying and “optimal” or “near optimal” is a common type of engineering problem which can be solved with several methods.

1.3 General objectives and structure of this work

The aim of this work is the development of a method and an associated calculation platform to identify the most adequate design solutions for residential NZEB design, considering the influence of the local climate, the endogenous energy resources and the local economic conditions. The translation of ‘most adequate” is something that, according to decision theory, implies knowing and understanding a decision maker. For this work, no specific decision perspective will be adopted. It will be intended to characterize essentially the investment cost, expected life-cycle cost and level of energy use at which the net zero import-export balance is met. The lowest life-cycle cost (LLCC) solution will be taken as a reference for the analysis of the results, but the methodology and the tool will be structured to allow any future user to adopt a different solution, valuing different criteria, with the advantage that in that case it will be possible to know how distant the chosen solution is from the lowest life cycle cost one or from the lowest initial cost (LIC) one. Once the analysis tool is developed, it will also be an aim of this study to gain insights on the characteristics of the space of design solutions for NZEBs. By using building case studies and considering different climatic contexts, it will be sought to answer to questions such as:

- Which are the design variables that have higher impact on the energy performance & optimal design of NZEBs?
- Is there a trade-off trend between Life Cycle Cost (LCC) &Initial Cost (IC) for the buildings that provide a net zero energy yearly balance? If yes, does this happen in all climate-economic contexts or only in some?
- Do energy-efficient NZEBs have higher, similar or lower LCC and /or IC costs than non-energy efficient buildings?
- What is the impact of pricing policies electricity for the electricity bought to buildings in:
    - Economic Indicators (Initial Cost, Life Cycle Cost);

    - Best design solutions (features that appear frequently in the optimal or near-optimal solutions);
    - The level of energy use at which the net zero import-export balance is met

- Are high-rise NZEBs technically feasible, and in what way are the economic indicators and design solutions affected?

- What would be the influence of microgeneration cost variations on the economic indicators and design solutions?

The answer to these questions was achieved throughout a process, which is roughly in correspondence with the main chapters of this work. More specifically:

- *Chapter 2* is a review of the state of the art so far and a description on the recent progress of the policy context and scientific formulations around net zero energy buildings, analysed from different perspectives. It starts with a listing of all the definitions published so far, continues with presenting a number of residential and commercial demonstration buildings already built and reported and ends with an analysis of the current design practices of NZEBs.

- *Chapter 3* addresses the calculation methodologies used in order to characterize the energy demand and supply of a building as well as its economic performance. More specifically, steady state methodologies for calculating the heating, cooling and peak heating loads of a building were used based on existing and validated standards. Moreover, a peak cooling load calculation methodology was implemented in order to size the cooling equipment. Domestic hot water needs were sized depending on the number of occupants and the climatic conditions while default values for ventilation, lighting and appliances final needs were considered. Electricity generation from photovoltaic panels and wind turbines was estimated together with the annual energy produced from solar collectors. Finally, the economic effectiveness of the building project was based on the life cycle cost method.

- *Chapter 4* begins with the identification of the design variables relevant in order to shape the energy demand and supply of the building and continues with the implementation of the methodologies for characterizing the energy demand-supply and the economics, described in chapter 3, in a computer simulation program-computational tool developed in Matlab (Matlab 2011).

- *Chapter 5* and *Chapter 6* demonstrate two application examples of the tool implemented in chapter 4, and present the results on which the answer to the research questions will be based on.

- *Chapter 7* is the chapter with the conclusions and final remarks as well as a brief description of future research opportunities in the NZEB area.

1.4 Delimitations of scope

The coverage of this work is limited as regards the following:

- The net zero energy balance is made in terms of final energy. However, it can be overcome using the “level of compensation”, which is the fraction of the annual energy imports to the building to be offset with exports (chapter 5.1);
- PV panels are installed only in the roof or other horizontal planes but not on the façades. Nevertheless, it is known that the productivity of PV panels on vertical walls is significantly lower than when placed in the optimal inclination so it is not expected that these solutions would be chosen as economically optimal;

2 Review of net zero energy buildings design methodologies and practices

This chapter intends to present a critical assessment of the progress on Net Zero Energy Buildings in the latest years. The progress was analyzed in several perspectives, which became a sub-chapter each: i) Progress in defining the concept of NZEB; ii) Progress on Demonstration Buildings (residential and non-residential); iii) Progress on Design Strategies. It ends with the major conclusions.

2.1 Progress in defining the concept of NZEB

The literature shows that there are different definitions of a net zero energy building. The first major difference found is of formal nature and concerns whether or not the word 'net' must be explicit in the expression, thus the difference being between 'zero energy building' and 'net zero energy building'. It presents little doubt that, while the first may be more practical, the latter is the scientifically correct. While some of the founding documents in NZEB definition where addressing it simply as "ZEB" (Torcellini, et al. 2006), a search in the major search engine (google.com) in the internet in November 2010 found that actually the correct expression was then more used by a factor of 2.5 over the simplified one. NZEB is also the expression appearing in latest reference publications in the area (Robert e Kummert 2012), (Marszal, et al. 2012), (Sartori, Napolitano e Voss 2012), (Kurnitski, et al. 2011) .In terms of conceptual substance, two main differentiation factors were found: a) the level of the energy chain at which the balance is made; and b) the requirement for a high level of energy efficiency.

Concerning the issue of the level of the energy chain at which the balance is made, Torcellini et al. addressed four main definitions of NZEBs (Torcellini, et al. 2006):

1. Net Zero Site Energy: A site NZEB produces at least as much energy as it uses in a year, when accounted for at the site.

2. Net Zero Source Energy: A source NZEB produces at least as much energy as it uses in a year, when accounted for at the source. Source energy refers to the primary energy used to generate and deliver the energy to the site. To calculate a building's total source energy, imported and exported energy is multiplied by the appropriate site-to-source conversion multipliers.

3. Net Zero Energy Costs: In a cost NZEB, the amount of money the utility pays the building owner for the energy the building exports to the grid is at least equal to the amount the owner pays the utility for the energy services and energy used over the year.

4. Net Zero Energy Emissions: A net-zero emissions building produces at least as much emissions-free renewable energy as it uses from emissions-producing energy sources.

In a similar level of analysis, the International Energy Agency (IEA) defines NZEBs as buildings that do not use fossil fuels but instead get all their required energy from solar energy and other renewable energy sources (Laustsen 2008). It proposes the following variants:

1. Zero Net Energy Buildings are buildings that over a year are neutral, meaning that they deliver as much energy to the supply grids as they use from the grids. Seen in these terms they do not need any fossil fuel for heating, cooling, lighting or other energy uses although they sometimes draw energy from the grid.

2. Zero Stand Alone Buildings are buildings that do not require connection to the grid or do so only as a backup. Stand-alone buildings can autonomously supply themselves with energy, as they have the capacity to store energy for nighttime or wintertime use.

3. Plus Energy Buildings are buildings that deliver more energy to the supply systems than they use. Over a year, these buildings produce more energy than they consume.

4. Zero Carbon Buildings are buildings that over a year do not use energy that entails carbon dioxide emission. Over the year, these buildings are carbon neutral or positive in the term that they produce enough CO2-free energy to supply themselves with energy.

IEA’s definition of ‘Net Zero Energy Buildings**’** thus seems to correspond to the ‘Net Zero Site Energy’ of Torcellini et al., while the ‘Zero Carbon Emissions’ is closely related to the ‘Net Zero Energy Emissions’ of Torcellini et al. It could also relate to the ‘Net Zero Source Energy’ variant if only the fossil component primary energy were considered.

In another definition variant, Hernandez and Kenny provide a definition that accounts for the embodied energy, together with energy use and reclaims the original concept of ‘net energy’ to define life cycle energy building (LC- ZEB): ‘ A LC-ZEB is defined as a building whose primary energy use in operation plus the energy embedded in materials and systems over the life of the building is equal or less than the energy produced by renewable energy systems within the building (Hernandez and Kenny 2010). This definition however doesn’t seem to have been adopted by most authors, be it for its concept be it for the practical difficulty in knowing the embodied energy of most materials.

Addressing now the second main differentiating factor regarding the definition, it was found that some sources make an explicit requirement that, to be classified as NZEB, the balance between the energy ‘on-site production’ and the energy demand be made at a low level of energy demand, i.e., that the on-site generation be added to a building where significant energy-efficiency measures were taken to decrease the demand. This is the case e.g. of the United States Department of Energy (DOE) : ‘ A net-zero energy building is a residential or commercial building with greatly reduced needs for energy through efficiency gains, with the balance of energy needs supplied by renewable energy technologies’ (U.S Department of Energy, Building Technologies Program:Planned Program Activities for 2008-2012 2008) and of Wang et al: ‘The zero energy building design concept is an extension from passive sustainable design (Wang, Gwilliam and Jones 2009).In line with the explicit requirement for the zero balance to be met at a high level of energy-efficiency, the following three examples could be found:

1. The California Energy Commission (CEC) states that ‘a zero net energy building merges highly energy-efficient building construction, state of the-art appliances and lighting systems, and high performance windows to reduce a building’s load and peak requirements and can include on-site solar water heating and renewable energy, such as solar photovoltaic, to meet remaining energy needs (Figure 2.1). The result is a grid-connected building that draws energy from, and feeds surplus energy to, the grid (California Energy Commission 2009).

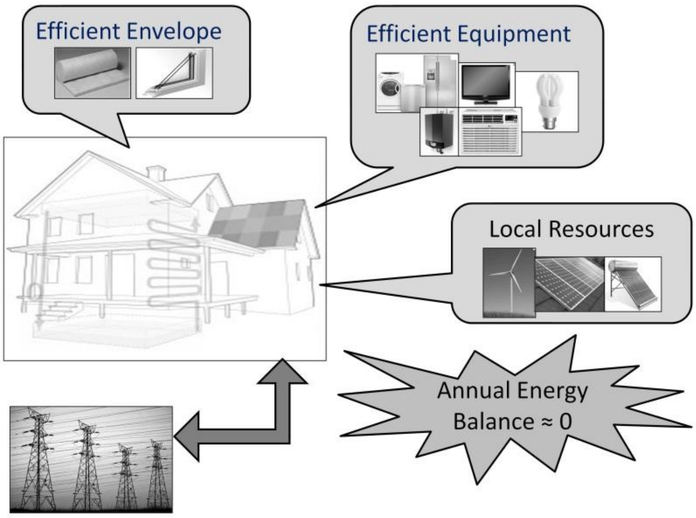


Figure 2.1: *‘A zero net energy building merges highly energy-efficient building construction, state of the-art appliances and lighting systems, and high performance windows to reduce a building’s load and peak requirements and can include on-site solar water heating and renewable energy, such as solar photovoltaic, to meet remaining energy needs. The result is a grid-connected building that draws energy from, and feeds surplus energy to, the grid’.* (California Energy Commission 2009)

2. The Massachusetts Zero Net Energy Buildings Taskforce in 2009 defined a NZEB as a building that is optimally efficient and, over the course of a year, generates energy onsite, using clean renewable resources, in a quantity equal to or greater than the total amount of energy consumed onsite (Massachusetts Zero Net Energy Buildings Task Force 2009).

3. Members of the European Parliament adopted a definition of zero-energy buildings as buildings ‘where, as a result of the very high level of energy efficiency of the building, the overall annual primary energy consumption is equal to or less than the energy production from renewable energy sources on site’ (European Parliament 2010). By the end of 2010, the Commission was planning to establish a detailed common European definition of ‘net zero energy buildings’. Although the mandatory adoption of NZEBs was not followed by the Commission the requirement for a high level of energy efficiency was adopted in the revised EPBD.

The approach above of having an explicit requirement for the zero balance to be met at a high level of energy-efficiency comes in opposition to the strategy, which would also lead to net-zero balance, of adopting no special measures regarding the energy efficiency and then installing enough on-site generation to offset the (high) consumption. In respect to this question, it can be commented that, in a performance driven society, only the goals and not the means should be part of the requirements. This would reason in favor of a definition that does not have an explicit requirement for energy efficiency, leaving to the results themselves to show that the most rationale options are those that result from the complete consideration of all NZEB alternatives converging from the perspective of energy efficiency, cost effectiveness and local climate context. This will be the perspective adopted in this work, because in this way it will be possible to assess the hypothetical added costs of including an explicit requirement of high energy-efficiency in the definition. I.e., to explore the space of design solutions without this requirement results in a more comprehensive analysis than without it. E.g., if even without the requirement of “high energy efficiency” the results show that the cost-optimal solutions are of this nature, then it becomes concluded that high energy efficient solutions are the ones that “naturally” result in the cost-optimal; If by the contrary it is found that the solutions with high energy efficiency are more costly overall than the non-high energy efficient ones, then the policy makes may still adopt them based on other criteria, but he is informed about the “added cost” of such decision.

Another important issue at the level of concept definition is the one of performance indicators for NZEBs. Some derive directly from the base-variables selected for the balance definition, as are the case of yearly primary energy balance, yearly associated carbon emissions and yearly energy costs (Torcellini, et al. 2006). In many NZEB case studies, the Estimated Net Energy Produced (ENEP) is often computed (Iqbal 2004) (Wang, Gwilliam e Jones 2009) (Zhu, et al. 2009)(Zhu, Hurt, Correa et al., 2009). These are the energy carriers produced via renewable sources minus the energy required for the building operation for a specified period of time (Kolokotsa, Rovas, et al. 2011). Furthermore, Hernandez and Kenny in 2010 introduced the concept of the Net Energy Ratio (NER) which is the ratio of the decrease of annualized embodied energy to the increase of annual energy use (Hernandez e Kenny 2010). Kolokotsa et al in the same year, addressing the issue of NZEB operation under real conditions, introduced another indicator called “Net Energy Consumed” (NEC) which is the amount of energy that needs to be purchased from the utility company and equals to the negative of the “Net Energy Produced” (NEP) (Kolokotsa, Rovas, et al. 2011). The same authors introduce some performance indicators of Building Optimization & Control (BO&C) systems for NZEBs, which can be used to assess energy performance, thermal comfort, and cost efficiency. More specifically, these indicators include: 1) the Generation–Consumption Effectiveness Index (GCEI), which measures the quality of the decision/control strategy compared to the optimal strategy; it actually compares the effect different decision/control strategies have on system performance; 2) the CI1 index which integrates thermal comfort, visual comfort and indoor air quality measured by specific sensors in the building. It can be linked to the requirements of CEN standard EN 15251 (CEN, 2006); 3) the CI2 index which depends on the end users responses as a result of their interaction via a user interface where the thermal comfort preferences are inserted to the system; 4) the Building Optimization and Control (BO&C) Payback Period (PP) which is the period required to amortize BO&C implementation and operational costs from cost-savings due to reduced energy consumption.

2.2 Progress on NZEB demonstration buildings

Many modern NZEBs, both residential and commercial, have been built, tested and reported in different parts of the world starting in the early 1990’s. The adjective ‘modern’ is employed here to differentiate these buildings from buildings without provision of electricity and using mainly biomass for cooking and heating, which dominated most of the world’s history and still dominate significant parts of the African and Asian continents. Even if these modern NZEB buildings were not built for a specific scientific purpose but rather for a normal use, they will be considered here as demonstration buildings in the sense that they demonstrate the feasibility of the concept. The progress in demonstration NZEBs is presented starting with two very early examples that have set the pathway, continuing with more recent constructions of new buildings and ending with 2 examples of retrofits to NZEB target.

2.2.1 Residential NZEBS

Historically, NZEBs can be seen as an extension from the concept of “solar” or “passive” buildings which had been developed since the 1970’s, and of which many demonstration buildings have been built around the World (Nichols 1976), (Maldonado, Fernandes e Gonçalves 1987).

In 1992, the Fraunhofer Institute for Solar Energy Systems ISE set about the operation of the Self-Sufficient Solar House in Freiburg (Figure 2.2) (ISE 2000); this can be considered the first ‘modern’ ZEB. For three years 1992 to 1995, the house was occupied by a family of two adults and one child and demonstrated that the sun can provide a house with all the energy that it needs, even in the Central European climate where the solar radiation available is moderate. During that period, the home was not connected to the grid and there was no other external supply of non-solar energy; the success of the project was based on solar generated hydrogen as the energy storage form for electricity & heat and a fuel cell as a miniature cogeneration power plant. Nowadays, the building is used as a research platform.

Another ‘early’ example of a NZEB was constructed in Lakeland, Florida in 1998; an experimental residential building called ‘PVRES’ (super-energy-efficient photovoltaic residence); constructed together with a conventional one (both had the same floor plan) which played the role of the project control (Building America U.S Department Of Energy 2005). The ‘PVRES’ home (Figure 2.2) had higher levels of thermal insulation, a white reflective roof system, solar water heating and efficient interior appliances and lighting, a high efficiency heat pump and a photovoltaic (PV) system (Florida Solar Energy Center 2007). Even though the project, did not reach zero energy annual balance (the annual energy needs in terms of final energy were covered by 75%), it showed that virtually zero net utility peak coincident demand was possible and became the flagship for the program of the U.S Department of Energy: Zero Energy Homes (Parker 2009).

Figure 2.2.: The Solar House in Freiburg (left) (ISE 2000), PVRES, Lakeland Florida (right) (Parker 2009)

Another net zero energy home (NZEH) is the ‘Solar Harvest’, a 426 m^2 house designed and constructed by Eric Doub and his company Ecofutures Building Inc in 2005 (Doub, Solar Harvest : City of Boulder ’ s First Zero Energy Home. 2009). It is located in Boulder, Colorado, U.S (Figure 2.3). The concept is a combination of active and passive solar design features with heavy thermal insulation, high performance glazing and windows and highly efficient equipment. All the appliances in the house are electric since 2007, with all its electricity needs covered from PV panels while space heating and domestic hot water is provided by solar thermal flat-plate collectors. Moreover, it features extended engineered heat recovery ventilation (HRV) system and a PVC pipe buried underground for seasonal thermal pre warming and pre cooling of the incoming fresh air.

Figure 2.3: Solar Harvest, Boulder, Colorado (Doub, Solar Harvest : City of Boulder ’ s First Zero Energy Home. 2009)

In 2005, the University of Nevada launched a zero energy house (ZEH) research (Hurt, et al. 2006). The result was two homes of the same area (150m^2) constructed side-by-side (Figure 2.4); a baseline house built with conventional materials and techniques and a ZEH. The ZEH featured on one hand many energy saving measures like high thermal mass walls, spectrally selective low-e windows, compact fluorescent lighting, foundation insulation and a radiant heat barrier and on the other hand solar power generation through a PV array and a supplemental water heating (solar water heater).

The Plus Energy Housing (Plusenergiewohnen) ‘Tanno meets Gemini’ (Figure 2.5) was built in Weiz, Steiermark, Austria, in 2006 (Novakova 2006). The construction was Austria’s first energy positive project and it includes 22 flats within an area of 3294 m^2. All flats feature high-level insulation and triple low-e windows, a high efficiency heat pump to cover the heating needs of the residences, while the energy consumption is being offset through installed PV panels.

Figure 2.4: University of Nevada ZEH (Hurt, et al. 2006)

Another NZEH is located in Flieden, Hessen, Germany was constructed in 2006; the ‘Solar Plus Haus’ in Flieden covers a 212m^2 area (Pedro Castro Ricardo 2009). The construction incorporates high levels of insulation, triple windows and controlled mechanical ventilation with a heat recovery system while the energy needs are covered with the combined use of solar collectors, PV panels and a wind turbine.

Figure 2.5: Pluesenergiewohnen,Weiz,Austria (Novakova 2006)

The ‘Eco Terra’ house located, in Eastman, Quebec, Canada is a 140m^2 Net Zero Energy house built in 2007 (Noguchi, et al. 2008); it is Canada´s first net zero energy home (Figure 2.6). The home features a super air tight envelope with high levels of insulation, triple low-e coated windows and high efficiency appliances. It integrates conventional heating technologies such as geothermal heat pump (GHP), building-integrated photovoltaic thermal (BIPV/T) roof system, ventilated concrete slab (VCS), passive solar design and active thermal storage.

Hawkes Architecture in 2009, in Staplehurst, Kent, UK, constructed the ‘Crossway Eco-House’ (Hawkes 2009) (Figure 2.7) a 285m^2 NZEH with increased insulation, high performance gypsum board used in wet and high humidity applications, triple glazing and high efficiency appliances. The heating energy needs are supplied from a Photo Voltaic Thermal (PV-T) system and a salt phase change material thermal store backed up by a biomass boiler.

Doub in 2008 presented a retrofit towards NZEB target of a 1970s ranch home in South Boulder, Colorado (Doub 2008). The retrofit resulted in a super insulated opaque envelope (thermally broken wall U-value= 0.2 W/m^2°C, roof & attic U-value= 0.1 W/m^2°C) & airtight building shell with high performance double heat mirror windows. Mechanical ventilation with an energy recovery ventilator was also used. The energy needs for DHW were fully covered by 180 evacuated tube solar collectors and the electricity needs from a 6 KW PV system.

Attia in 2010 presented the results of a study regarding a possible retrofit to NZEB level of a chalet in Ain- Sukhna, Egypt (Attia 2010). The author investigated several passive and active design strategies and concluded that on an economical level the most active design strategies (i.e., those dealing with equipment) and even the thermal upgrade of the envelope were not advantageous due to the long term Payback Period. The only measures with low pay-back periods were compact fluorescent lighting and a solar collector thermosyphon for Domestic Hot Water, with less than 1 year and 2-7 years payback period respectively. Wall external thermal insulation (U-value= 0.234 W/m^2°C), roof insulation (U-value= 0.177 W/m^2°C), double pane low-e windows, 1m overhang on the east façade, 1.1 kWp PV system and a small scale wind turbine expected to deliver 660 KWh/yr, were considered not attractive economically, with pay-backs ranging from 19 to 41 years.

Figure 2.6: The Eco-Terra House, Canada (Noguchi, et al. 2008)

Figure 2.7: The Crossway Eco-House, Kent (Hawkes, 2009)

Table 2.1 presents a ‘summary’ of the main technical features of the residential NZEBs mentioned above. The solar house in Freiburg is not included in the summary due to lack of information data.

Table 2.1: Main Technical Features of Residential ZEB examples

Residential Case Studies	**Main Technical Features**					
	Envelope	*Air change*	*Heating/Cooling & Hot Water*	*Lighting & Appliances*	*Electricity Production*	*Energy Management Systems*
PVRES	Wall U-value 0.57W/m^2.K Roof U-value 0.19W/m^2.K White reflective roof Thermal break + argon filled windows Overhangs around the building	Air tight construction (average ACH=0.13) No mechanical ventilation	Solar water heating High efficiency HVAC system	CFL lighting Efficient appliances	Photovoltaic crystaline modules	Data logger for weather and thermal conditions and major end-use electric loads
Solar Harvest	Wall U-value 0.17W/m^2.K Ceiling U-value 0.126W/m^2.K Double glazed fiberglass windows Shading provided by solar panels and trees	Air tight construction(average ACH=0.1) Heat recovery (HR) ventilation system Natural Ventilation	Solar thermal heating (12 roof-mounted solar thermal collectors) Summer cooling by natural chimney effect through skylight Ground cooled air through buried pipes High efficiency AC	CFL lighting Efficient appliances	8.74 kW roof-mounted PV array	Data monitoring with temperature, energy and comfort system sensors
ZEH Nevada	Thermal mass walls Radiant barrier sheeting Blown in attic insulation(U=0.15W/m^2.K) Low-e windows Large overhangs 2.43m	-	AC system with evaporative condenser 2.3 m^2 solar collector Tankless gas hot water heater	CFL lighting Efficient appliances	Photovoltaic system of 4.8KWp	Data monitoring to measure weather conditions and electricity and gas consumption
Tanno meets Gemini	Wall U-value 0.11W/m^2.K) Roof U-value 0.09W/m^2.K Triple glazed low-e windows	Mechanical ventilation	High efficiency heat pump for space heating and domestic hot water purposes	CFL lighting Efficient appliances	Roof integrated photovoltaic system	-
Solar Plus House	Wall U-value 0.11W/m^2.K) Triple windows	Mechanical ventilation with HR	Solar collectors	CFL lighting Efficient appliances	PV panels Wind turbine	-
Eco- Terra	Wall U-value 0.16 W/m^2.K Roof U-value 0.125W/m^2.K Triple glazed low-e coated argon filled windows	Air tight construction Mechanical ventilation	Geothermal Heat Pump (GHP)	CFL lighting Efficient appliances	3KW building integrated photovoltaic thermal system (BIPV/T)	Data monitoring with sensors for thermal performance and energy efficiency assessment
Crossway Eco-House	Wall U-value 0.12W/m^2.K Roof (U=0.12W/m^2.K) Triple glazed argon filled windows Vault overhangs & integrated blinds within some windows	Mechanical ventilation with HR	No conventional heating Extracted heat is stored in phase change materials (PCMs) creating heat battery for hot water & top up heat	CFL, LED & halogen lighting Efficient appliances	26m^2 of photovoltaic thermal (PV/T) system Biomass boiler	Built in sensors measure themal performance, electricity, water consumption and solar thermal monitoring

2.2.2 Non residential/commercial NZEBs

Even though non-residential buildings will not be part of the focus of this work, their inclusion in the bibliographic review may be useful in establishing the context of design features and practices.

The Adam Joseph Lewis Center (Figure 2.8) for Environmental Studies is an all-electric ZEB located on the Oberlin College campus in Oberlin, Ohio, which covers an area of 1260m^2. The construction was complete in 2000. The Lewis Center generates its own on-site electricity through a roof mounted 60 kW photovoltaic system and a 100 kW PV system located over the parking lot (Pless, Torcellini e Petersen 2004).

The Science House at the Science Museum of Minnesota (Figure 2.9) is a ZEB recognized by the European Council for an Energy-Efficient Economy (ECEEE) in 2005 for its innovation (Steinbock, et al. 2006). The building makes use of high performance windows, daylight dimming controls, south side overhangs, north side clerestory windows, high levels of insulation for the walls and roof and occupancy sensor controls of all interior lighting systems. Moreover, premium efficiency ground source heat pumps are used to heat and cool the building, a heat pump assisted domestic hot water (DHW) system and ventilation energy recovery. Electricity is produced by integrated photovoltaic roof systems of flat plate polycrystalline silicon panels.

Figure 2.8: The Adam Joseph Lewis Center for Environmental Studies, Ohio (Pless, Torcellini e Petersen, Oberlin College Lewis Center for Environmental Studies: A Low-Energy Academic Building 2004)

Figure 2.9: The Science House at the Science Museum of Minnesota (Steinbock, Eijadi, Mcdougall, Vaidya, & Weier, 2006)

The Hawaii Gateway Energy Center (Figure 2.10) is another example of a net zero energy commercial building with an area of $334m^2$ built in 2005 that serves the Natural Energy Laboratory of Hawaii (U.S Department of Energy 2008). The building combines extensive daylighting due to its orientation and configuration, a passive thermal chimney, and a cooling system that utilizes seawater to reduce energy consumption; nowadays it actually exports more electricity than it produces via a PV array system.

Figure 2.10: Hawaii Gateway Energy Center, Kailua-Kona, Hawaii (U.S Department of Energy 2008),

Figure 2.11: The Aldo Leopold Legacy Center, Baraboo, Wisconsin (Thermal Energy Systems Specialists 2007)

The Aldo Leopold Legacy Center (Figure 2.11) is a commercial (Interpretive Center, Commercial office) carbon-neutral ZEB covering an area of 1100 m^2, completed in 2007 in Baraboo, Wisconsin (Thermal Energy Systems Specialists 2007). The construction maximizes the use of daylighting to reduce the need of electric lighting during the day; heating is provided by ground source heat pumps connected to a radiant slab and an earth tube system provides fresh air to the building. Finally, a rooftop PV array produces 10% more of the annual electricity needed for the building to operate.

In San Jose, California, in 2007, a 609m^2 area commercial office carbon neutral ZEB was constructed and called the IDeAs Z Squared Design Facility (Figure 2.12). The building utilizes a high-efficiency HVAC system featuring a ground-source water-to-water heat pump system that provides radiant heating and cooling via the floor slabs and a rooftop integrated photovoltaic system, which also uses PV panels for solar shading over the entrance (U.S Department of Energy 2009), (Nesler e Palmer 2009). Skylights and high performance windows maximize the amount of daylighting entering the building while east windows use electrochromic glass; an automatic lighting control system exists and high efficiency equipment is used.

Figure 2.12: The IDeAs Z Squared Design Facility, California (left) (U.S Department of Energy 2009)

A rather new example of a mixed use (office/ retail/residential) ‘beyond’ zero energy building is still under construction in Masdar city, United Arab Emirates and is planned to be completed in the end of 2010. The Masdar Headquarters building (Figure 2.13) is planned to be the world’s large-scale positive energy building. The building will feature integrated wind turbines, outdoor air quality monitors and one of the world’s largest building-integrated solar energy arrays while all materials used will be sustainable. Wind towers will be used to exhaust warm air and naturally ventilate the building while at the same time bringing cool air up (Smith e Gordon 2008). Natural daylight will be provided to the building through cones which will support the building’s roof and allow for the creation of a shaded micro climate.

Figure 2.13: Masdar City Headquarters, United Arab Emirates (right) (Smith e Gordon 2008)

Table 2.2 presents a ‘summary’ of the main technical features of the commercial NZEBs described in this section, while Table 2.3 shows which NZEB examples discussed so far have their performance comproved by monitored data rather than only on design data.

Table 2.2: Main Technical Features of the Commercial NZEBs

Commercial Case Studies	**Main Technical Features**					
	Heat Gain/Loss through Envelope	*Heat Loss through Ventilation*	*Heating/Cooling & Hot Water*	*Lighting & Appliances*	*Electricity Production*	*Intelligent Energy Management Systems*
Adam Joseph Lewis Center	Wall U-value 0.4W/m^2.K Triple pane, argon filled, low-e glazing South-facing curtain wall Thermal mass through concrete floors Exposed masonry walls Window shades	Mechanical ventilation with HR	Closed-loop geothermal wells	Energy efficient lighting and appliances	Roof integrated 60KW+100KW PV system	Monitoring of building systems Occupancy sensors Photoelectric daylight sensors Carbon dioxide sensors Automated operable windows
Science House in Minnesota	Wall U-value 0.14W/m^2.K Roof U-value 0.2W/m^2.K High performance windows 1.21m overhangs (south) Maximum daylight	Mechanical ventilation with heat recovery Multi-modal natural ventilation	Premium efficiency ground source heat pumps Heat pump assisted DHW Electric resistance back-up	Energy efficient lighting and appliances	8.8KW PVsystem	Daylight dimming controls Occupancy sensor controls Continuous computer monitoring Control of mechanical systems
Hawaii Gateway Energy Center	Walls U-value 0.9W/m^2.K Roof U-value 0.23W/m^2.K High performance windows Daylight harvest	Passive thermal chimneys	Deep seawater pumping for passive cooling	Energy efficient lighting and appliances	20KW PV system	Occupancy and photosensors
Aldo Leopold Legacy Center	High levels of insulation High performance windows Overhangs Increased daylight penetration	Mechanical ventilation with heat recovery Natural ventilation	Ground-source heat pumps Wood burning stoves Earth tubes to preheat or pre-cool	Energy efficient lighting and appliances	39.6-kW PV array	-
IDeAs Z2 Design Facility	Highly rated insulation High efficiency windows Skylights Daylight harvesting	-	High efficiency HVAC system Radiant heating & cooling Ground-source heat pump	Energy efficient lighting and appliances	30 KW roof membrane integrated PVsystem	Occupancy sensors Automatic controls Monitoring equipment
Masdar City Headquarters	No available data					

Table 2.3: Monitored Data

Case Studies	*NZEB according to Design Data*	*NZEB according to Comproved Performance Data*
PVRES	√	*
Solar Harvest	√	√
ZEH Nevada	√	√
Tanno meets Gemini	√	√
Solar Plus House	√	-
Eco- Terra	√	√
Crossway Eco-House	√	√
Adam Joseph Lewis Center	√	√
Science House in Minnesota	√	√
Hawaii Gateway Energy Center	√	√
Aldo Leopold Legacy Center	√	√
IDeAs Z2 Design Facility	√	√
Masdar City Headquarters	√	-
*in this case we have a low energy building, not zero		

2.3 Progress on design strategies and procedures

There are many different ways to achieve net zero energy balance over a year. The simplest of these would be to design ‘as usual’ (or even very inefficiently) in what regards the envelope and the equipment, and then simply add enough local generation to offset the demand/consumption. This strategy would possibly require big size systems for local generation from renewable resources, which tend to be expensive. On the opposite extreme it would be to design an extremely efficient envelope and to select very efficient equipment (both the appliances as the specific energy-services equipment), so that the size and cost of the local generation equipment could be significantly decreased. However, it can be expected that a certain moment in can become more expensive to further decrease the demand than to invest in offset microgeneration. It is thus arguable that there is an optimum trade-off point between decreasing the demand and investing in local generation from renewable resources. It is also arguable that this optimum may very likely depend on the local climatic conditions (Kapsalaki e Leal 2010) e.g., investment in triple low-e glazing is clearly more cost-effective in cold than in mild climates.

This section thus intends to analyze the current design practices of NZEBs, trying to assess to which extent the search for an optimum, or at least the comparison of several alternatives all leading to net-zero balance, has been internalized.

The main line of thinking in the design seems to follow that defends a high level of energy efficiency l (Torcellini, et al. 2006).

Demand side management of energy use in buildings can be controlled through energy efficient construction technologies; this makes the use of renewable energy sources more viable (Kadam 2001). The main general design principles according to this source are:

- Passive solar design, which takes advantage of the heat transfer processes contributing to the thermal balance (Fig.2.13) of a building.
    - Passive solar heating systems, which (in the Northern hemisphere) include south facing glazing to let the sunlight in and thermal mass to absorb, store and distribute heat.
    - High level of thermal Insulation helps the building to preserve the heat and at the same time it prevents the building from releasing the unwanted heat.
    - High airtightness: Infiltration leads to enlarge energy losses; an energy efficient building should have between 0.35 and 0.5 ach^{-1} (air changes per hour) if mechanical ventilation is not present, and below 0.35 ach^{-1} is there is mechanical ventilation.
    - Advanced low-U value and high solar factor windows specified for each climate. E.g. for cold climates, windows with proper coatings that maximize solar heat gains are ideal.
    - Solar protection: Window overhangs, which if properly designed provide shading that prevents solar gain or heat during the summer while during the winter that the sun is lower the solar and heat gains are more. Controllable external shading can also be a good solution.
    - Interior space planning, which involves placing rooms in strategic locations e.g. locating a room that produces the most heat on the coolest side of the house increases the heating/cooling efficiency.
    - Landscaping, which if well designed can leverage different greenery e.g. placement of trees on the east and west side of the building could help keeping it cool during the summer.
- High efficiency lighting.
- High efficiency appliances: the appliances used in NZEBs should be carefully chosen in order to reduce energy consumption as much as possible.
- Energy generation technologies included photovoltaic systems, solar water heating and geothermal heat pumps.

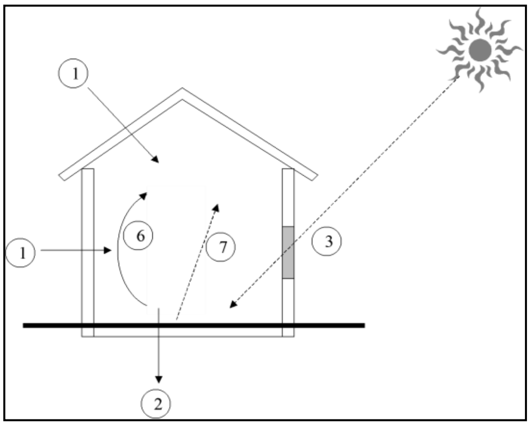


Figure 2.14: Thermal Balance of a building (Hassid e Geros 2006): 1)Heat conduction through walls, roofs and other elements, 2)Heat conduction into the ground from slab-on-grade elements, 3) Solar radiation gains through glazing elements, by transmission through and/or absorption by the glass,4) Internal heat gains – from people, lighting and equipment,5)Latent internal heat gains (losses) through evaporation (condensation) of water involving the latent heat of humidity,6)Convective heat transfer from the building envelope to the air and longwave radiative heat transfer to the upper atmosphere (sky) and clouds, 7)Convective heat transfer from internal surfaces of building elements to indoor air and radiative heat transfer between the internal surfaces of building elements, or absorption of solar radiation and light radiation by internal surfaces, 8)Heat transfer by convection due to infiltration through cracks, to natural ventilation through openings and forced ventilation using fans, 9)Storage in different building elements, both external (walls, roofs, floors) and internal (structures and internal walls), resulting in the attenuation of internal temperature swing,10) Artificial heating and cooling by HVAC equipment.

In a more recent paper Kolokotsa et al (Kolokotsa, Rovas, et al. 2011) suggest:

- Improvement of the building fabric, i.e. improvement of insulation, increase of thermal mass, cools materials, phase change materials, etc.
- Innovative shading devices.
- Incorporation of high efficiency heating and cooling equipment e.g. AC equipment with higher EER (Energy Efficiency Rating), heat pumps combined with geothermal energy or solar collectors, solar air-conditioning, etc.
- Use of renewables (solar thermal systems, buildings integrated photovolatics, hybrid systems, etc.).
- Use of ‘intelligent’ energy management, i.e., advanced sensors, energy control (zone heating and cooling) and monitoring systems.

The concept of mixing increased energy efficiency and reduced energy demand while using carbon emissions free renewables has remained stable; the main change through time was the use of the new technologies available.

Iqbal in 2004 published the description and simulation results of the energy system of a zero energy home in Newfoundland, Canada (Iqbal 2004) following the R2000 standard; a Canadian voluntary standard which exceeds minimum building code requirements related to energy efficiency, indoor air quality and the use of environmentally responsible products and materials (Natural Resources Canada. 2005). The home featured double glazed windows with a U-value of around 1.0

W/m^2°C and a wall U-value equal to 0.2 W/m^2°C while the space and water heating was all electric. It was concluded that all energy requirements for a R-2000 single family home in Newfoundland could be provided by a 10 kW wind turbine system assuming that exchange of electricity with the grid is possible. A sensitivity analysis made to study the effects of variations of wind speed and the building electric load, indicated that zero energy homes based on wind conversion system are feasible in Newfoundland.

Biaou et al in 2006 simulated another zero energy R2000 home in Montreal**;** its low energy design features included: double pane, low-e, argon, insulated spacer window with a U=1.5 W/m^2°C and a SHGC=0.596; wall, roof, and floor U-values respectively equal to 0.2, 3.3 and 0.26 W/m^2°C and a geothermal heat pump to cover the space heating and cooling needs as well as to preheat water (Biaou, Bernier e Ferron 2004). The grid connected NZEB studied was equipped with photovoltaic panels for on-site electrical production. The results of the simulation showed that if the house was electrically heated and cooled, including DHW with an air conditioning with a COP of 3 then the amount of electricity needed by the house would be 24.1 MWh/year. If the same house would be equipped with a 2.5 tons ground-source heat pump, the annual amount of electricity required would drop to 13. 60 MWh; this level of electricity production could be accomplished using 85.4 m^2 of south-facing PV panels tilted at 45°.

Norton & Christensen in 2007 presented the performance results of the NREL/Habitat zero energy home in Denver- Colorado (Norton and Christensen 2008). The construction attributes were: wall, roof and floor U-values equal to respectively 0.14, 0.1 and 0.2 W/m^2°C; low-e high SHGC south windows (U=1.7 W/m^2°C) and low-e (SHGC=0.27) heat mirror north-east-west windows (U=1.3W/m^2°C); 90cm overhangs for summer shading; an energy recovery ventilation system; CFL lights throughout the house and high efficiency appliances; natural gas and electric baseboard heaters for space heating as well as 9m^2 collectors with 757 liters storage tank natural gas tankless water heaters as a DHW backup system; energy was produced by a 4KWp photovoltaic array.

Wang et al in 2009 presented the simulation results of a case study of zero energy house design in the UK (Wang, Gwilliam and Jones 2009). The whole design was a result of a three-stage procedure: 1) analysis of the local climate data; 2) application of passive design methods and advanced façade design to minimize load requirements and 3) the use of a simulation tool (TRNSYS) to investigate various energy efficient mechanical systems and RE systems. They concluded that the optimum design solutions for a house in the UK is: south oriented, wall to window ratio (WWR) equal to 0.4 for the south facade, equal to 0.1 or less for other orientations, and the external walls and roof U-value = 0.1 W/m^2°C. Moreover, it was found that a combined under floor heating and heat pump system can significantly reduce the energy consumption compared with other electric heating or typical radiant heating systems. The optimum solar collector area for solar domestic hot water system with 98 liters/day hot water load is 5m^2, with a mass flow rate of 20 kg/h. The efficiency of the flat-plate solar collector was 35% while the solar fractional energy saving was found 78.5%. Finally, two small wind turbines, with a total rated power of 5.0 kW in total contributed to 91% of annual electricity generation, while a 1.3 kW PV array contributed to 9% of annual electricity generation.

Zhu et al in 2009 compared a conventional house to a zero energy house in suburban Las Vegas in terms of both energy and economics (Zhu, et al. 2009). The ZEHs energy saving features included an insulated slab, a very low attic U-value of only 0.15 $W/m^2°C$, high performance windows, massive exterior walls, water-cooled AC system, a radiant barrier and an on demand gas heater. The roof assembly of the ZEH was north-south oriented for a favorable solar orientation for the roof mounted PV; a DHW pre heater was also used. The radiant barrier and a water-cooled air conditioner were major contributors to the energy savings, while the insulated floor slab and thermal mass walls were not effective as regards energy-conservation during cooling periods; thermal mass walls were also considered too costly. Four items were proved economically valuable: the high performance windows, the compact fluorescent lights, the highly insulated roofs and the air conditioners with water-cooled condensers. Photovoltaic roof tiles produced enough power to cover the use in the ZEH.

Kapsalaki & Leal in 2010 performed a general comparative analysis of seven already existing NZEBs located in Europe and in North America (Kapsalaki and Leal 2010). The case studies under comparison were the Eco Terra house in Quebec-Canada, the Solar Harvest in Boulder- Colorado, the Plus Energy Housing in Weiz-Austria, the Crossway Eco House in Kent-UK, the Solar Plus House in Flieden-Germany, the Mariolopoulos Kanaginis Foundation that is still under construction in Athens-Greece and the PVRES in Lakeland-Florida. They concluded that net zero energy residential buildings located in cities experiencing colder climate conditions are equipped with significantly higher levels of thermal insulation for the walls and the roofs, while NZEBs built for milder climates are less insulated. The same ‘rule’ applies to the types of glazing used; while mostly triple glazed windows are favored for colder climates, double glazed ones are considered sufficient for milder climates. Additionally, NZEBs constructed for cold climate conditions have super air tight envelopes and lower infiltration rates compared with NZEBs of milder climates. As far as the equipment to offset the energy consumption are concerned, it was found that NZEBs constructed for northern colder climates depend less on renewable systems and more on energy efficiency measures while the opposite is observed for NZEBs in milder and sunnier climates.

Table 2.4 summarizes the information above regarding the design process and shows which were the several design alternatives (as regards the envelope, the appliances and lighting, the energy service equipment and the energy generation equipment) ‘tested’ (numbers represent the number of design alternatives variations evaluated); the criteria of choice stated and the tools used are also summarized.

Table 2.4: Intuitive design versus Several Alternatives design

Case Studies	*Several Design Alternatives*					*Criteria of Choice*	*Tools Used*
	Envelope	*Appliances*	*Lighting*	*Energy Service Equipment*	*Energy Generation Equipment*		
Zero Energy Home in Newfoundland	1	1	1	1	2	Optimum sizing of a wind energy conversion system	Hybrid system sizing and simulation software
Zero Energy House (Biaou et al)	1	1	1	2	2	Minimization of electricity required	Simulation Software
NREL/Habitat Zero Energy Home	1	1	1	1	1	Special needs and economics Simple, easily maintained mechanical systems Volunteer-friendly construction techniques	Building optimization and simulation software
Zero Energy House UK	64	1	1	2	2	Minimization of energy requirements	Simulation Software
Zero Energy House vs Conventional	2	1	2	2	2	Energy savings and economic feasibility	Simulation Software

A major conclusion from the table above was that the design alternatives that were examined in all cases include several design approaches as regards the energy generation equipment. Three out of five cases used various options before choosing the energy service equipment e.g. Biaou et al chose a ground source heat pump over an electrically driven air conditioning system while Wang et al also concluded on a heat pump system for heating having already considered other electric heating systems. Two out of five cases examined different alternatives for the envelope e.g. Wang et al tested several U-values, orientations and WWR. Also one out of five cases considered alternatives regarding the lighting e.g. Zhu et al chose highly efficient appliances and CFL lighting over ‘traditional’ ones. In all cases the tools used include building optimization and simulation software while the criteria for the choice of the alternatives analyzed varies from the minimization of the energy requirements, the energy savings, the economic feasibility and the optimum sizing of the microgeneration systems.

In a complementary perspective, Pless & Torcellini in 2010 developed some guiding design principles in order to minimize the energy transfers from generation source to end use and provide long-term maintainability in the built environment (Pless, Shanti e Torcellini 2010).These principles serve for minimizing the overall environmental impact by encouraging energy-efficient building designs, using emissions free renewable energies (RE) and reducing transportation, transmission and conversion losses; they are supposed to be available over the lifetime of a building and are widely available, highly scalable and have high replication potential for future NZEBs (Pless, Shanti e Torcellini 2010). Table 2.5 presents a hierarchy of RE sources in the NZEB context that reflects these principles.

Table 2.5: Hierarchy of RE sources

Option Number	NZEB Supply-Side Options	Examples
0	Reduce site energy use through energy efficiency and demand-side renewable building technologies.	Daylighting; insulation; passive solar heating; high-efficiency heating, ventilation, and air-conditioning equipment; natural ventilation, evaporative cooling; ground-source heat pumps; ocean water cooling
On-Site Supply Options		
1	Use RE sources available within the building footprint and connected to its electricity or hot/chilled water distribution system.	PV, solar hot water, and wind located on the building
2	Use RE sources available at the building site and connected to its electricity or hot/chilled water distribution system.	PV, solar hot water, low-impact hydro, and wind located on parking lots or adjacent open space, but not physically mounted on the building
Off-Site Supply Options		
3	Use RE sources available off site to generate energy on site and connected to the building's electricity or hot/chilled water distribution system.	Biomass, wood pellets, ethanol, or biodiesel that can be imported from off site, or collected from waste streams from on-site processes that can be used on site to generate electricity and heat
4	Purchase recently added off-site RE sources, as certified from Green-E (2009) or other equivalent REC programs. Continue to purchase the generation from this new resource to maintain NZEB status.	Utility-based wind, PV, emissions credits, or other "green" purchasing options. All off-site purchases must be certified as recently added RE. A building could also negotiate with its power provider to install dedicated wind turbines or PV panels at a site with good solar or wind resources off site. In this approach, the building might own the hardware and receive credits for the power. The power company or a contractor would maintain the hardware.

While the discussion so far in this chapter was essentially centered in the design strategies for new buildings, it must be recognized that the approach for retrofitting towards NZEB potentially presents some specificities. These are essentially related to the loss of freedom regarding some design features (e.g. the building shape and solar orientation or, in some cases as in historical areas, even some elements of the envelope) and to the cost-effectiveness of measures regarding the replacement of building components that are still functional. Regarding this last one, the issue is that while for new buildings the added efficiency needs to pay-back only the cost difference between a standard option and a more efficient one, in the case of the replacement of building equipment or envelope components that are still good from the functional point of view, the added efficiency often needs to generate a pay-back for the *whole cost* of the system (and not only for the *cost difference* and in the case of new buildings). Considerations regarding the remaining life-time of these existing equipment or components may sometimes attenuate this added difficulty, e.g. when it becomes clear that the existing components even if still working will/would need a replacement in a near future. The expected result of these added constrains in the retrofitting is that the optimum trade-off point between energy efficiency and local generation will likely be reached at a higher level of consumption (and consequently of local generation) than in the case of new buildings.

3 Methodology for detailed energy demand and supply characterization & economic evaluation

This chapter addresses the calculation methodologies that were chosen or developed to characterize the energy demand of the building, as well as the microgeneration needed to offset that demand and the main economic indicators of each design alternative.

On the demand side, the energy uses identified as typical of residential buildings are: space heating & cooling, water heating, lighting, cooking, refrigeration and appliances (dishwasher, oven/cooker, TV, PC and clothes dryer). The energy needs for cooking, lighting and refrigeration and appliances are directly estimated from the average power of the equipment and the assumed weekly/yearly usage profile.

Regarding the uses for heating and cooling – as well as, to some extent, for domestic hot water, their calculation depends very significantly on the characteristics of the envelope, the climate and internal gains and patterns of use of the building. Specific calculation methodologies were thus chosen and implemented for determining the needs of useful (thermal) and of final (delivered) energy under nominal conditions.

Estimating the energy needs for heating and cooling in buildings can be done through dynamic or through quasi steady state methods. Dynamic methodologies calculate the heat balance with short time steps and account for the heat storage in building elements in a detailed way, while quasi steady state methods calculate the heat balance over a sufficiently long time (typically a month or a whole season) and without a detailed consideration of the effects of thermal inertia (ISO-13790 2008). Dynamic methods in general are more precise compared to quasi steady state methods, but at the same time, demand much more detailed input data. Often this input data is not available at an early design stage. Dynamic methods usually also need considerably more computation time to run. Although thus is not a problem when analyzing a few design alternatives, when it becomes necessary to analyze thousands of them it could be a significant barrier, maybe even possible to overcome. Considering that the goal of this thesis is to provide a strategic assessment at the initial design phase, with emphasis in comparing many alternatives with only the essential data, the choice that fits better this purpose is the quasi-static methods.

Regarding the quasi steady state methods, an important reference is the EN ISO 13790 (EN-ISO-13790 2008) (steady state methods) where the dynamic effects are taken into account by an empirically determined gain and loss utilization factor. A fully-operationalized method based on the ISO 13790 (although chronologically preceding it) is the Portuguese thermal building code RCCTE (Portuguese Government 2006) The RCCTE, a national building regulation, was supported by draft versions of the ISO13790 in its early stages of development. It has been validated and found to correlate well to heating and cooling loads results obtained from detailed dynamic simulation (Leal, Ferreira and Oliveira Fernandes 2008) .

Besides the annual energy needs for heating and for cooling, peak loads estimation is also necessary so as to account for the capacity of the equipment, in order to have appropriate cost-estimates. Design heating loads calculations was based on a steady-state methodology proposed by ASHRAE (ASHRE 2005). While more advanced methodologies nowadays exist, this methodology presents a good balance between accuracy and ability to run fast and with little input data. For the cooling peak load, the existing methods require an accounting of the thermal inertia of the building in a way that requires detailed building data, as well as some dynamic accounting. E.g., ASHRAE methods like the heat balance (HB) or the Radiant Time Series (RTS) methods (ASHRE 2005) require a detailed accounting of the type of flooring, layers of the walls, etc. They also imply accounting for the "thermal history" of the building during some hours. For this work, in which the goal is not to size the cooling system but just to have a rough indication of its cost, it was considered that the ratio of complexity to relevance did not justify its adoption, and instead a new method was developed as will be presented in sub-chapter 3.5.Calculation methodologies are also adopted to address the renewable microgeneration systems necessary to offset the energy use. Two options are available: Photovoltaic panels (PV) and wind turbines (WT).

The chapter ends with the description of the methodologies chosen in order to weight the financial impact of each combination of the design variables, in terms of first cost and in terms of life cycle costs.

3.1 Energy uses in residential buildings

Characterizing the energy demand of a residential building involves firstly identifying which are the specific energy end uses involved. According to the fourth assessment report of the IPCC the major energy end uses in the residential sector include the following: space heating & cooling, water heating, refrigeration, cooking and lighting (Levine, et al. 2007). The pie charts of figure 3.1 & 3.2 show the energy use breakdown of the residential sector in Europe in 2007 and the United States in 2005 respectively.

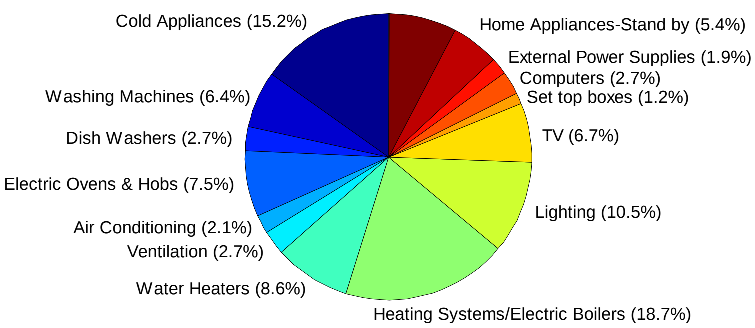


Figure 3.1: Breakdown of EU-27 residential electricity consumption, year 2007 (Bertoldi e Atanasiu 2009)

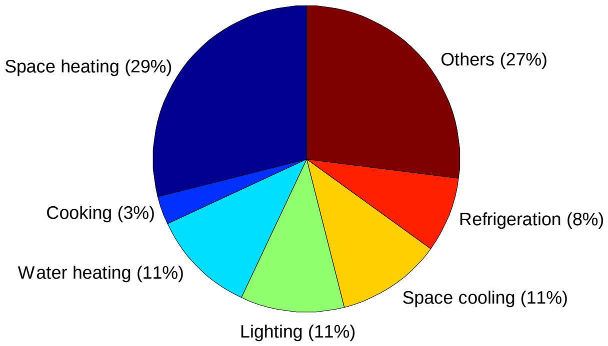


Figure 3.2: Breakdown of residential sector energy use in United States (2005 (Levine, et al. 2007)

Once the major end uses are identified, the electricity and gas consumption profiles can be assessed and the overall domestic load can be characterized. In this way the needs for imported energy can be estimated and specifically in the case of NZEBs the needs of microgeneration to exported an equivalent amount of energy to that imported can be determined.

For the purpose of this work, all major end uses discussed above were taken into account individually, with the exception of refrigeration and cooking, which were considered as one under the 'tag' appliances, together with end uses related to multimedia. A detailed characterization of these uses will be shown in subchapter 4.1 (table 4.1).

3.2 Useful heating needs

The buildings´ annual useful energy need for space heating is calculated as given by equation 3.1 (Portuguese Government 2006). The use of this equation has implicit that the building is maintained at a comfort temperature continuously during the winter.

$$HN_{usf} = (Q_{env} + Q_{air} - n_h * Q_g)/A \qquad [kWh/m^2.year] \qquad eq.3.1$$

Where:

HN_{usf} is the annual useful energy need for space heating (kWh/m^2.year).

Q_{env} is the heat loss through the envelope due to conduction (kWh/year) (heating season).

Q_{air} is the heat loss resulting from the air renewal (kWh/year) (heating season).

n_h is the gain utilization factor due to the effect of thermal inertia (dimensionless).

Q_g is the total heat gain due to lighting, equipment and occupants, plus the solar gains through the glazed elements (kWh/year)(heating season).

A is the buildings´ useful-heated area (m^2).

3.2.1 Heat loss through the envelope

The heat loss through the envelope Q_{env} is calculated as the result of the sum of the heat losses through the walls (Q_{walls}), roof (Q_{roof}) and glazed areas (Q_{glz}) in contact with the exterior and the heat loss through the walls in contact with non-heated areas and/or adjacent buildings (Q_{adj}) and is expressed in kWh/year. These losses result from the temperature difference between the internal and external building environment. Consequently:

$$Q_{env} = Q_{walls} + Q_{roof} + Q_{glz} + Q_{adj} \qquad [kWh/year] \qquad eq.3.2$$

3.2.1.1 Elements in contact with the exterior

The elements in contact with the exterior include walls, roof and glazed areas. The heat loss resulting from the walls (Q_{walls}) is expressed in kWh/year and is equal to:

$$Q_{walls} = A_{walls} * (U + \Delta U) * HDD * 0.024 \qquad [kWh/year] \qquad eq.3.3$$

Where:

A_{walls} is the external wall area (m^2).

U is the thermal transmittance (U- Value) of the wall area (W/m^2.^{0}C).

ΔU is a default surcharge taking into account the effect of thermal bridges in (W/m^2.^{0}C) (EN-ISO-13790 2008).

HDD are the heating degree days per year during the heating season; they were calculated using the method of Eurostat (Gikas e Keenan 2006).

The heat loss resulting from the roof (Q_{roof}) is also expressed in kWh/year and is given by the following equation:

$$Q_{roof} = A_{roof} * (U + \Delta U) * HDD * 0.024 \qquad [kWh/year] \qquad eq3.4$$

With:

A_{roof} the roof area (m^2).

Accounting for the thermal bridges was done following the methodology of the International Standard Organization (EN-ISO-13790 2008), according to which the U-value of each opaque construction can be corrected with a surcharge that serves as a default effect of thermal bridges (EN-ISO-13790 2008). Table 4.3 of chapter 4 shows the default values that were taken into account in this work.

The glazed elements of the building induce a heat loss given by:

$$Q_{glz} = A_{glz} * U_{gl} * \ HDD * 0.024 \qquad \textit{[kWh/year]} \qquad eq.3.5$$

Where:

A_{glz} is the external glazed area (m^2).

U_{glz} is the thermal transmittance (U- value) of the glazed area (W/m^2.^{0}C).

3.2.1.2 Elements in contact with non- heated areas and/or adjacent buildings

The heat loss caused by the temperature difference to adjacent buildings and/or non-heated areas, is defined by equation 3.6 that follows:

$$Q_{adj} = (A_{adj} + A_{int}) * U * \tau * HDD * 0.024 \qquad \textit{[kWh/year]} \qquad eq.3.6$$

Where:

A_{adj} is the wall area in contact with adjacent buildings (m^2).

A_{int} is the wall area in contact with non-heated spaces (m^2).

U is the U- Value of the wall (W/m^2. ^{0}C).

τ is a coefficient of thermal loss reduction (-).

The value of τ represents the ratio of the temperature difference between the indoor and the outdoor temperature to the temperature difference between the interior and the non-heated space. For the purpose of this work, at the level of strategic assessment in the pre-design phase, a constant value equal to 0.6 was adopted.

3.2.2 Heat loss resulting from the air renewal

Heat loss during the heating season can be calculated according to equations 3.7 and 3.8, expressed in kWh/year:

$$Q_{air} = V * R_{ph} * \left(\rho * \frac{C_p}{3600}\right) * HDD * 0.024 \qquad \textit{[kWh/year]} \qquad eq.3.7$$

And:

$$R_{ph} = \frac{\dot{V}_{NV}}{V} + \frac{\dot{V}_{MV}}{V} \qquad [ach^{-1}] \qquad eq.3.8$$

Where:

V is the volume of the building (m^3).

R_{ph} is the sum of the rate of mechanical ventilation and infiltration rates (ach^{-1}).

ρ is the air density (kg/m^3).

C_p is the specific heat of air (J/kg.^{0}C).

$\dot{V_{NV}}$ is the air flow rate due to natural ventilation (m^3/h).

$\dot{V_{MV}}$ is the air flow rate due to mechanical ventilation (m^3/h).

When there is a heat recovery system , eq.3.8 becomes:

$$R_{ph} = \frac{\dot{V_{NV}}}{V} + \frac{\dot{V_{MV}}}{V} * (1 - n_{HR}) \qquad [ach^{-1}] \qquad eq.3.9$$

Where

n_{HR} is the efficiency of the heat recovery system (-).

3.2.3 Thermal heat gains

In the RCCTE/ISO13790 methodology, the heat gains of the building in the heating season include two components as given by the following equation:

$$Q_g = Q_{o,e,l} + Q_{sol} \qquad [kWh/year] \qquad eq.3.10$$

Where:

$Q_{o,e,l}$ is the heat gain resulting from lighting, equipment & occupants (kWh/year).

Q_{sol} is the solar gain through the glazed areas (kWh/year).

3.2.3.1. Thermal internal gains (heating season)

The thermal internal gains from occupants, lighting and equipment are given as follows:

$$Q_{o,e,l} = q_i * A * M * 0.72 \qquad [kWh] \qquad eq.3.11$$

Where:

q_i is the average thermal internal gains (W/m^2).

M is the duration of the heating season (months).

0.72 accounts for the conversion of 1 month into hours and then of the overall result into kWh

In subchapter 4.4.10, an occupancy profile is implemented in order to account for the thermal internal gains resulting from occupants.

3.2.3.2. Thermal solar gains

The thermal solar gains from the glazed elements are equal to:

$$Q_{sol} = A_{ef} * R_{sol} * M \qquad [kWh] \qquad eq.3.12$$

Where:

A_{ef} is the collective effective area of each element (m^2).

R_{sol} is the average solar energy impinging on a vertical surface facing the south during the heating season in kWh/m^2 per month.

The collective effective area depends on: the orientation factor (X_k) for each k orientation; the obstruction factor (F_s) or shading reduction factor representing the reduction of the solar energy impinging on the glazed area due to permanent shading caused by different obstacles like buildings, orography, vegetation and other parts of the building itself; the frame area fraction (F_g), ratio of the overall projected area of the glazed element to the projected frame area; a correction factor (F_w) representing the reduction of the solar energy due to the variation on the glass properties with the angle of incidence of the direct solar radiation; the window area ($A_{W(i,k)}$) of each element i; the solar factor of the glazing (g). Consequently:

$$A_{ef} = F_w * F_s * F_g * g * \sum_k X_k \sum_i A_{W(i,k)} \qquad [m^2] \qquad eq.3.13$$

According to the RCCTE the product of $F_w * F_s * F_g$ can be considered equal to 0.46 in the simplified method (Portuguese Government 2006).

3.2.4 Gain utilization factor for heating

When a building has low thermal inertia, it can happen that solar or internal heat gains concentrated in a short period reach the indoor air very quickly and cause overheating. In such a case part of the gains lose their useful effect. In RCCTE this accounting is done through a gain utilization factor for heating, whose value depends on the class of thermal inertia of the building. The dimensionless gain utilization factor for heating (n_h) is a function of the heat-balance ratio and a numerical parameter that depends on the building inertia (a), as given by an expression that is a function of γ_h.

$$\gamma_h = \frac{Q_g}{Q_{walls} + Q_{roof} + Q_{adj} + Q_{glz} + Q_{air}} \qquad eq.3.14$$

Then, for $\gamma_h \neq 1$

$$n_h = \frac{1 - {\gamma_h}^{\alpha}}{1 - {\gamma_h}^{\alpha+1}} \qquad eq.3.15$$

And for $\gamma_h = 1$

$$n_h = \frac{a}{a+1} \qquad eq.3.16$$

The numerical parameter a takes different values of 1.8, 2.6 and 4.2 for buildings with low, medium and high inertia respectively (Portuguese Government 2006).

3.3 Peak heating needs

Peak design heating load calculations determine the maximum rate of mechanically supplied heating energy needed during the year needed to keep the indoors at the prescribed comfort temperature (20ºC in the RCCTE). A possible way of estimating this load is to perform the heat balance for the coldest hour of the year, assuming no internal and no solar heat gains, under steady state conditions (ASHRE 2005). It is known that by ignoring thermal inertia effects, this method leads to some overestimation of the heating needs. On the other hand, it is also known that designers usually like to keep some safety margin for these equipment. Because of this and, also because of the good compatibility of the method with the unavailability of detailed data in the early design stages, the method was adopted. Space heating load (KWp_h) was calculated by computing the heat transfer rate through the building envelope elements plus the heat that is required due to outside air infiltration (ASHRE 2005), through the following equation:

$$KWp_h = \left[(U + \Delta U) * A_{walls} + (U + \Delta U) * A_{roof} + U_{glz} * A_{glz} + 1.23 * 10^3 * \frac{V}{3600} * R_{ph}\right] * \Delta T \qquad eq.3.17$$

Where:

ΔT_1 is the temperature difference between the indoor design temperature and the dry bulb temperature corresponding to 99.6% annual cumulative frequency of occurrence in the heating season (ºC).

The number 1.23 represents the air heat sensible factor (W/m^3.s.^{0}C).

3.4 Useful cooling needs

The buildings´ annual useful energy need for space cooling (CN_{usf}) is calculated as given by equation 3.18 expressed in kWh/m^2.year:

$$CN_{usf} = Q_{gn,c} * \frac{1 - n_c}{A} \qquad [kWh/m^2.year] \qquad eq.3.18$$

Where:

$Q_{gn,c}$ are the internal and solar heat gains (kWh/year).

n_c is the loss utilization factor (-).

A is the useful area in (m^2).

As happened for heating, the equation above implies that the calculation is made in the assumption that the space is maintained continuously within the set-point during the whole cooling season. The next subsections detail each of the heat gains type.

3.4.1 Heat sources

Heat sources account for internal gains, solar gains through transparent elements (windows, skylights) and solar gains through opaque elements (walls, roof), according to the following equation:

$$Q_{gn,c} = Q_i + Q_s + Q_{opq} \qquad [kWh] \qquad eq.3.19$$

Where:

Q_i are the internal heat gains caused by occupants, equipment and lighting(kWh).

Q_s are the solar gains of the transparent surfaces-glazed areas (kWh).

Q_{opq} are the solar gains of the opaque surfaces(kWh).

3.4.1.1 Thermal internal heat gains (cooling season)

The thermal internal gains during the cooling season resulting from occupants, lighting and equipment are a function of the average thermal internal gains q_i in Watts per square meters and the useful area A, expressed in Kilowatt-hours and are given as follows (Portuguese Government 2006):

$$Q_i = q_i * A * 2.928 \qquad [kWh] \qquad eq.3.20$$

The factor 2.928 accounts for the conversion of 4 months of cooling into hours and then the total result to kWh.

3.4.1.2 Solar gains from transparent surfaces

Solar gains from the glazed elements of the building (Q_s) are calculated according to equation 3.21 that follows (Portuguese Government 2006):

$$Q_s = \left(F_w * F_s * F_g\right) * g_c * \sum_k R_k \sum_i A_{wi} \qquad \textit{[kWh]} \qquad \textit{eq.3.21}$$

With:

R the integrated solar radiation during the cooling season for each k orientation (kWh/m^2).

g_c the solar factor of the window assembly, computed as the weighted average of 30% of the g-value of the glazing plus 70% of the g-value of the window considering the blinds closed.

3.4.1.3 Solar gains from opaque surfaces

Solar gains from opaque surfaces are a function of the wall area of each element (A_i) , the integrated solar radiation during the cooling season for each orientation (R_k) , the U-value of the opaque element and the absorption coefficient (a_c) ; they are given by the following equation:

$$Q_{opq} = a_c * U * 0.04 * \sum_k R_k \sum_i A_i \qquad \textit{[kWh]} \qquad \textit{eq.3.22}$$

3.4.2 Loss utilization factor

The loss utilization factor due to the thermal inertia, which reduces the total seasonal heat gains, is calculated as follows:

$$\gamma_c \neq 1 \;\; => \;\; n_c = \frac{1 - {\gamma_c}^{\alpha}}{1 - {\gamma_c}^{\alpha+1}} \qquad \textit{eq.3.23}$$

$$\gamma_c = 1 \;\; => \;\; n_c = \frac{\alpha}{\alpha + 1} \qquad \textit{eq.3.24}$$

With:

$$\gamma_c = \frac{Q_{gn,c}}{2.928 * (T_{in} - T_{out}) * (A_{ext} * U + A_{roof} * U + A_{glz} * U_{glz} + V * R_{ph} * 0.34)} \qquad \textit{eq3.25}$$

Where:

T_{in} is the indoor reference temperature (^{0}C).

T_{out} is the average outdoor temperature during the cooling season(^{0}C).

3.5 Peak cooling load

Peak design cooling load calculations determine the maximum rate of cooling energy transfer needed at any point during the cooling season in order to maintain the indoor temperature below the cooling set point. Typically, peak cooling load computing is much more complicated than peak heating load computing, since in this case the inertia effects are more important and usually must be taken into account. However, since a dynamic method would not be compatible with the requirements of an algorithm that must be very fast and require little input data, a method was developed based on steady state, under the most severe conditions of the year (hottest day and highest outdoor temperature), in analogy with the method of the heating season. Due to the fact that the above method is very likely to overestimate the cooling load, a correction factor will be introduced, based on a comparison with the results of dynamic simulation for a numerous set of buildings. Space cooling load was therefore calculated in a first phase by computing the heat transfer rate through the building envelope elements plus the heat that is transferred due to outside air infiltration, the internal gains (occupants, equipment and lighting) and the solar heat gains through the glazed areas, in a steady-state method. The contribution of each building element is presented below together with the equation used to calculate the peak cooling needs, both expressed in Watts:

- Walls, roof, windows : $U * A * \Delta T$
- Infiltration: $1.23 * 10^3 * R_{ph} * \frac{V}{3600} * \Delta T$
- Internal gains: $q_i * A * \Delta T$
- Solar gains: $F_g * g_c * S_r * A_{glz} * \Delta T$

$$KWp_c = \left[(U + \Delta U) * A_{walls} + (U + \Delta U) * A_{roof} + U_{glz} * A_{glz} + 1.23 * 10^3 * \frac{V}{3600} * R_{ph} + q_i * A + F_g * g_c * S_r * A_{glz}\right] * \Delta T \qquad eq.3.26$$

With:

ΔT_2 the temperature difference between the dry bulb temperature corresponding to 99.6% annual cumulative frequency of occurrence (cooling season) and the inside design temperature (^{0}C).

S_r the maximum solar insolation (W/m^2).

In a second stage of the method, calculation results using equation 3.26 were compared to peak cooling load calculation that derived from dynamic computer simulation. Calculation &

simulation with ESP-r (ESRU 2002) was conducted for six climate scenarios (Stockholm, London, Paris, Prague, Rome and Lisbon) and six design alternatives. The graph of figure 3.3 shows the result of the conducted calculations according to equation 3.5a versus the results of the dynamic simulations with ESP-r.

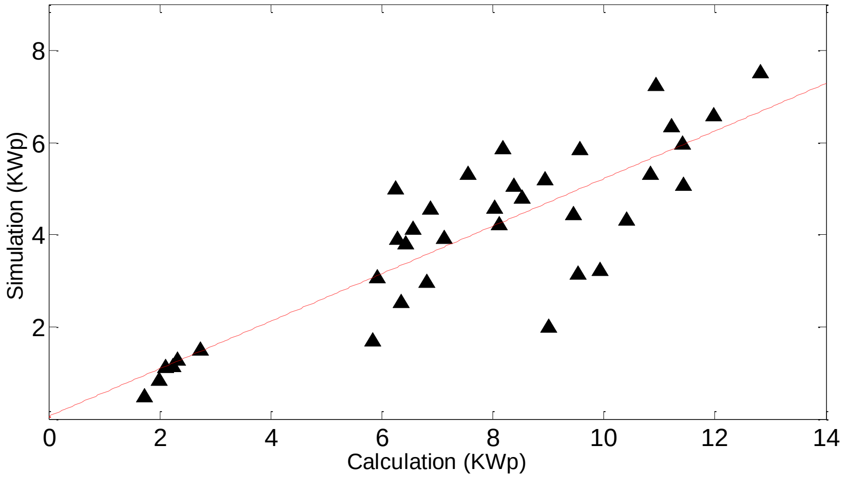


Figure 3.3: Linear regression of the peak cooling load calculation versus simulation

The linear regression equation is equation 3.27:

$$y = 0.5159x + 0.0593 \qquad eq.3.27$$

As expected, the values obtained by the steady-state method were significantly overestimating the peak load, as the detailed simulation results in values around half of those from the simple method. The coefficient of determination of the correlation has a reasonable value of 0.72. The calculation of the peak cooling load KWp_c was therefore corrected, resulting in equation 3.28.

$$KWp_{c,final} = 0.0593 + 0.5159\left[(U + \Delta U) * A_{walls} + (U + \Delta U) * A_{roof} + U_{glz} * A_{glz} + 1.23 * 10^3 * \frac{V}{3600} * R_{ph} + q_i * A + F_g * g_c * S_r * A_{glz}\right] * \Delta T_2 \qquad eq.3.28$$

3.6 Useful energy needs for domestic hot water (DHW)

Useful energy needs for domestic hot water (DHW_{usf}) were estimated based on the following equation (Portuguese Government 2006):

$$DHW_{usf} = \frac{HW_N * C_{pw} * \Delta T_{DHW} * 365}{3600000} \qquad [kWh/m^2.year] \qquad eq.3.29$$

Where:

HW_N are the needs for hot water per day (lt/day.person) (The RCCTE considers a default value of 40 liters per person).

C_{pw} is the specific heat of the water which is equal to 4187 (J/kg.K).

ΔT_{DHW} is the temperature difference between hot water furnished and the water entering the system to be heated (^{0}C).

The RCCTE assumes a temperature difference of 45^{0}C. For the purpose of this work , three temperature differences were assumed, depending on the climate (for the climate of Stockholm the temperature difference considered is equal to 55^{0}C, for the climates of Brussels, Wien and Venice 50^{0}C and for the climates of Porto, Lisbon, Funchal, Iraklion and Athens is equal to 45^{0}C).

3.7 Total needs of final energy

This chapter assesses the needs of final energy, which is the amount of electric, gas or other energy carriers need to provide the useful energy estimated in the previous sub-chapter.

The needs of final energy for heating, cooling and DHW were estimated by dividing the useful energy needs by the efficiency of the systems providing each of the services, according to equations 3.30, 3.31 and 3.32 respectively:

$$HN_{final} = \frac{HN_{usf}}{n_{HS}} \qquad \textit{[kWh/year]} \qquad \textit{eq.3.30}$$

$$CN_{final} = \frac{CN_{usf}}{n_{CS}} \qquad \textit{[kWh/year]} \qquad \textit{eq.3.31}$$

$$DHW_{final} = \frac{DHW_{usf}}{n_{DHWS}} \qquad \textit{[kWh/year]} \qquad \textit{eq.3.32}$$

Where:

n_{HS} is the efficiency of the heating system (-)

n_{CS} is the efficiency of the cooling system (-)

n_{DHWS} is the efficiency of the DHW system (-)

The final energy needs (electricity) for driving the fans of mechanical ventilation during the heating season were computed as given by the equation 3.33 (Portuguese Government 2006).

$$MV_{final} = P_{MV} * 24 * 0.03 * M \qquad \textit{[kWh/year]} \qquad \textit{eq.3.33}$$

P_{MV} is the power consumption of the mechanical ventilation system considering continuous ventilation (24 hours per day).

Finally, as regards the final energy needs for lighting and appliances, default annual electricity consumption values were considered (chapter 4).

3.8 Thermal solar collection for DHW

The annual energy produced by the thermal solar collector was estimated as given by the equation that follows (Souza 2012).

$$AESC = \{E_{sc} * A_{SC} * n_{SC} * n_0 * 365 - a_1 * (T_m - T_a) - a_2 * (T_m - T_a)^2\} * 10^{-3} \quad [kWh] \qquad eq.3.34$$

With:

E_{sc} the solar irradiation (Wh/m^2.day).

n_{SC} the solar system efficiency (-).

n_0 the zero loss efficiency(-).

a_1 the 1st order heat loss coefficient (W/^{0}C).

a_2 the 2nd order heat loss coefficient (W/^{0}C^2).

T_m the collectors mean fluid temperature (^{0}C).

T_a the average ambient air temperature (^{0}C).

A_{SC} the collectors area (m^2).

For this study, the values considered are presented in table 3.1.

Table 3.1: Data for the calculation of the annual energy produced by the thermal collector

Data needed	Values
Solar system efficiency n_{SC}	0.86
Zero loss efficiency n_0	0.7
1st order heat loss coefficient	5
2nd order heat loss coefficient	0.05
Collectors mean fluid temperature T_m	60^{0}C

The annual energy incident on the solar collector $\mathrm{E_{sc}}$ was estimated using the resource quantification methodology for PV of chapter 3.9 (equation 3.9c) ahead.

3.9 Microgeneration from PV

One of the key-features of NZEBs is the fact that they have on-site equipment which “produce” locally energy carriers that they can export and offset the imports. In practice, the only energy carrier that is relatively easy to export is electricity. The mainstream microgeneration technology is Photovoltaic panels, which is addressed in this subchapter.

The starting points of the method are the global horizontal & diffuse solar radiation data of climatic files (METEOTEST 2009).

For each one of the locations the first step was to compute the declination (ordinal date (N) dependent) (Couper 1969). A second step included the calculation of the sunset hour angle (ω_{ss}) and the sunset hour angle for a tilted surface ($\omega_{ss}^{'}$) (Creider, Curtiss e Rabl 2005).

According to Liu and Jordan (Liu e Jordan 1960) the ratio of the average daily beam radiation on a tilted surface to that on a horizontal surface for a month, can be estimated by assuming that it has the value which would be obtained if there were no atmosphere (Duffie e Beckman 1980). For surfaces that are sloped toward the equator in the northern hemisphere the above ratio is given by:

$$R_b = \frac{\cos(\varphi - \beta) * \cos\delta * \sin H_0^{'} + \frac{\pi}{180} * H_0^{'} * \sin(\varphi - \beta) * \sin\delta}{\cos\varphi * \cos\delta * \sin H_0 + \frac{\pi}{180} * H_0 * \sin\varphi * \sin\delta} \qquad eq.3.35$$

With:

$H_0^{'}$ the actual sunset sunrise hour angle equal to the minimum between the sunset hour angle (ω_{ss}) and the sunset hour angle for a tilted surface ($\omega_{ss}^{'}$) (Creider, Curtiss e Rabl 2005).

R_b the ratio of the average daily beam radiation on a tilted surface to that on a horizontal surface.

φ the latitude of the location.

β the optimum inclination-slope of the PV module which was obtained from the PVGIS website (PVGIS 2008).

δ the declination.

The third and final step of the calculation methodology involves the calculation of the ratio of the total radiation on the tilted surface to that on the horizontal surface (R) from equation 3.36.

$$R = R_b * \left(1 - \frac{\dot{D_H}}{\dot{G_H}}\right) + \frac{\dot{D_H}}{\dot{G_H}} * \frac{1 + \cos\beta}{2} + \rho * \frac{1 - \cos\beta}{2} \qquad eq.3.36$$

With:

ρ_0 the albedo.

$\frac{\dot{D_H}}{\dot{G_H}}$ the ratio of the diffuse horizontal radiation to the global horizontal radiation.

The yearly solar radiation incident on the PV is first calculated at an hourly basis, then added to result in monthly and yearly totals. After the previous variables have been calculated, the daily energy produced (Wh) by the PV (E_{PV}) is given as follows:

$$E_{PV} = R * G_H * n * A_{PV} \qquad [Wh] \qquad eq.3.37$$

Where:

n is the panel efficiency.

A_{PV} the panel area (m^2).

The quantification of the electricity produced by a PV system over a year is used for economic aspects but also to find the size of the PV system that is needed for zero yearly balance and thereafter estimate its initial cost.

3.10 Microgeneration from wind

Although PV is currently the mainstream methodology for producing and exporting electricity in buildings, significant developments have occurred in micro wind turbines, and it is considered in this study. This chapter thus describes the quantification methodology that was used for the application as regards the wind energy supply, for the cases when the offset of the energy needs is done at least partially with this technology.

While the method followed so far for both the thermal collector and photovoltaics made use of yearly data (temperatures and solar irradiation), the quantification methodology for the wind energy supply was made with hourly wind velocity data. In this case this was done because it was critically necessary to ensure a good accuracy of the calculation, even if this means that the optimization tool will take significantly more time to run when offset with wind turbines is allowed.

Starting with the wind velocity existing in climatic files (v_0), which is measured at 10 meters of height, it is necessary to correct it for the effects of drag and turbulence caused by ground obstructions.

More specifically, in order to compute-correct wind velocity at any height, equation 3.38 (Manwell, McGowan e Rogers 2002) was used as given by:

$$v = ({}^{h}/_{h_0})^{a_r} * v_0 \qquad [m/sec] \qquad eq.3.38$$

Where:

h is the height at which the wind velocity v is being computed-corrected (m).

h_0 is the corresponding height (10m) of the initial wind speed measurements (v_0) (m).

a_r is a dimensionless roughness coefficient which depends on the landscape (Table 3.2).

Moreover, in order to account also for the wind speed reduction due to turbulence another correction was considered necessary given by equation 3.39 (Givoni 1998):

$$v_1 = v * (1 - 0.01b) \qquad [m/sec] \qquad eq.3.39$$

With:

b the percent turbulence coefficient, which depends on the site type (Table 3.2)

v_1 the corrected wind speed (m/sec).

Table 3.2: Roughness and percent turbulence coefficients (Kelleher e Ringwood 2008)

Site Type	a_r	b
Rural	0.01	0
Rural with obstacles	0.3	10
Urban	0.7	30

The effective power P for any given wind speed is given by the graphs of figure 3.4 for three reference wind turbines, with rated powers of 400 Watts, 1.8 Kilowatts and 2.2 Kilowatts. For the calculation, these curves were approached to step functions with a width of 1m/sec.

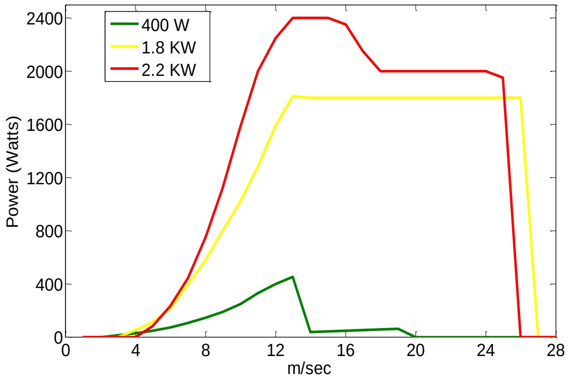


Figure 3.4: Wind turbine power curves (TWTC 2004), (NHEOLIS 2009), (Southwest wind power 2009)

The corrected wind speed measurements were ‘converted’ to total annual power output (TPO) for three available types of wind turbines with a rated respectively, according to equation 3.40 :

$$TPO = \sum_{v=1}^{28} n_v * P(v) \qquad [kWh] \qquad eq.3.40$$

Where:

n_v is the number of hours per year in which the velocity has approximately the value v.

$P(v)$ is the power output of the wind turbine when the velocity has the value v.

The choice of these wind turbines with the specific rated power was made upon consideration of their residential application and use and are considered to be typical for roof top turbine installations.

3.11 Economic indicators

The commonly used indicators for the economic evaluation of a project, which seem sensible for the purpose of this work, are the Life Cycle Cost (LCC) & the Payback Period (PB) methods. For the purpose of this work, these two "discount" techniques were used in order to evaluate the economic performance of the design solutions. The equations used in order to calculate the LCC and the PB are given as follows (Geros 2006):

$$LCC = \sum_{j=0}^{N} (C_j - B_j)/(1+d)^j \qquad \text{eq.3.41}$$

$$\sum_{j=1}^{PB} \frac{B_j - C_j}{(1+d)^j} = C_0 \qquad \text{eq.3.42}$$

Where:

C_j is the cost in year j for the system being evaluated.

C_0 is the initial cost for the system being evaluated.

B_j are the benefits (positive cash flows) in year j for the system being evaluated.

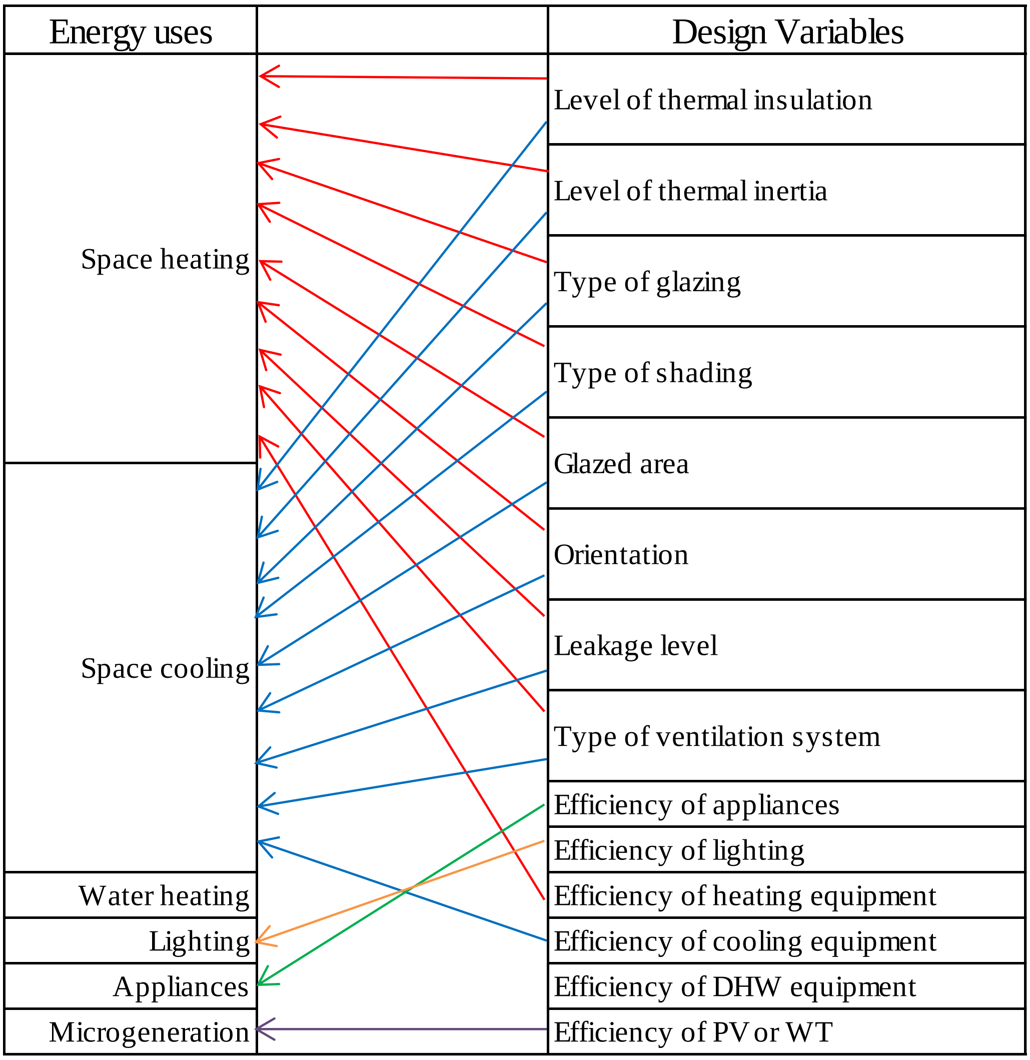
d is the discount rate.

4 Analysis and sorting of design alternatives (application tool)

4.1 Building design variables and design alternatives

In the beginning of chapter 3 the energy end uses that shape the energy demand of a residential building were identified and characterized. They were listed as space heating & cooling, water heating, lighting, cooking, refrigeration and appliances. Each end use can be influenced by a number of design variables, and typically each design variable has a wide range of possible values or choices. Table 4.1 that follows shows the dependence of each end use on each design variable.

Table 4.1: Energy uses versus design variables



Each combination of design variables will lead to a certain total yearly energy demand, which in turn will require a certain amount of building-integrated renewables to offset the demand on a yearly balance basis. It therefore is of interest to characterize the full spectrum of possible combinations of variables, in order to identify those that have expected lower initial costs and those that have lower life-cycle costs, but also how distant from the best some other solution may be. The expression ‘Building Design Alternative’ will be adopted here as referring to a certain combination of values or options for the variables. If two combinations differ in at least one value/option of a variable, then they are considered as different design alternatives.

In principle it would be possible to adopt intelligent search algorithms with techniques based on traditional optimization - linear or nonlinear depending on the problem - or stochastic optimization approaches to search for the ‘best’ design alternatives . Another possibility, compatible with the goals of this thesis, is to discretize the search space by discretizing first each variable, and then compute the results for all the possible building design alternatives. This has the advantage of characterizing the full spectrum of design possibilities rather than focusing the discussion on the “optimum”. This also allows to assess how “far from optimal” a given solution chosen by the designer for non-energy reason may be. To follow this option, the number of possible values or options for each variable to be set in the discretization process must be selected carefully to achieve a good balance between ensuring enough diversity in the range of the variable and not inflating unnecessarily the search space. The next section provides a description of the discretization adopted for each variable

4.2 Discretization of the design variables

4.2.1 Thermal insulation level

Thermal insulation was characterized by four different levels - alternatives. These levels of thermal insulation are represented by the U-value, which ranges from 0.2 W/m^2.K (e.g. AECB Silver Standard requirement: U ≤0.24 W/m^2 K (AECB 2006)) up to 0.8 W/m^2.K, which is the minimum level of thermal insulation required in practice to comply with the performance requirements of the Portuguese thermal building regulation (Portuguese Government 2006). An intermediate U-value of 0.35 W/m^2.K was also considered, which is the maximum limit of wall insulation in compliance with the part L of the 2006 Edition of the Building Regulations for England and Wales (ODPM 2006). Finally, an option of ‘no insulation’ was also considered, with a U-value of 3 W/m^2.K.

Besides the U-Value itself, in fact each alternative is translated through a corrected U-value which is the sum of the U-value plus a default surcharge ΔU taking into account the effect of thermal bridges according to the ISO 13790:2008 (ISO-13790 2008) shown in table 4.2. Table 4.3 summarizes the details of each alternative in terms of thermal insulation.

Table 4.2: Default values for the surcharge on the U-value to take into account the effect of the thermal bridges (ISO-13790 2008)

Mean U-Value of the opaque part of the construction, excluding framed panels and ground floor (W/m^2.C)	ΔU (W/m^2.C)
$U \geq 0.8$	0.0
$0.4 \leq U < 0.8$	0.05
$U < 0.4$	0.1

Table 4.3: Corrected values of thermal insulation taking into account the effect of thermal bridges

Alternative	Regular U-Value (W/m^2.C)	Surcharge (W/m^2.C)	Corrected U-Value (W/m^2.C)
1	0.2	0.1	0.3
2	0.35	0.1	0.45
3	0.8	0	0.8
4	3	0	3

4.2.2 Leakage level and ventilation type

The infiltration levels chosen to characterize the airtightness of the residence, expressed in air changes per hour on average, were 0.1 ach, 0.6 ach and 1.1 ach. Linked to the infiltration levels, three types of ventilation were considered as possible alternatives. The choices were based on the literature review on NZEBs and consider both natural, mechanical and mechanical with heat recovery. Combining the 3 alternatives on the leakage with the 3 alternatives on the ventilation results in 9 alternatives overall. Behind these qualitative characterizations, the quantitative parameters that are predefined include the four following:

- The air changes per hour (ach^{-1}) due to infiltration;
- The ventilation rate per occupant in the case of mechanical ventilation, which is considered equal to 35 cubic meters per hour;
- The heat recovery efficiency, which is considered equal to 75%.

Table 4.4 shows all the combinations of infiltration & ventilation systems together with the pre-set values of air changes for each one.

Table 4.4: Air changes per hour default values

ACH	Ventilation		
Infiltration	Natural	Mechanical	Mechanical with heat recovery
Low	(0.1**)	0.1+(35 x occupants)/V	0.1+0.25 x (35 x occupants)/V
Medium	0.6	0.6+(35 x occupants)/V	0.6+0.25 x (35 x occupants)/V
High	1.1	1.1+(35 x occupants)/V	1.1+0.25 x (35 x occupants)/V
****The combination of natural ventilation with low infiltration is not advised and therefore not considered as a possibility in this study**			

4.2.3 Window and shading types

The range of different windows was chosen to reflect the variety found in the market, considering different climate zones.

In the “Window Type” variable, eight possibilities are considered. These are:

1) Single glazed clear with aluminum frame,

2) Double glazed clear with aluminum frame,

3) Double glazed clear with aluminum frame and thermal break,

4) Double glazed low-e with aluminum frame and thermal break,

5) Triple glazed clear with aluminum frame,

6) Triple glazed clear with aluminum frame and thermal break,

7) Triple glazed low-e with aluminum frame and

8) Triple glazed low-e with aluminum frame and thermal break.

Regarding shading, the range of shading devices available in the market was numerous and in order to limit it significantly but maintain a rational representation of the variety, two kinds of shading were chosen, with most relevance to their placement: indoors or outdoors.

The “Shading” variable therefore defines the existence or not of a shading system and whether the shades are inside (pleated shades) or outside (shutters). In accordance, the options available are:

1) Inside;

2) Outside and

3) None

Table 4.5 shows the U-value and g-values of each combination of glazing and shading type.. The data was retrieved from the RCCTE (Portuguese Government 2006), the ISO 13790:2008 (EN-ISO-13790 2008), the ASHRAE Fundamentals (ASHRE 2005) and the “Efficient Windows Collaborative” (EWC 1998).

The g-values for the cooling season were calculated according to the RCCTE as sum of the 30% of the g-value of the glazing plus 70% of the g-value of the window considering the blinds closed. As regards the g-values for the heating season the blinds were considered open.

Table 4.5 presents the above values considered for each one of the potential combinations between the window type and the shading.

Table 4.5: U-Values & g-values of each window type and shading

Windows Type	**Shading**								
	Inside			**Outside**			**None**		
	U (W/m^2.°C)	g_h	g_c	**U (W/m^2.°C)**	g_h	g_c	**U (W/m^2.°C)**	g_h	g_c
Single glazed clear Aluminum (Al)	5.68	0.70	0.65	5.68	0.70	0.30	5.68	0.70	0.70
Double glazed clear Al	4.83	0.63	0.62	4.83	0.63	0.27	4.83	0.63	0.63
Double glazed clear Al with thermal break (Al+TB)	3.58	0.63	0.62	3.58	0.63	0.27	3.58	0.63	0.63
Double glazed low-e , AL+TB	2.73	0.63	0.60	2.73	0.63	0.25	2.73	0.63	0.63
Triple glazed clear Al	2.85	0.50	0.61	2.85	0.50	0.26	2.85	0.50	0.50
Triple glazed clear, Al+TB	2.49	0.50	0.61	2.49	0.50	0.26	2.49	0.50	0.50
Triple glazed low-e	2.23	0.50	0.55	2.23	0.50	0.20	2.23	0.50	0.50
Triple glazed low-e, Al+TB	1.86	0.50	0.55	1.86	0.50	0.20	1.86	0.50	0.50

4.2.4 Glazed area

Regarding the glazed area, an effort was made to represent different levels of it as percentage of the heated useful area. It was discretized into three levels: 10%, 20% or 40% of the useful area..

4.2.5 Orientation

Facade may be orientation another important factor to determine the thermal energy needs of the building. For the needs of this work, and in view of limiting the search space, priority two options were considered:

- One, which gives preference to the South orientation for the installation of the windows/glazings, representative of the passive solar design (Kadam 2001). In this case it is assumed that 70% of the glazed area is facing south while north, east and west glazed areas have each a 10% share over the total;
- Another one where there is no preferential south-orientation, and the glazings are uniformly distributed through all orientations.

The parameters set in accordance to each orientation include the orientation factor (X) to be used in equations 3.2.3.2b and 3.4.1.3 from chapter 3, east and west. Table 4.6 shows the orientation factors for each facing-direction of the walls based on data retrieved from the RCCTE (Portuguese Government 2006).

Table 4.6: Orientation Factors

	North	South	East	West
X	0.27	1	0.57	0.57

4.2.6 Thermal mass

Thermal mass was discretized into three levels of inertia. These were, following to the RCCTE:

- Low: useful thermal mass smaller than 150 kg per m^2 of floor area;
- Medium: useful thermal mass between 150 and 400 per m^2 of floor area;
- High: useful thermal mass bigger than 400 per m^2 of floor area.

A dimensionless numerical parameter for use in equations 3.2.4b, 3.2.4c, 3.4.2a and 3.4.2b of chapter 3) is predefined depending on the building thermal inertia. According to the RCCTE, for buildings with low thermal inertia it gets the value of 1.8 while for medium and high thermal inertia it´s equal to 2.6 and 4.2 respectively (Portuguese Government 2006).

4.2.7 Heating and cooling system

The heating system options considered consist of: 1) a gas boiler, 2) a condensing gas boiler, 3) an electric radiator, 4) a conventional reversible cycle heat pump (RCHP) and 5) a class A RCHP. For the cooling systems the options considered were: 1) a conventional RCHP and 2) a class A RCHP. Each option is characterized by the Annual Fuel Utilization Efficiency (AFUE), which is the ratio of heat output to the total energy consumed by the boiler, or the Coefficient of Performance (COP) for the heat-pump based systems, and the typical lifetime of each system. For the case of the RCHP and the RCHP class A two values for the COP were considered, since heat pumps have a different efficiency during the heating and the cooling season. Table 4.7 shows the values considered for each one of the systems. These values were retrieved from the National Residential Efficiency Database of the National Renewable Energy Laboratory (NREL) (NREL 2010) and the Energy Star web page (EPA 1992). The values for the RCHP class A can also be somewhat representative of a ground-source heat pump solution.

Table 4.7: AFUE or COP & lifetime of the heating systems considered

	AFUE or COP		Lifetime (year)
Boiler	0.85		25
Condensing boiler	0.94		25
Electric radiator	0.99		8
RCHP	3.4(summer)	2(winter)	16
RCHP class A	5.5 (summer)	2.6 (winter)	16

4.2.8 Occupants

. The number of occupants needs to be defined so as to determine the hot water needs as well as the thermal internal gains. For the software to be presented in the next subchapter, a default value of four occupants is considered and displayed but it can be modified to a larger or smaller number.

The occupancy schedule that is assumed is fixed throughout the year and presented in figures 4.1 and 4.2, representing the hours that the occupants are inside the building during non-holiday and holiday periods. For children, the building is assumed to be occupied for 38 weeks under normal schedule, plus 14 weeks under the holiday schedule. Adults have a different occupancy schedule: 48 weeks under the normal schedule and 4 weeks under the holiday schedule. The sensible internal gain resulting from each occupant is assumed to be equal to 70 Watts.

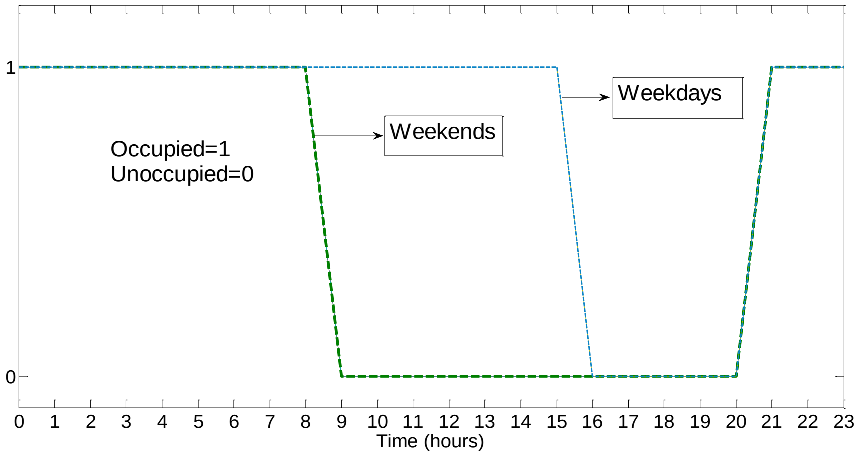


Figure 4.1: Weekly occupancy schedule (normal days)

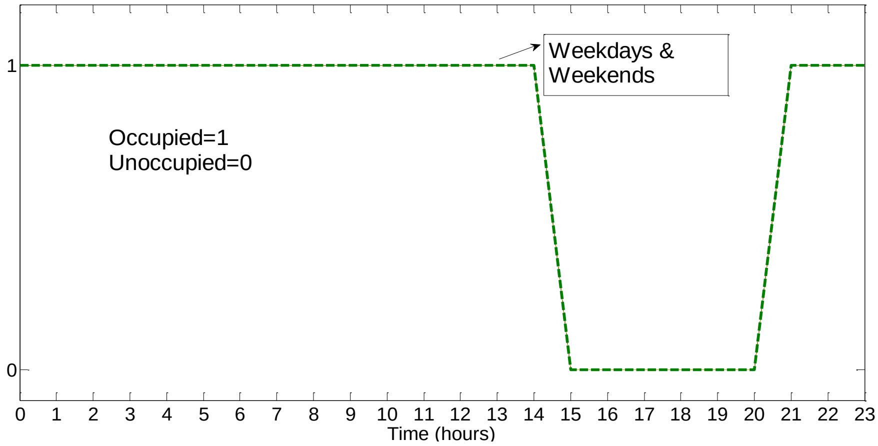


Figure 4.2: Weekly occupancy schedule (holidays)

4.2.9 Domestic hot water system

The options considered to provide domestic hot water for the building are the following systems: 1) a heat pump water heater; 2) a conventional storage electric boiler water heater; 3) a conventional storage gas boiler water heater; 4) a conventional storage gas condensing boiler water heater and 5) a tankless or instantaneous gas water heater. These hot water systems can also serve as auxiliary systems with the co-existence of a solar collector (options 6, 7, 8, 9 & 10).

The quantitative parameters that characterize each systems include the energy factor (EF) of the DHW system,(which is the ratio of useful energy output from the water heater to the total amount of energy delivered to the water heater) (EPA 1992), the expected lifetime, expressed in years, and the annual energy produced by the solar collector expressed in Kilowatt hours per year.

Table 4.8 shows the energy factors considered for each DHW system. These values were retrieved from the National Residential Efficiency Database of the National Renewable Energy Laboratory (NREL) (NREL 2010) and the Energy Star web page (EPA 1992).

Table 4.8: Energy factors - DHW systems

	EF	**Lifetime (years)**
Heat pump	2.1	10
Conventional storage electricity	0.95	13
Conventional storage gas	0.67	13
Conventional storage condensing	0.94	13
Tank less or Instantaneous gas	0.82	20
Solar collector	0.12	19

4.2.10 Lighting and appliances

Two alternatives were considered for Lighting and Appliances: high efficiency or average efficiency. The electric appliances considered include a refrigerator & freezer, clothes dryer, a dishwasher, an oven/cooker, a TV and a desktop PC. Their annual consumptions, for each of the efficiency alternatives, in Kilowatt-hours per year are presented in table 4.9 (Grinden e Feilberg 2006).

Table 4.9: Consumptions per appliance (kWh/year)

	Average Annual Energy Consumption (KWh/year)	
Appliances & Lighting (per dwelling)	**Average Efficiency**	**High Efficiency**
Refrigerator & Freezer	451	219
Washing machine	184	136
Clothes dryer	347	174
Dishwasher	234	163
Oven/Cooker	301	226
TV	400	337
Desktop PC	276	100
Lighting	487	184

4.2.11 Microgeneration system

Finally, the range of available microgeneration technologies considered the most widely used for residential on site electricity generation: PV cells and small scale wind turbines. The PV modules were characterized from their efficiency with regard to available PV cells efficiencies nowadays, while the wind turbines range was based on their power and on whether they are applicable or not for residential use.

The photovoltaic (PV) panels were discretized in two alternatives: average 12% efficiency and high 18% efficiency.

Regarding the wind turbines, three types were considered: 400 Watts, 1.8 Kilowatts & 2.4 Kilowatts. This was due to the fact that the power curves are considerably different according to the rated power.

The annual energy production for each one of the systems is pre-defined based on the climate data of each location (solar radiation and wind speed) as well as the 'site description', which is also user defined and includes the following options: rural, rural with obstacles and urban. The characterization of the site serves for the calculation and correction of wind speed at different heights and for different ground obstructions (see chapter 3). Finally, the user needs to define the 'height of turbine' taking into account also the total height of the building.

4.2.12 Climate

A database with 9 climates is pre-built in the design tool to be presented in subchapter 4.3 , but new ones can be added. Each climate is characterized through the following parameters:

- The Heating Degree Days (HDD), for a base temperature of 18 ºC, calculated according to the Eurostat HDD calculation method (Gikas e Keenan 2006).
- The average monthly solar energy incident on a vertical surface facing the south during the heating season (kWh/m^2.month).
- The total solar radiation energy during the cooling season for the east, west, north, and south orientations and on the horizontal (kWh/m^2).
- The duration of the heating season (months) (Gikas e Keenan 2006).
- The average outdoor air temperature during the cooling season (ºC).
- The heating design outdoor air temperature, here computed as the dry bulb temperature corresponding to 99.6% annual cumulative frequency of occurrence in the heating season (ºC).

- The cooling design outdoor air temperature, here computed as the the dry bulb temperature corresponding to 0.04% annual cumulative frequency of occurrence in the cooling season (ºC).

- The design indoor air temperature in the heating season (ºC), here taken as 20ºC

- The design indoor air temperature in the cooling season (ºC), here taken as 25ºC

- The average hourly wind speed for every hour of the year (m/s)

4.2.13 Summary of the Design Variables and its Discretization

Table 4.10 shows a summary of the considered design variables options chosen to discretize the space of design solutions, following the description of the previous sections of this subchapter.

Table 4.10: Design Variables

ENVELOPE							
Insulation level	Inertia	Infiltration	Ventilation	Window Type	Shading	Glazed Area	Orientation
1. >15cm (high) 2. around 8cm (medium) 3.> about 3cm (low) 4. None	1.Low 2.Medium 3.High	1.Low 2.Medium 3.High	1.Natural 2.MV 3.MVHR	1.Sngl_Glz_Clr (Al) 2.Dbl_Glz_Clr (Al) 3.Dbl_Glz_Clr (Al+TB) 4.Dbl_Glz_low-e (Al+TB) 5.Trpl_Glz_Clr (Al) 6.Trpl_Glz_Clr (Al+TB) 7.Trpl_Glz_low-e (Al) 8.Trpl_Glz_low-e (Al+TB)	1.Inside 2.Outside 3.None	1.10% of floor area 2.20% of floor area 3.40% of floor area	1.South 2.Other

EQUIPMENT FOR ENERGY SERVICES					MICROGENERATION SYSTEMS
Heating Equipment	Cooling Equipment	DHW Equipment	Lighting	Appliances	Microgeneration
1.Boiler 2.Condensing Boiler 3.Electric Radiator 4.RCHP 5.RCHP class A	1.RCHP 2.RCHP class A	1.Heat Pump 2.Storage Electricity 3.Storage Gas 4.Tankless Condensing 5.Tankless Gas 6. Heat Pump & SC 7.Storage Electricity & SC 8.Storage Gas & SC 9. Tankless Condensing & SC 10.Tankless Gas & SC	1.Average Efficiency 2.High Efficiency	1.Average Efficiency 2.High Efficiency	1.PV (Average Efficiency) 2.PV (High Efficiency) 3. WT 400W 4.WT 1.8KW 5. WT 2.4 KW

4.3 Calculation and optimization software

4.3.1 Structure

The equations for characterizing the energy demand-supply and the economics described in chapter 3 were implemented in a computer simulation program developed in Matlab (Version 7.12.0) (Matlab 2011) featuring a graphical user interface (GUI) for data entry and presentation.

There are two kinds of inputs:

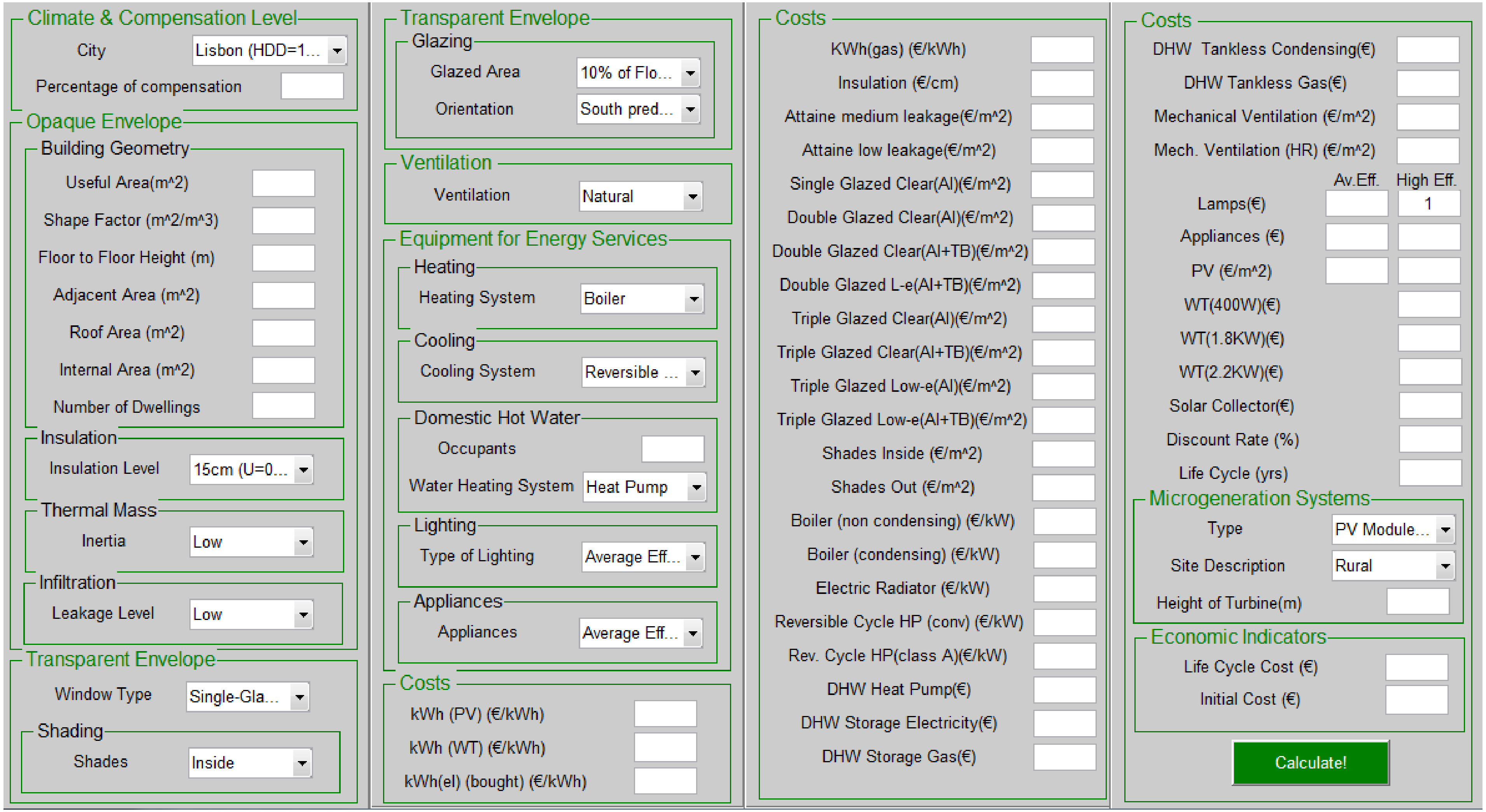
i) Mandatory, like the climate, the geometry of the building, the energy purchase and sell prices and the intended level of compensation. These inputs define a case-study, since once they have been inputted they will be treated as fixed during the simulations;

ii) Optional inputs: These are the inputs that correspond to the variables defined in sub-chapter 4.2, comprising the insulation level, the thermal inertia, the infiltration, the ventilation, the window type, the shading, the glazed area, the orientation, the thermal inertia, the heating system, the cooling system, the domestic hot water system, the lighting, the appliances, and the microgeneration systems. If the user selects one if the design alternatives regarding each of these variables, then it becomes fixed and the software will only analyse building design alternatives that consider this option. Otherwise the variable will be treated with the ‘sweep’ mode, which runs through all the discretized values of the variable.

The ‘sweep’ feature is an option that is available for all the design variables that were chosen for the ‘optimization’ part of the tool. For instance, choosing the ‘sweep’ option in the insulation level input popup, will make the software analyze building design alternatives with all the discretized values considered (wall U-values of 0.2, 0.35, 0.8 and 3 $W/m^2.^0C$). When the ‘sweep’ options is chosen in all the design variables, the outputs such as the Initial Cost and the Life Cycle Costs of all the combinations of design variables are computed.

The outputs given by the application for each building design alternative are the useful heating and cooling needs, the final heating and cooling needs, the total final energy at which the balance is met, the area of PV or number of wind turbines needed for the offset, the annual electricity and/or gas bill the life cycle cost and the initial cost. They are exported to a text file every time a simulation is conducted. In the end of the simulation the interface displays the combination of design alternatives that results in the lowest life cycle cost, as well as the corresponding values of heating energy needs and cooling energy needs.

The graphical user interface is shown in figure 4.3 that follows, while figure 4.4 shows the calculation flowchart of the software.



City: Lisbon (HDD=1...
Insulation Level: 15cm (U=0...
Inertia: Low
Leakage Level: Low
Window Type: Single-Gla...
Shades: Inside
Glazed Area: 10% of Flo...
Orientation: South pred...
Ventilation: Natural
Heating System: Boiler
Cooling System: Reversible ...
Water Heating System: Heat Pump
Type of Lighting: Average Eff...
Appliances: Average Eff...
Lamps(€): 1
Type: PV Module...
Site Description: Rural

Figure 4.3: Interface

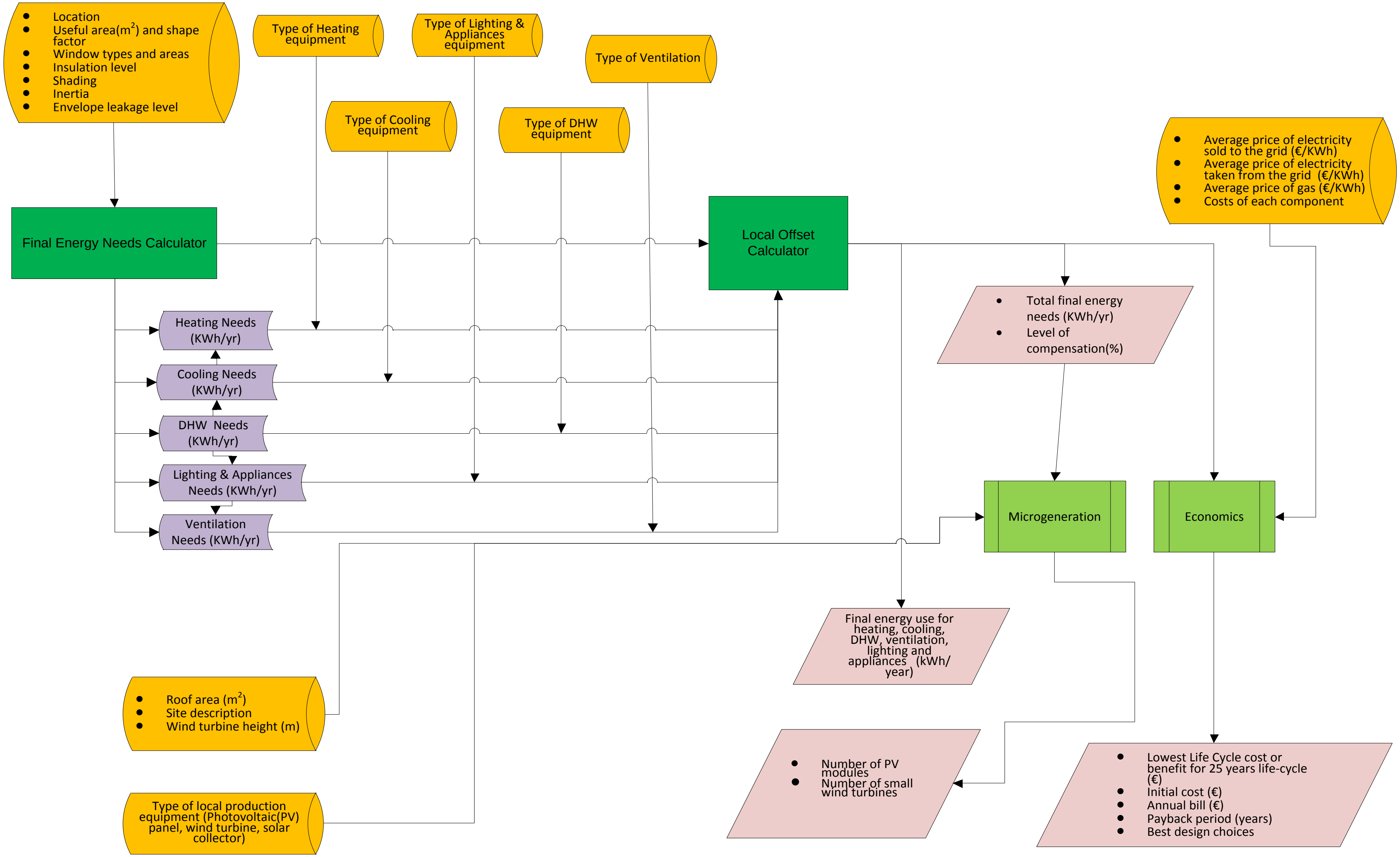


Figure 4.4: Flowchart of the application tool

4.3.2 Mandatory inputs

Figure 4.5 illustrates the choice of the location input option, which determines the climate data that will be used for the simulations.

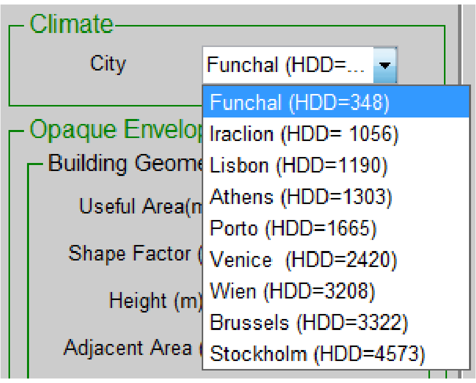


Figure 4.5: Location input option

The ‘building geometry’ part of the interface (Figure 4.6) consists of seven inputs that need to be specified, and which are fixed for each building, i.e. they do not change with the design alternatives. These inputs are:

- The useful area of the building (m^2)
- The shape factor, (defined as the rate of the total area (external and internal) to the volume of the building (m^2/m^3)
- The floor to floor height of the building (m)
- The adjacent area, which is the area of other buildings in contact with the studied building (m^2)
- The roof area (m^2)
- The internal area, which is the area in contact with non heated spaces (m^2)
- The number of dwellings in the project

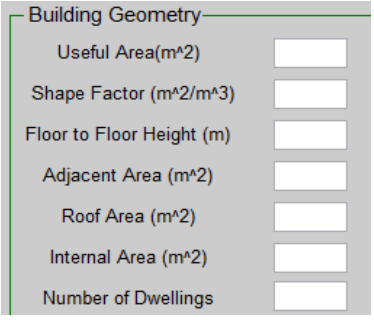


Figure 4.6: Building geometry inputs

In the ‘costs and outputs’ part of the interface the user is prompt to fill in information related to the cost of each component of the building.

The user needs to fill in the costs related to:

- The thermal insulation, expressed in euro per centimeter per square meter (€/cm*m^2). The default value of 1 €/cm*m^2 is considered in the absence of insulation cost information (Table 5.3, Chapter 5.1).Seals that yield a medium (45%) or a high (90%) leakage reduction compared to the high leakage option. The cost is expressed in euro per square meter of useful area (€/m^2). In the absence of user-specified values, the default values of 13.8 and 38.9 €/m^2 (Table 5.3, Chapter 5.1) to attain medium and low leakage level respectively are considered (NREL 2010).

- The mechanical ventilation without or with heat recovery related costs, expressed in €/m^2 of useful area and set by default equal to 24 and 48 €/m^2 respectively (Table 5.4, Chapter 5.1).

- All costs regarding each type of window are expressed in €/m^2 of glazed area. The default values are shown in Table 5.4 of Chapter 5.1 that follows, summarizing data retrieved from the Adelaide City Council web page (ACC s.d.), the National Residential Efficiency Database of the National Renewable Energy Laboratory (NREL 2010) and the Retscreen Clean Energy Project Analysis Software of the Natural Recources of Canada (NRC 1997).

- Default values of costs for the inside and outside shades (table 5.3, chapter 5.1) are estimated at 112 and 165 €/m^2 of glazed area respectively (Shades Shutters Blinds, 2001).

- The costs for the heating and cooling equipment are expressed in euro per Kilowatt (€/kW) and default values are available for the user if this information is not applicable (NREL 2010) (Table 5.4, Chapter 5.1). Costs related to the water heating system and solar collector are expressed in euros (€) with their default values presented in Table 5.4 & 5.5 of chapter 5.1 and were acquired from the National Residential Efficiency Database of the National Renewable Energy Laboratory (NREL) (NREL 2010).

- Default values expressed in euros accounting for the sum of the cost of each appliance are provided in the absence of information on cost (Preços 2004). The default costs for the lighting fixtures considered were attained from the National Residential Efficiency Database of the National Renewable Energy Laboratory (NREL) (NREL 2010) while one lighting fixture is assumed per 10 square meter of useful area (Table 5.4, chapter 5.1).

- In the case of the PV panels the cost is expressed in euro per square meter (€/m^2) of panel while for the wind turbines the cost is expressed in euro per each wind turbine. Default values for the costs are applicable (Table 5.5) if information is not available (Novas Energias 2010).

4.3.3 Optional inputs

Figure 4.7 shows the menu for the inertia input, which allows the user to choose between three options low, medium and high inertia (or sweep among them).

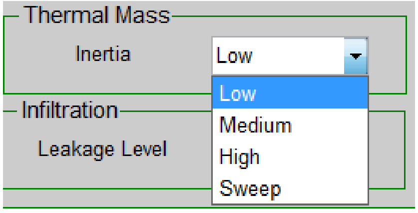


Figure 4.7: Inertia input menu

The user is prompt to choose between four levels of insulation, according to section 4.2.1, represented by its thickness and U-value (Figure 4.8).

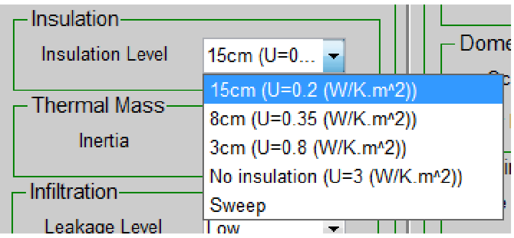


Figure 4.8: Insulation level input menu

Figures 4.9 and 4.10 show the infiltration and ventilation input menus of the interface, in which the user needs to choose between low medium and high infiltration and natural, mechanical or mechanical with heat recovery ventilation, in accordance to section 4.2.2.

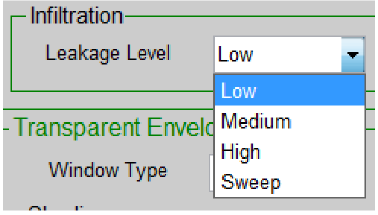


Figure 4.9: Infiltration input menu

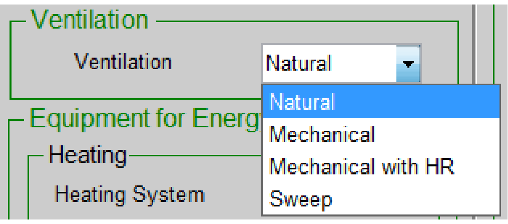


Figure 4.10: Ventilation input menu

Figures 4.11 and 4.12 that follow show the menus for the choices regarding the window type and shading inputs.

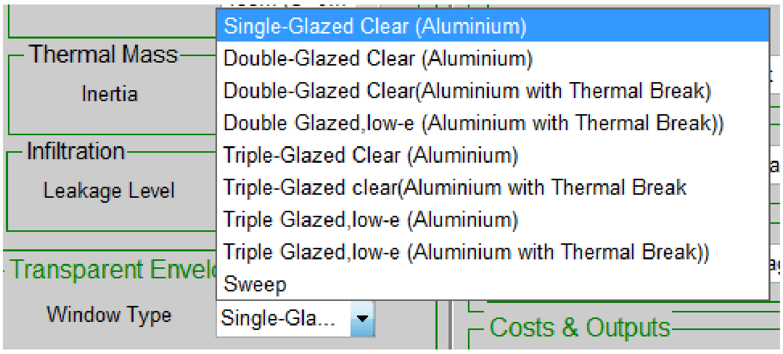


Figure 4.11: Window type input menu

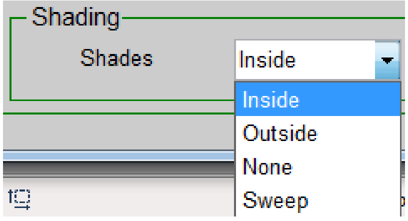


Figure 4.12: Shading input menu

Figure 4.13 shows the menus of the interface where the user needs to specify the glazed area of the envelope of the building, expressed as a percentage of the useful or heated area.

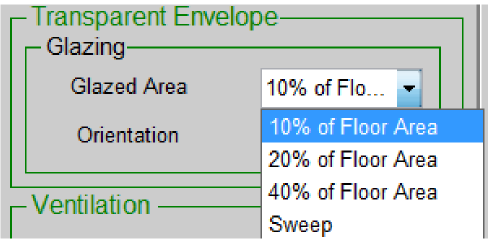


Figure 4.13: Glazed area input menu

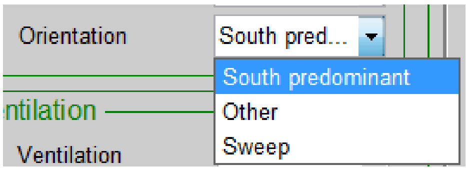


Figure 4.14: Orientation input menu

The orientation input option is shown in figure 4.14. The user can choose between two orientations: ‘south predominant’ or ‘other’.

Figures 4.15, 4.16 and 4.17,show the menus where the user is prompt to choose between five types of heating systems, 2 types of cooling systems and 10 types of DHW systems respectively – or just let the software sweep them all.

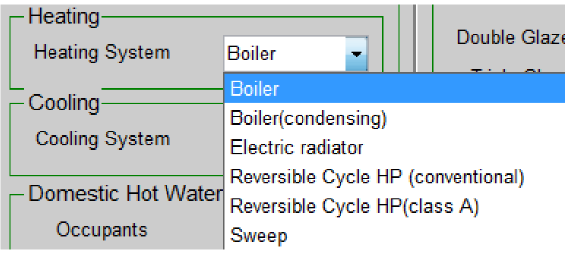


Figure 4.15: Heating System input menu

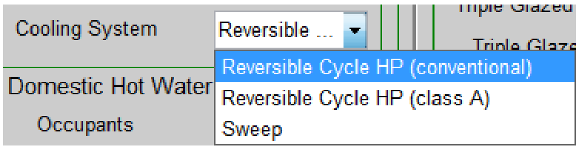


Figure 4.16: Cooling System input menu

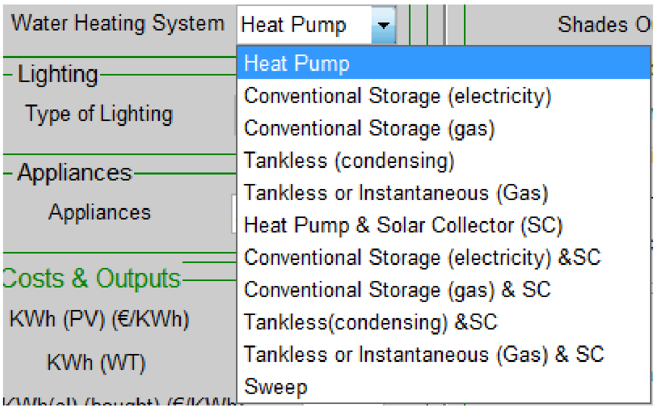


Figure 4.17: Domestic Hot Water input menu

Figures 4.18 & 4.19 show the menus where the user may pre-define the types of lighting and appliances.

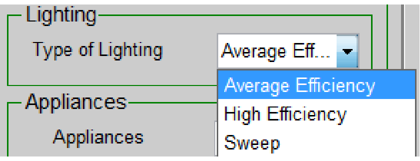


Figure 4.18: Lighting input menu

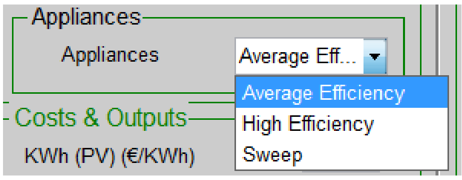


Figure 4.19: Appliances input menu

Finally, figures 4.20 and 4.21 that follow show the part of the interface where the type of microgeneration system is defined as well as the description of the site, which can be 'rural', 'urban' or 'rural with obstacles'.

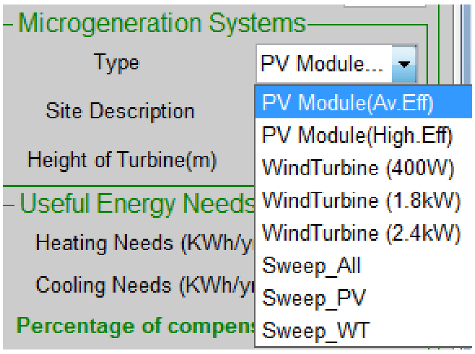


Figure 4.20: Microgeneration Systems Input

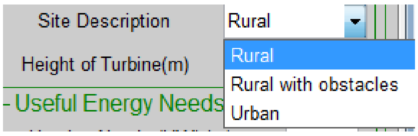


Figure 4.21: Site Description Input

4.3.4 Outputs

The following outputs are generated for each design alternative analysed (i.e., for each combination of alternatives from the variables):

- Useful Heating Needs,
- Useful Cooling Needs,
- Final Heating Needs,
- Final Cooling Needs,
- Total Final Energy,
- Area PV or Number of Wind Turbines,
- Annual Electricity and/or Gas Bill,
- Life Cycle Cost;
- Initial Cost.

The values of each design alternative are stored in a file, ordered by ranking of life cycle costs. All solutions deviating less than 20% from the lowest Life Cycle Cost are displayed in an ascending order, with the lowest life cycle cost solution al the top. Annex 1 shows a summary of all inputs and outputs of the application tool.

4.4 Validation of calculation algorithms for heating and cooling

As described in chapter 3, the calculation methodologies implemented with respect to the heat balance of the building were based on the latest Portuguese thermal building code- the RCCTE (Portuguese Government 2006) - and on the EN ISO 13790 (EN-ISO-13790 2008). The RCCTE, has been validated and found to correlate well to heating and cooling loads results obtained from detailed dynamic simulation (Leal, Ferreira e Oliveira Fernandes 2008) (ESRU 2002). More specifically, heating energy demand calculations computed with the simplified method of RCCTE versus those assessed through detailed simulation using the ESP-r were found have a relationship approaching a linear pattern with a correlation factor of 0.96. The same comparison regarding the cooling needs resulted in a less linear pattern of correlation with an r value close to 0.6; the values of the cooling needs were however much lower than those of the heating needs in all cases.

In order to assess the accuracy of the calculation algorithms developed for the purpose of this thesis, it was performed a comparison of results obtained from the RCCTE method versus the computer simulation program developed in Matlab, described in subchapter 4.3. Both calculation platforms were applied to six case studies of apartments with the characteristics detailed in Table 4.11. Since the inputs of the tool are prefixed e.g. there are 3 types of wall thickness that represent 3 different U-values, the same values were input in the RCCTE calculation platform so as to avoid discrepancies resulting from the inputs and not from the method.

Table 4.11: Detailed building characteristics for each case study of the tool validation.

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Useful Area (m^2)	187	150	266	100	137	221
Shape factor (m^2/m^3)	0.35	0.73	0.74	1	0.7	0.6
Floor to floor height (m)	2.4	2.4	2.5	2.6	2.6	2.4
Adjacent area (m^2)	0	21	0	0	0	0
Internal area (m^2)	0	0	17	52	2	7.2
Insulation level (cm)	8	8	3	3	3	8
Inertia	High	High	High	High	High	High
Leakage level	Medium	High	High	High	High	Medium
Window type	Trpl_Glz_low-e_(Al+TB)	Dbl_Glz_Clr (Al+TB)	Trpl_Glz_Clr (AL)	Dbl_Glz_low-e (Al+TB)	Dbl_Glz_low-e (Al+)	Trpl_Glz_low-e (Al+TB)
Shading	Outside	Outside	Outside	Outside	Outside	Outside
Glazed area	40%	20%	20%	40%	20%	20%
Orientation	Other	South	Other	Other	South	South
Ventilation	Natural	Natural	Natural	Natural	Natural	Natural

The graphs of figures 4.22, 4.23, 4.24, 4.25, 4.26 and 4.27 show the results from both calculation methodologies in what regards the thermal losses and heat gains from each component of the thermal balance and the resulting yearly useful heating and cooling energy needs (Figures 4.28 and 4.29).

The results show that the outputs are identical in both cases whether obtained from the RCCTE calculation platform or from the simulation program developed, both in what regards the totals as for each balance of the heat balance. Given that the RCCTE had previously been well validated, it is considered that the tool is validated as well, at least for the scope of strategic assessment in the early design stage of this work.

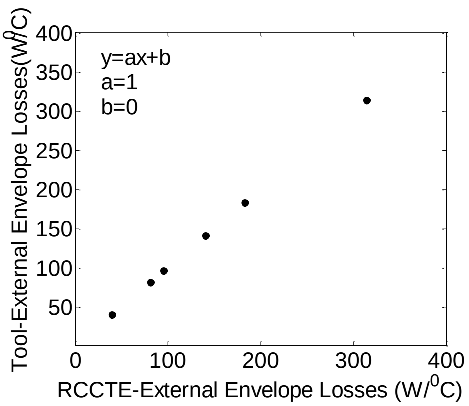


Figure 4.22: Losses from the external envelope calculated with the RCCTE & the Tool

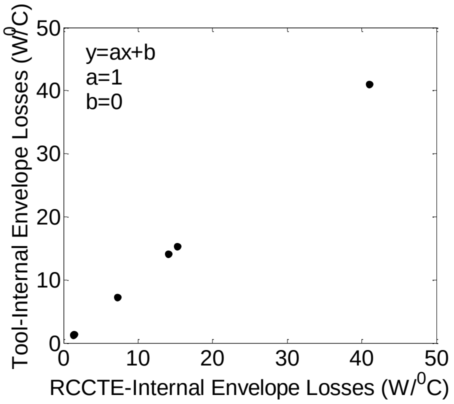


Figure 4.23: Losses from the internal envelope calculated with the RCCTE & the Tool

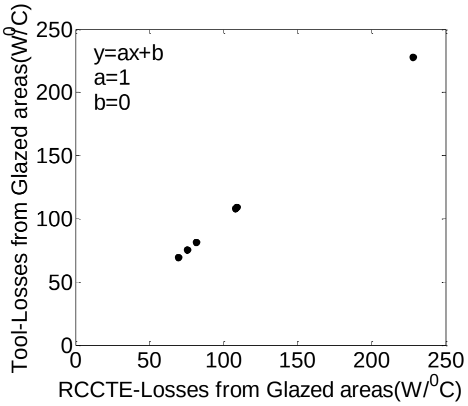


Figure 4.24: Losses from glazed areas calculated with the RCCTE & the Tool

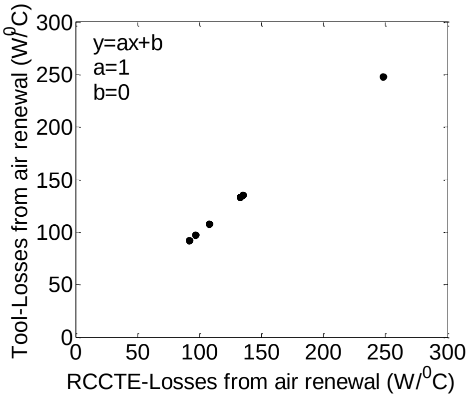


Figure 4.25: Losses from the air renewal calculated with the RCCTE & the Tool

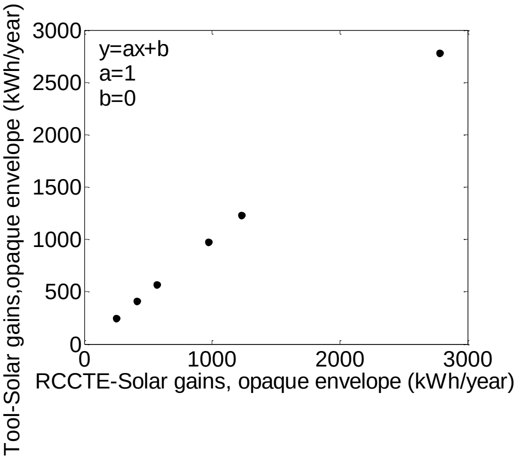


Figure 4.26: Solar gains from the opaque elements calculated with the RCCTE & the Tool

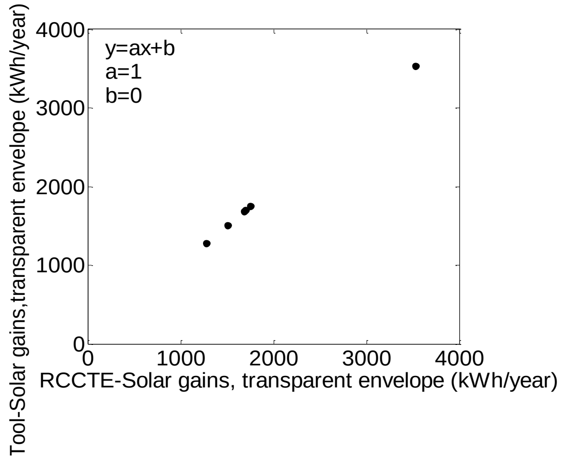


Figure 4.27: Solar gains from the transparent elements calculated with the RCCTE & the Tool

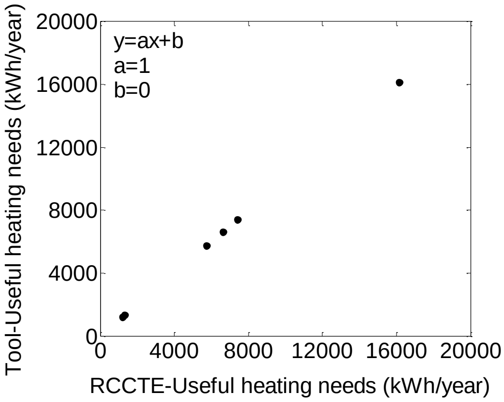


Figure 4.28: Useful heating needs calculated with the RCCTE & the Tool

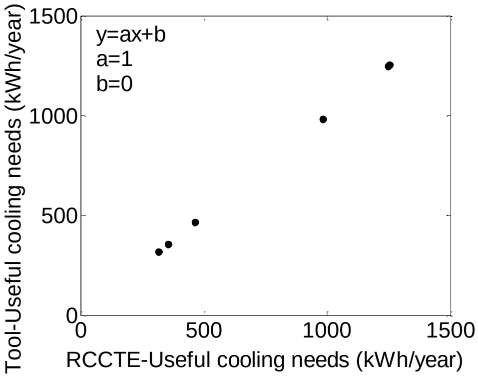


Figure 4.29: Useful cooling needs calculated with the RCCTE & the Tool

5 Case study 1: low rise building

The application case studies of this chapter and of chapter 6 serve two main goals. The first is to provide a first application example of the methodology and tool described in chapters 3 and 4. The second is to use the case study to gain insights on the potential impact of geographical context variables such as the climate and the electricity buy and sell prices upon the optimal and near-optimal design solutions.

5.1 Case study description

The first building chosen to serve as case study is a large one-floor single-family detached dwelling, with 266 m^2 of heated floor area and five bedrooms (Figure 5.1). It was originally designed to be built in Portugal, and is constituted by 4 bedrooms, a kitchen, 3 bathrooms, 2 offices, a living room, a hall, a corridor and 2 storerooms.

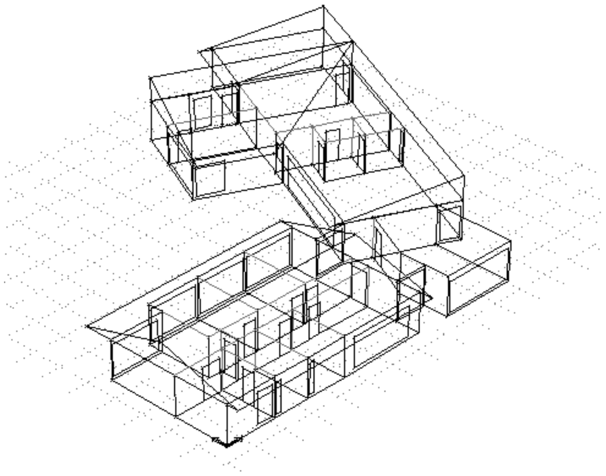


Figure 5.1: The single-family detached residence adopted as first case study

As presented in chapter 4, there are a number of mandatory inputs to study a building. Table 5.1 shows the mandatory inputs adopted in the current case study, which provides also a basic description of the building.

Table 5.1: Building geometry

Useful area (m^2)	266
Shape factor (m^2/m^3)	0.74
Floor to floor height (m)	2.5
Adjacent area (m^2)	29
Roof area (m^2)	266
Internal area (m^2)	18
Number of dwellings	1

Regarding the variables, in a first approach to explore the entire space of design alternatives, the adopted strategy was to set all the design variables to the 'sweep' option. However, it was found that, this strategy produced a number of solutions too high to be stored; therefore, a two-stage procedure was adopted:

i) In a first stage some of the variables with less expected influence were fixed;
ii) In a second stage, all variables were addressed in the "sweep" mode, but only the results of the solution within less than 20% distance from the lowest life cycle cost were stored.

Three climates scenarios were analyzed: Stockholm (Sweden), representing a climate with a cold winter, Lisbon (Portugal), representing a climate with a mild winter, Iraklion (Crete, Greece) representing a climate with very mild winter but warm summer. The choice of the climates was made upon consideration regarding the HDD and Cooling Degree Days (CDD) of each one. Table 5.2 shows that the HDD of Stockholm are almost 4 times more than then HDD of Lisbon and Iraklion, while the CDD range from nearly 0 (Stockholm) to near 500 (Lisbon) and to about 1000 (Iraklion).

Table 5.2: HDD & CDD

Climate	HDD	CDD
Stockholm	4573	36
Lisbon	1190	474
Iraklion	1056	1076

The costs assumed regarding the envelope, the equipment for the energy services and the renewable energy systems are shown in tables 5.3, 5.4 and 5.5 respectively. For the purpose of this sensitivity study, they were kept equal among the three climates analyzed. The sources of cost information for each item where detailed in subchapter 4.3.2.

To focus the analysis of the differences of the results in the climatic differences, for the purpose of this study the tariffs were also assumed to be equal among the three climates.

Table 5.3: Envelope related costs

Envelope		**Costs**	
Thermal Insulation	Insulation	€/m^2*cm	1
Leakage Reduction	Attain medium leakage	€/m^2	13.8
	Attain low leakage	€/m^2	38.9
Windows	Single glazed clear (Al)	€/m^2	185
	Double glazed clear (Al)	€/m^2	241
	Double glazed clear (Al+TB)	€/m^2	281
	Double glazed low-e (Al+TB)	€/m^2	316
	Triple glazed clear (Al)	€/m^2	297
	Triple glazed clear (Al+TB)	€/m^2	337
	Triple glazed low-e (Al)	€/m^2	334
	Triple glazed low-e (Al+TB)	€/m^2	374
Shades	Cost of Shades (Inside)	€/m^2	112
	Cost of Shades (Outside)	€/m^2	165

Table 5.4: Equipment for energy services related costs

Equipment for Energy Services		**Costs**	
Heating or Cooling Equipment	Cost of Boiler (non -condensing)	€/kW	79
	Cost of Boiler (condensing)	€/kW	115
	Cost of Electric Radiator	€/kW	19
	Cost of RCHP system (conventional)	€/kW	310
	Cost of RCHP system (class A)	€/kW	454
DHW equipment	Cost of DHW system (HP)	€	693
	Cost of DHW system (storage electricity)	€	490
	Cost of DHW system (storage gas)	€	595
	Cost of DHW system (tankless condensing)	€	1260
	Cost of DHW system (tankless gas)	€	700
Ventilation	Cost of Mechanical Ventilation	€/m^2	24
	Cost of Mechanical Ventilation with HR	€/m^2	48
Lighting	Lamps (average efficiency)	€	3
	Lamps (high efficiency)	€	10
Appliances	Appliances (average efficiency)	€	2892
	Appliances (high efficiency)	€	6534

Table 5.5: Microgeneration costs

Renewable Energy	**Systems**	**Costs**	
Photovoltaic Panels	PV (average efficiency-12%)	€/m^2	600
	PV (high efficiency-18%)	€/m^2	800
DHW equipment	Solar collector	€	2221
Wind Turbines	400W	€	2250
	1.8 kW	€	4900
	2.2 kW	€	5665

During this chapter there will be sensitivity studies performed to the following variables:

1. <u>Price of the electricity sold to the grid (SP) in relation to that of the electricity bought (BP)</u>: The central scenario (CS), which has SP=BP, was assessed in order to represent the absence

of feed in tariffs, which is the reality in some countries (e.g. Sweden, Finland etc.) and that even in the countries with feed-in tariffs, could somehow be seen as representing the cost to the society. .Two alternative scenarios were considered: AS1 that has SP=230% representing a scenario of feed-in tariff (e.g. Portugal, Greece); and AS2, that has SP=50%BP, representing a scenario where the operator buys the electricity to the customers at a level of the costs of its own production or market purchase; this scenario reflects the price that represents about the current electricity generation price of the utilities and it therefore is the level needed for them to 'buy' from the individuals without significant incentives. The energy tariffs considered are shown in table 5.6. They were inspired by Europe's Energy Portal (EU 2012).

2. The compensation level: The compensation level expresses what fraction of the annual energy imports to the building is offset with exports. In the "standard" NZEB definition this has a value of 100%, but this parameter was included to consider the cases of plus-energy buildings and of partial NZEBs. For each one of the climates and price scenarios five levels of compensation were considered, ranging from 0% to 200 % with a step of 50% considering a maximum of 80% of the roof area available for PV covering. The introduction of this parameter also allows to deal with cases when part of the electricity imported from the grids comes from renewables and it is only intended to offset the non-renewable part (off-site NZEB).

3. Roof area available for PV installation: For the above climate and price scenarios, the level of compensation was kept fixed and equal to 100%, while the available PV covering area varied in three levels: unlimited area, 80% of the roof area and 40% of the roof area. This variation was considered since it can happen that part of the roof is occupied with other installations (e.g. solar thermal panels, lifts, etc.), and since in some cases there may be extra terrain available near the building while in other it may not.

Table 5.6: Electricity purchase price for the all electricity price scenarios

Tariffs		**Costs**			
		Units	AS1	CS	AS2
Electricity & Gas	kWh of electricity	€/kWh	0.165	0.165	0.165
	kWh of gas	€/kWh	0.165	0.165	0.165
Feed In Tariffs	kWh of PV sold	€/kWh	0.380	0.165	0.083
	kWh of WT sold	€/kWh	0.380	0.165	0.083

Table 5.7 summarizes the scenarios that were studied and whose results are going to be shown in the next sections.

All the combinations of climate and price scenarios (Table 5.7) were analyzed in first stage considering only offset from PV modules, since the deployment of Wind Turbines in the urban building environment is still somewhat immature and often considered non suitable due to restrictions related to urban planning and location. Is a second stage the case was re-run, considering also Wind Turbines as an electricity generation option, for all climates and all price scenarios, with full compensation and unlimited area for PV covering or WT placement.

Table 5.7: Scenarios Analyzed for the detached-house case study

Climate Scenario			Electricity Purchased Price Scenario		
			SP=BP	SP=230%BP	SP=50%BP
Stockholm Lisbon Iraklion	Compensation level	0%	•	•	•
		50%	•	•	•
		100%	•	•	•
		150%	•	•	•
		200%	•	•	•
		Unlimited	•	•	•
	PV covering area	80%	•	•	•
		40%	•	•	•

5.2 Analysis of solutions in the central scenario (SP=BP)

As described in chapter 4, setting all design choices to the ‘sweep’ option of the application tool enables the calculation of the initial (IC) and life cycle (LCC) costs resulting from all combinations of the design variables and ranks them in ascending order.

The number of combinations checked, considering the 14 variables identified in chapter 4, reaches up to 7.776.000. Figure 5.2 shows the relation between the Life Cycle Cost and the corresponding Initial Cost covering all the range of possible design solutions in the price scenarios presented in section 5.1 (80% roof area limit, 100% compensation and sell price=buy price), for the climate of Lisbon. For operational reasons that will be explained later on in this chapter (see section 5.6), some of the design variables whose effect is very small were kept fixed. The graph does however provide a very good characterization of the LCC and IC ranges of the possible design solutions.

To be noted that the IC costs included in the characterization are only those that somehow relate to energy. E.g., while thermal insulation of the envelope is accounted for, the structural and decorative elements are not. These, however, are not expected to depend significantly on the energy performance.

Figures 5.2 and 5.3 show the results of the energy-related IC versus LCC costs for the range of design solutions for Lisbon and Iraklion, while figure 5.4 shows the equivalent results for Stockholm. They show that for Lisbon the most expensive NZEB design solution in terms of initial cost is about 3 times more expensive than the cheapest design solution. The same about 3:1 ratio is observed in terms of life cycle cost. Furthermore, regarding the climate of Stockholm the same ratios in terms of IC and LCC convert to 7:1 and 6:1 respectively. Recalling that each of the points in the graph represents a building with zero energy balance over the year, this clearly illustrates the importance of an economic analysis at the early design stage.

Moreover, the graphs show that the general trend is that the more costly solutions in terms of initial cost are also more costly in terms of life cycle. This is somewhat contrary to the usual expectation that solutions more efficient in terms of life cycle are more costly in terms of initial cost. A detailed explanation for this will be sought ahead in subchapter 5.5., but it can be advanced that the main reason seems to be that by investing more on energy efficiency it is possible to save initial investment on PV, which tends to be costly. The major trend highlighted for Lisbon remains valid for Iraklion and Stockholm. The results of table 5.8 further validate the absence of trade off trends for all the considered climates.

Another important observation is that the range of initial costs for Stockholm is considerably higher than that of Lisbon and Iraklion. It will be shown in section 5.6.2 that this is due to the fact that, because of the lower solar radiation the area of PV necessary to perform the offset is much higher in Stockholm. This explains the higher ranger of IC observed in the results.

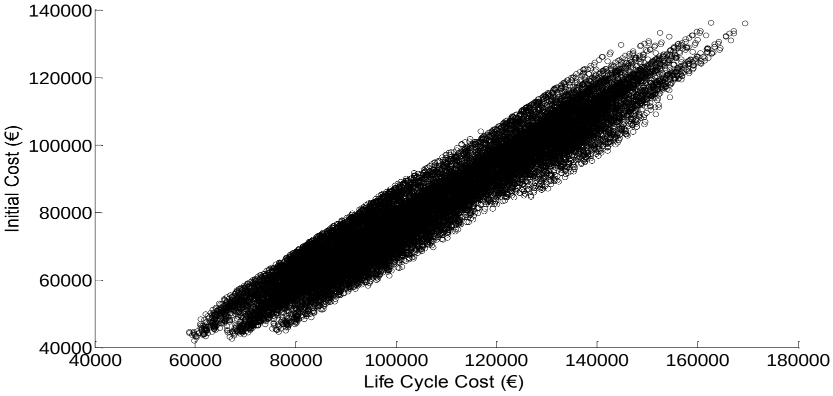


Figure 5.2: Relation between LCC and IC for the climate of Lisbon with hypothetical SP=BP

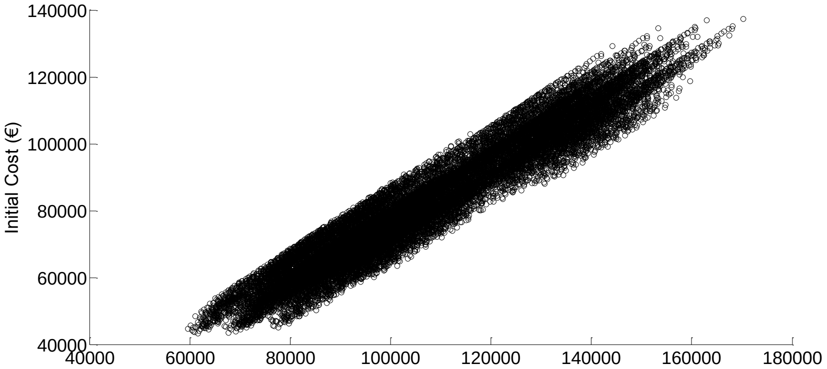


Figure 5.3: Relation between LCC and IC for the climate of Iraklion with hypothetical SP=BP

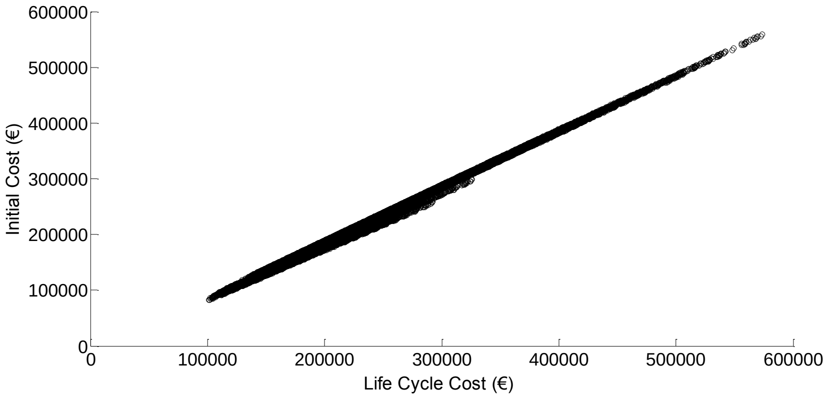


Figure 5.4: Relation between LCC and IC for the climate of Stockholm with hypothetical SP=BP

Table 5.8: Main cost indicators for the SP=BP electricity price scenario (LLCC represents the cost of the design solution with lowest life cycle cost, LIC the cost of the design solution with lowest initial cost)

	IC of LLCC (€/m^2)	IC of LIC (€/m^2)	Percentage difference ((IC-LIC)/IC)	LCC of LLCC (€/m^2)	LCC of LIC (€/m^2)	Percentage difference ((LLCC-LCC)/LLCC)
Lisbon	168	156	7%	221	227	-3%
Iraklion	168	159	5%	224	262	-17%
Stockholm	309	309	0%	380	380	0%

To gain further insights on the ‘near-optimal’ area of the space of design solutions, Figures 5.5, 5.6 and 5.7 show only the design solutions that deviate at most 20% from the LLCC.

A first conclusion from these graphs is that when the price of electricity sold is equal to the price of electricity bought, (i.e., the LCC is positive) there is no return in the initial investment in the life cycle of 25 years, regardless the climate. This does however also apply to a non-NZEB house, which also has a positive life-cycle cost of considerable value.

Secondly, the “optimal” design solutions for the climates of Lisbon & Iraklion (Figures 5.5 & 5.6) seem to be significantly cheaper than for the climate of Stockholm (Figure 5.7).

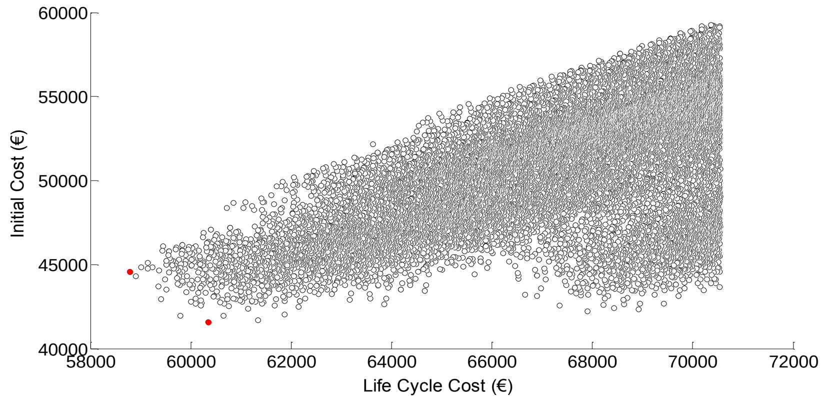


Figure 5.5: Relation between LCC and IC for the climate of Lisbon with hypothetical SP=BP, for the design solutions deviating less than 20% from the lowest LCC.

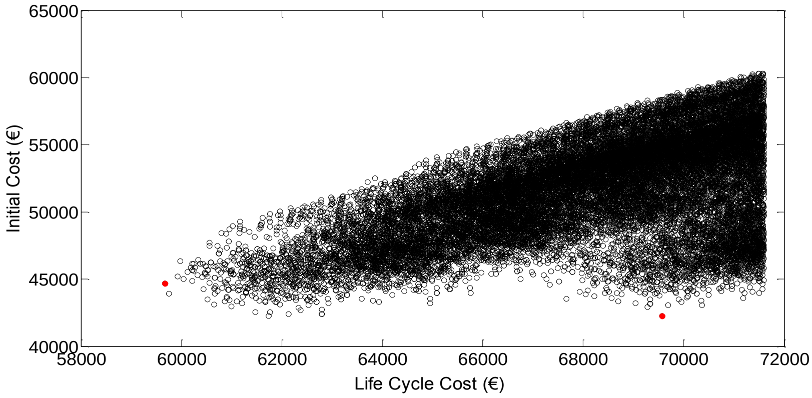


Figure 5.6: Relation between LCC and IC for the climate of Iraklion with hypothetical SP=BP, for the design solutions deviating less than 20% from the lowest LCC

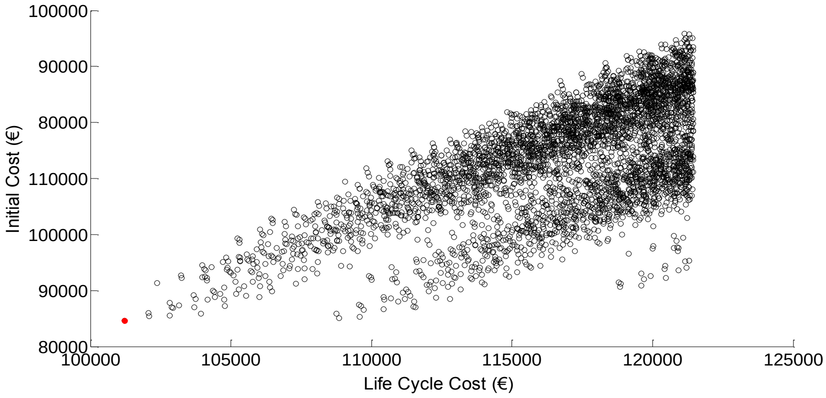


Figure 5.7: Relation between LCC and IC for the climate of Stockholm with hypothetical SP=BP, for the design solutions deviating less than 20% from the lowest LCC

5.3 Analysis of solutions in a scenario with SP=230%BP (AS1)

This section presents essentially the same type of analysis of section 5.2, but in a scenario where the electricity produced ‘on site’ is sold to the grid at a significantly higher price than it is bought from the grid. This is the case of countries or states that offer the so-called ‘feed-in tariff’ to incentivize the expansion of renewable energies. This work recognizes that there is political controversy on the adoption of feed-in tariffs, but it does not take a perspective of being in favor or against it. Instead, it pretends to provide information on the consequences that such tariff systems could have in the economic near-optimal design of NZEBs. The specific values of the tariffs adopted (0.165 €/kWh bought and 0.38 €/kWh sold) were inspired in the situation of Portugal in 2011 (EU 2011).

Figures 5.8, 5.9 and 5.10 show the relation between the IC and the corresponding LCC for the immense range of the possible NZEB design solutions, for the climates of Lisbon, Iraklion and Stockholm respectively.

As it can be seen from the figures, in this scenario for the zone of the pareto front curve there seems to be a significant trade off trend between the Initial Cost & Life Cycle Cost in all climate contexts, which is contrary to what had been observed in the SP=BP scenario. Table 5.9 verifies the trade off trends for the SP=230%BP electricity price scenario and exposes their presence for all climates. The reason of this inversion of IC versus LCC relation, will be analyzed in subchapter 5.5, although it can be advanced, that the main one identified is that a less efficient building requires more offset equipment, which in general are expensive in terms of initial cost, but which in the SP=230%BP scenario have a significant return over their lifetime.

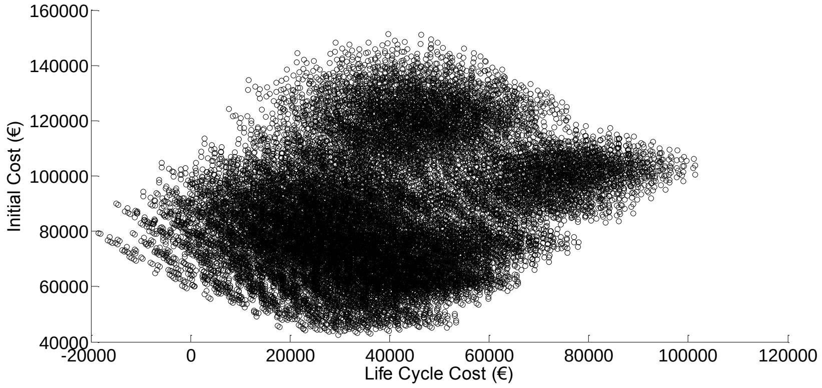


Figure 5.8: Relation between LCC and IC for the climate of Lisbon with hypothetical SP=230%BP

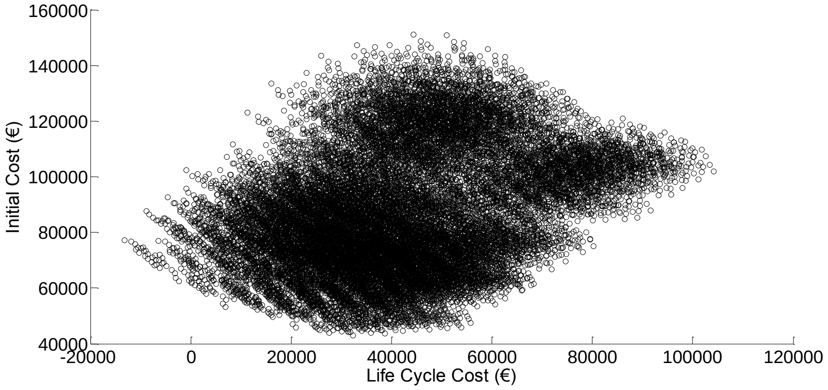


Figure 5.9: Relation between LCC and IC for the climate of Iraklion with hypothetical SP=230%BP

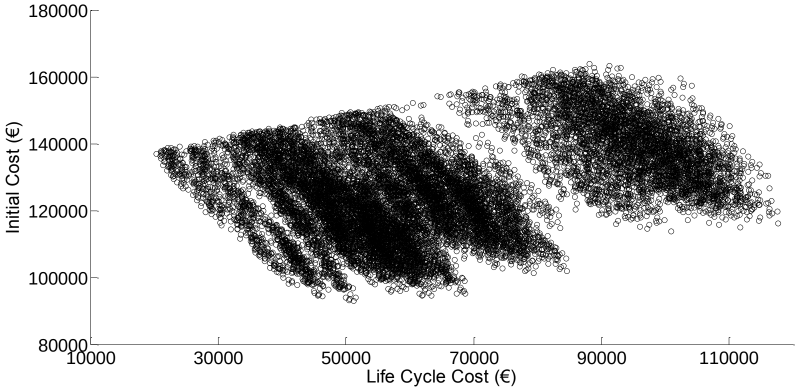


Figure 5.10: Relation between LCC and IC for the climate of Stockholm with hypothetical SP=230%BP

Table 5.9: Trade off trend verification for the SP=230%BP electricity price scenario

	IC of LLCC (€/m^2)	IC of LIC (€/m^2)	Percentage difference ((IC-LIC)/IC)	LCC of LLCC (€/m^2)	LCC of LIC (€/m^2)	Percentage difference ((LLCC-LCC)/LLCC)
Lisbon	299	159	47%	-69	112	261%
Iraklion	290	162	44%	-50	122	344%
Stockholm	723	309	57%	76	193	-152%

The graphs of figures 5.11, 5.12 and 5.13 represent the relation between the LCC and the corresponding Initial Cost (IC) considering only the design solutions that deviate at most 20% from the LLCC in this scenario with feed in tariffs (SP=230%BP). The red spots in the graphs represent the solutions with Lowest LCC and the lowest IC.

An important conclusion from these graphs is that in this scenario the best solutions have a positive cash flow for the climates of Lisbon and Iraklion (seen from the fact that the LCC is negative). More specifically, the initial investment is not only returned, but also turns out to be profitable in a life cycle of 25 years. Chapter 5.5 will provide a detailed explanation for this. It can however be advanced that with generous feed-in tariffs it would be economically more favorable, from the owners perspective, to not adopt high efficiency in the energy use, and therefore justify the installation of more micro generation, which with the feed-in tariff is profitable.

However, for the climate of Stockholm (Figure 5.13), this cash flow is negative likely because the lowest yearly solar radiation makes the PV have no or little return over the life time.

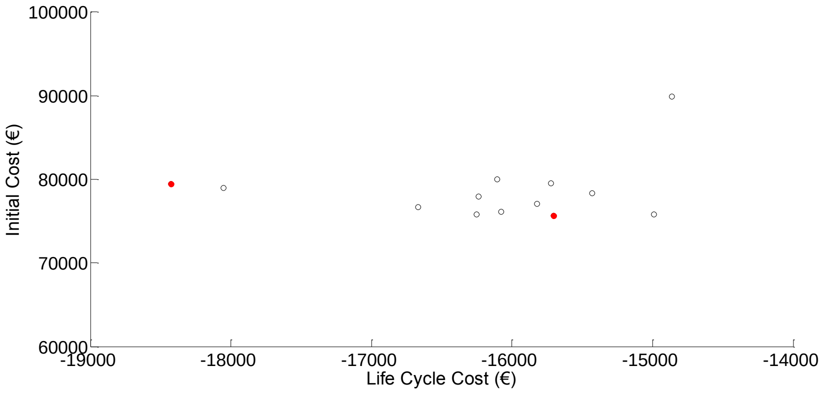


Figure 5.11: Relation between LCC and IC for the climate of Lisbon with hypothetical SP=230%BP for the design solutions deviating less than 20% from the lower LCC.

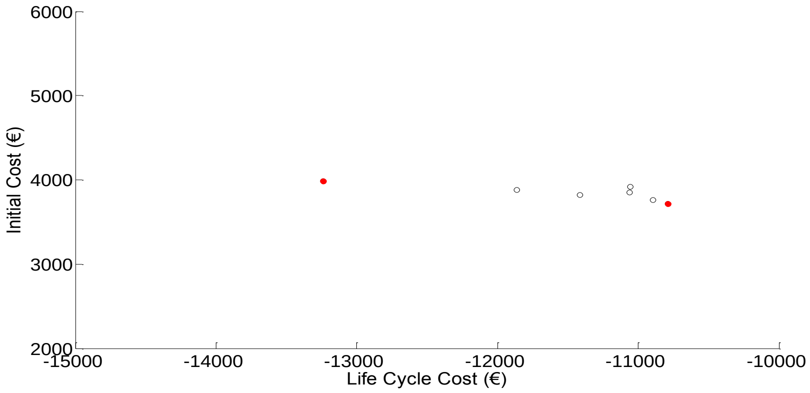


Figure 5.12: Relation between LCC and IC for the climate of Iraklion with hypothetical SP=230%BP for the design solutions deviating less than 20% from the lowest LCC

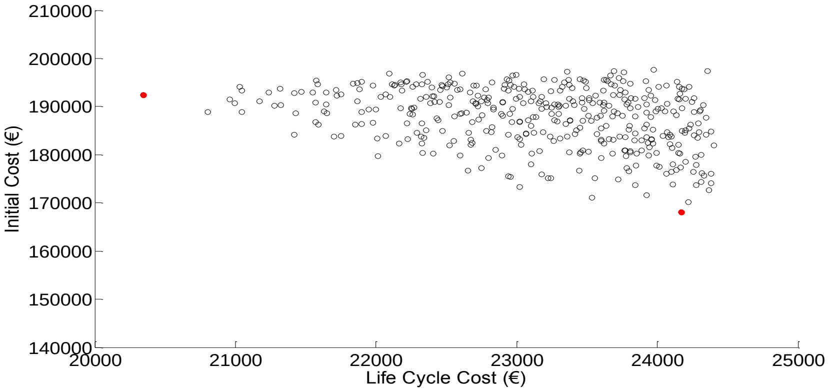


Figure 5.13: Relation between LCC and IC for the climate of Stockholm with hypothetical SP=230%BP for the design solutions deviating less than 20% from the lowest LCC

5.4 Analysis of solutions in a scenario with SP=50%BP (AS2)

This section repeats the analysis of sections 5.1 and 5.2, but now in a scenario where the electricity would be sold to the grid at a price significantly lower than the price of the electricity bought from the grid. This intends to somehow represent the fact that the electricity retailers usually produce or buy the electricity at a cost that is considerably lower than the price at which they sell it to their customers. This scenario thus represents a somewhat ‘pure market approach’, in which not just there are no feed-in tariffs but also even the electricity to be injected in the grid must have a price attractive to the electric grid operators.

Figures 5.14, 5.15 and 5.16 show the relation between the corresponding Initial Cost (IC) and the life cycle costs (LCC) for the wide range of all possible NZEB design solutions in this scenario with SP=50%BP.

As it can be seen from the figures, there doesn’t seem to exist any significant trade-off trend between the Initial Cost & Life Cycle Cost in respect to all climate contexts. On the contrary, the patterns are similar to those observed in section 5.1 and even reinforced: solutions with lowest LCC cost tend to be also those with lowest initial cost. Table 5.10 further exposes the absence of trade off trends between IC and LCC for all climates.

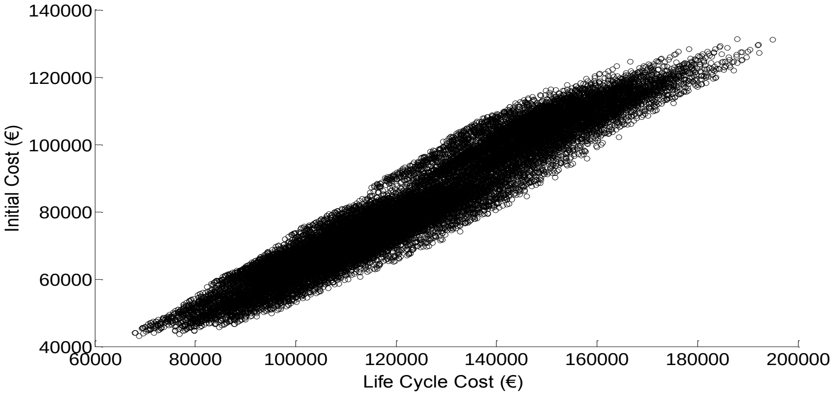


Figure 5.14: Relation between LCC and IC for the climate of Lisbon with hypothetical SP=50%BP

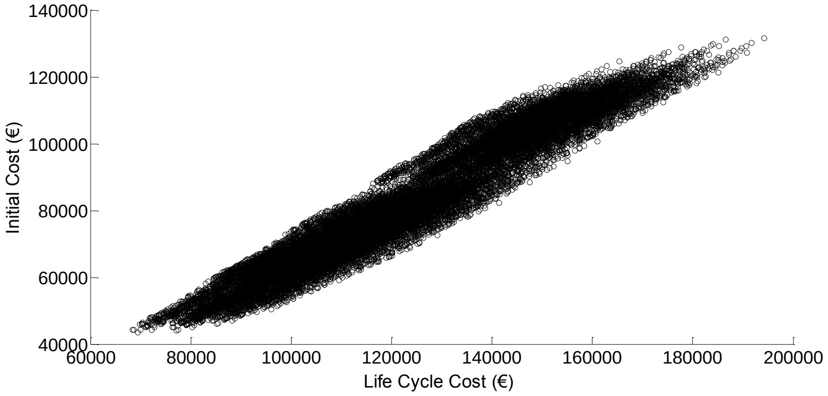


Figure 5.15: Relation between LCC and IC for the climate of Iraklion with hypothetical SP=50%BP

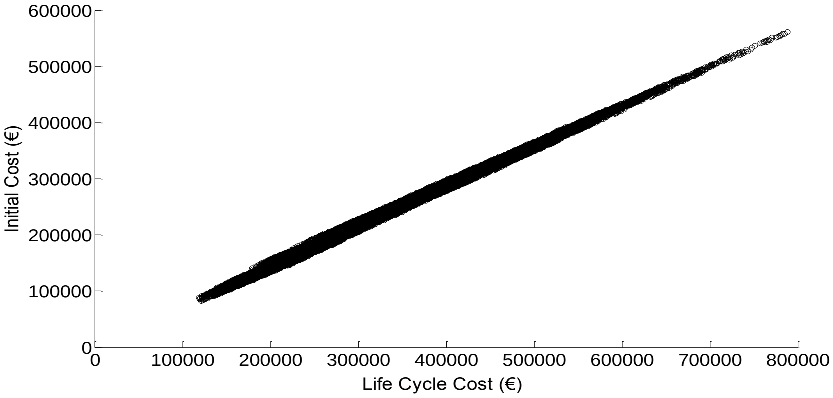


Figure 5.16: Relation between LCC and IC for the climate of Stockholm with hypothetical SP=50%BP

Table 5.10: Trade off trend verification for the SP=50%BP electricity price scenario

	IC of LLCC (€/m^2)	IC of LIC (€/m^2)	Percentage difference ((IC-LIC)/IC)	LCC of LLCC (€/m^2)	LCC of LIC (€/m^2)	Percentage difference ((LLCC-LCC)/LLCC)
Lisbon	165	156	5%	256	270	-6%
Iraklion	167	159	5%	257	302	-17%
Stockholm	330	309	6%	447	453	-1%

Figures 5.17, 5.18 and 5.19 show the same results as 5.14, 5.15 and 5.16 but now focused in the area with the LCC deviating less than 20% from the LLCC.

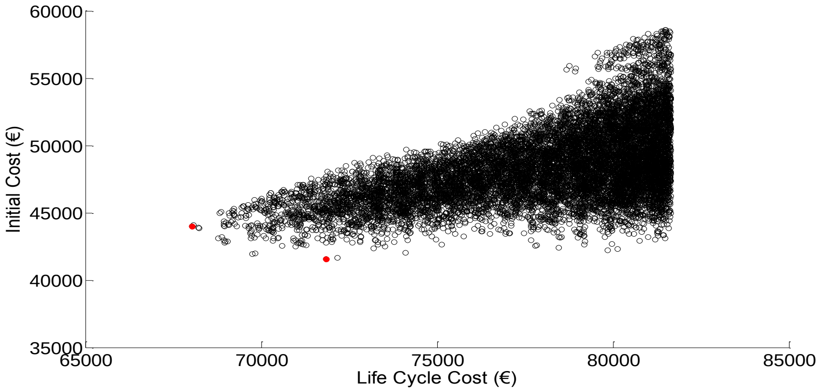


Figure 5.17: Relation between LCC and IC for the climate of Lisbon with hypothetical SP=50%BP for the design solutions deviating less than 20% from the lowest LCC

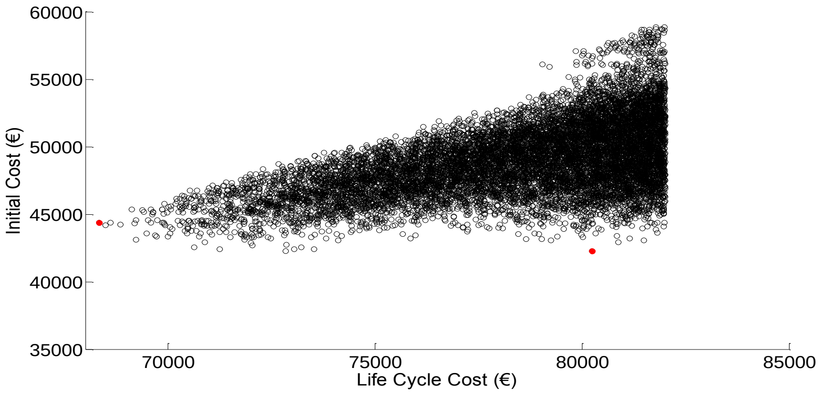


Figure 5.18: Relation between LCC and IC for the climate of Iraklion with hypothetical SP=50%BP for the design solutions deviating less than 20% from the lowest LCC

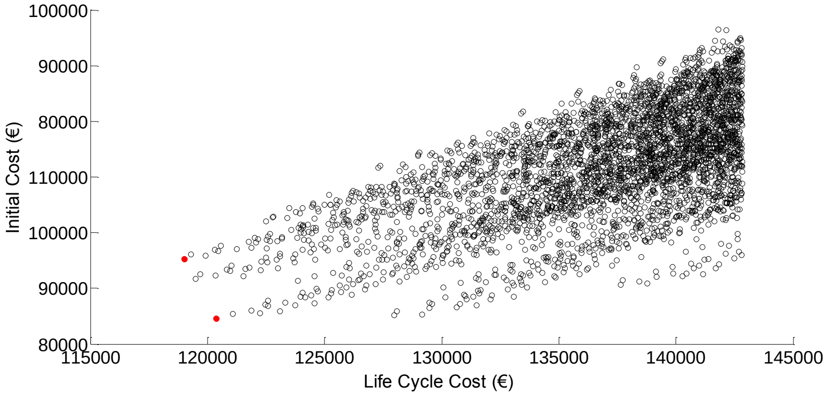


Figure 5.19: Relation between LCC and IC for the climate of Stockholm with hypothetical SP=50%BP for the design solutions deviating less than 20% from the lowest LCC

As expected, when the price of the electricity sold is significantly lower than that of the electricity bought, the life-cycle cash flow is negative (i.e., the life cycle cost is positive). More specifically, in the timespan of 25 years there is no profit.

Also without surprise, the fact that for the climates of Lisbon & Iraklion (Figures 5.17 & 5.18) the IC is much lower than for Stockholm indicates that the design solutions chosen seem to be much less energy efficient in the former than in the latter (Figure 5.19).

5.5 Sensitivity of the optimal building design to the price scenarios

The figures below show the annual imported and exported energy values that correspond to the lowest life cycle cost (LLCC) and Lowest Initial Cost (LIC) of each price scenario analyzed in the previous sections. CS is the scenario with SP=BP, AS1 the scenario with SP=230%BP and AS2 the scenario with SP=50%BP.

Figures 5.20, 5.21 and 5.22 show the energy density at which the net zero energy (NZE) balance is achieved for the LLCC and LIC solutions of the three price scenarios and for all climates. It is obvious from the graphs of that, in the absence of financial incentives (SP=BP & SP=50%BP), the design solutions with lowest LCC and lowest IC are achieved at a much lower energy density (i.e., with much more intrinsic efficiency) than in the scenario with feed-in tariffs. This can be concluded from the fact that the energy imported-exported in these scenarios is much lower than the energy imported-exported relevant to the SP=230%BP scenario.

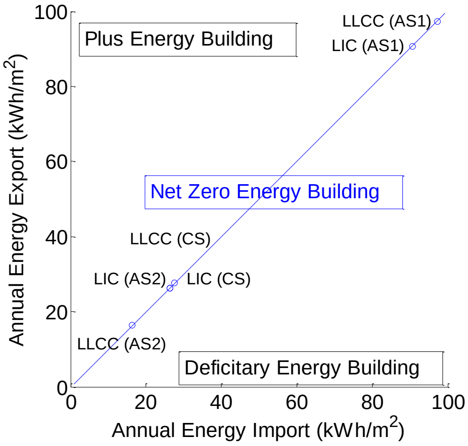


Figure 5.20:Energy density at which the NZE balance is achieved, for the LLCC and LIC solutions of the three price scenarios (CS, AS1 and AS2), for the climate of Lisbon.

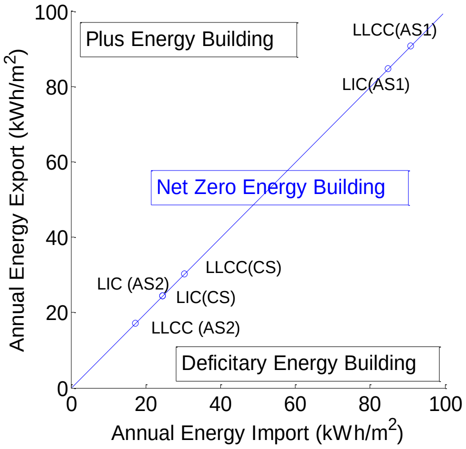


Figure 5.21: Energy density at which the NZE balance is achieved, for the LLCC and LIC solutions of the three price scenarios (CS, AS1 and AS2), for the climate of Iraklion

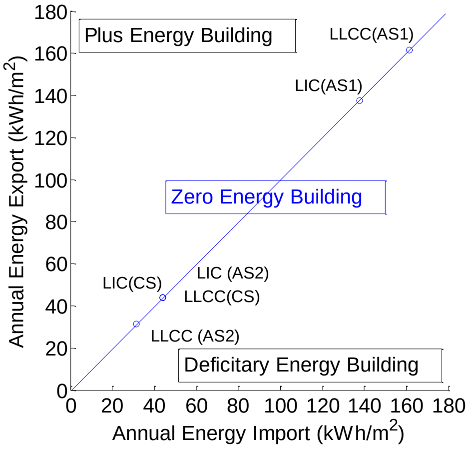


Figure 5.22: Energy density at which the NZE balance is achieved, for the LLCC and LIC solutions of the three price scenarios (CS, AS1 and AS2), for the climate of Stockholm

The results of figures 5.20, 5.21 and 5.22 show that when there are no significant financial incentives to the sale of electricity to the grid then the optimal design occurs at solutions with high intrinsic efficiency. The likely reason for this is that it is less expensive, even in a perspective of initial cost, to invest in energy efficiency that lowers the needs for on-site micro generation equipment, than to do have to buy large on-site micro generation equipment to offset a high amount of yearly energy. In order to confirm this explanation, following is presented an analysis of the design solutions that are in the economic near-optimal design area, i.e.in solutions within 20% of the Lowest LCC.

Table 5.11 shows the design variables values of the LLCC solution for each one of the sell-price scenarios. As it can be seen, when financial incentives are absent the design choices turn to be more efficient. The same thing applies for the design variable values of the LIC solution, as it can be seen from table 5.12.

Table 5.11: Design variable values of the LLCC solution versus the sell-price scenarios

Design Variables		Lisbon			Iraklion			Stockholm		
		SP=230%BP	SP=BP	SP=50%BP	SP=230%BP	SP=BP	SP=50%BP	SP=230%BP	SP=BP	SP=50%BP
Insulation	3cm	•			•					
	8cm					•				
	15cm		•	•			•	•	•	•
Infiltration	High	•			•			•		
	Medium		•	•		•	•		•	
	Low									•
Ventilation	Natural	•	•	•	•	•	•	•	•	
	MVHR									•
Windows	Single Glazed Clear (Al)	•	•		•	•				
	Double Glazed Clear (Al-TB)							•		
	Triple Glazed Low-e (Al)			•			•			
	Triple Glazed Low-e (Al+TB)								•	•
Shading	Inside	•			•					
	Outside		•	•		•	•	•	•	•
Glazed Area	10%	•	•	•	•	•	•	•	•	•
Orientation	Other	•			•					
	South		•	•		•	•	•	•	•
Heating System	Boiler	•			•					
	Electric Radiator							•		
	RCHP		•			•	•			
	RCHP Class A			•					•	•
Cooling System	RCHP	•	•		•	•		•	•	
	RCHP Class A			•			•			•
DHW System	Storage Gas	•			•					
	Storage Electricity							•		
	Heat Pump		•			•				
	Heat Pump & SC			•			•		•	•
Lighting	High Efficiency	•	•	•	•	•	•	•	•	•
Appliances	Average Efficiency	•	•	•	•	•	•	•	•	•
PV Module	High Efficiency	•	•	•	•	•	•	•	•	•

As it can be seen from tables 5.11 and 5.12, the glazed area design solution favored is the minimum one (10%). This could seem strange, as it holds even for the south-orientation and thus counters a usual recommendation from Passive design. In order to verify this choice from the software, the loads resulting from conduction and radiation for 1 m^2 of transparent and opaque envelope element were manually calculated using the equations of chapter 3. Tables 5.13, 5.14 and

5.15 show the results. They show that for the climate of Stockholm, maintaining the minimum glazed area is the best design solution regarding the heat losses shown in table 5.15. Yet, for the climate of Lisbon and Iraklion (tables 5.14 and 5.15), the case is not the same, since the total load results in heat gains. Therefore the question of “why can’t the glazed area be larger than 10%?” remains. Due to that observation, the Life Cycle costs for 25 years were also manually calculated for both transparent and opaque elements. The results showed that Life Cycle costs for a triple low-e glazing are up to 15 times higher than the respective insulation costs. It is thus considered that the software options were valid.

Table 5.12: Design variable values of the LIC solution versus the sell-price scenarios

Design Variables		Lisbon			Iraklion			Stockholm		
		SP=230%BP	SP=BP	SP=50%BP	SP=230%BP	SP=BP	SP=50%BP	SP=230%BP	SP=BP	SP=50%BP
Insulation	3cm	•			•					
	8cm		•	•		•	•			
	15cm							•	•	•
Infiltration	High	•	•	•	•	•	•			
	Medium							•	•	•
Ventilation	Natural	•	•	•	•	•	•	•	•	•
Windows	Single Glazed Clear (Al)	•	•	•	•	•	•	•		
	Triple Glazed Low-e (Al+TB)								•	•
Shading	Outside	•	•	•	•	•	•	•	•	•
Glazed Area	10%	•	•	•	•	•	•	•	•	•
Orientation	South	•	•	•	•	•	•	•	•	•
Heating System	Boiler	•			•					
	Electric Radiator							•		
	RCHP Class A		•	•		•	•		•	•
Cooling System	RCHP	•	•	•	•			•	•	•
	RCHP Class A					•	•			
DHW System	Storage Electricity	•			•					
	Heat Pump							•		
	Heat Pump & SC		•	•		•	•		•	•
Lighting	Average Efficiency					•	•			
	High Efficiency	•	•	•	•			•	•	•
Appliances	Average Efficiency	•	•	•	•	•	•	•	•	•
PV Module	High Efficiency	•	•	•	•	•	•	•	•	•

Table 5.13: Annual loads of transparent and opaque envelope elements (Lisbon)

Lisbon						
KWh/year	Opaque		Transparent			
	Wall (U-Value=0.3W/m^{2}.^{0}C)		Double Clear (g_h=0.63,g_c=0.27)		Triple Low-e (g_h=0.5,g_c=0.2)	
	Winter	Summer	Winter	Summer	Winter	Summer
Conduction	-9	1	-138	-28	-64	-13
Solar Radiation	0	0	166	47	132	35
Total	-9	1	304	75	195	48

Table 5.14: Annual loads of transparent and opaque envelope elements (Iraklion)

Iraklion						
	Opaque		Transparent			
KWh/year	Wall (U-Value=$0.3W/m^2.^0C$)		Double Clear (g_h=0.63,g_c=0.27)		Triple Low-e (g_h=0.5,g_c=0.2)	
	Winter	Summer	Winter	Summer	Winter	Summer
Conduction	-8	2	-122	-28	-57	-13
Solar Radiation	0	0	146	66	116	49
Total	-8	2	24	38	59	36

Table 5.15: Annual loads of transparent and opaque envelope elements (Stockholm)

Stockholm						
	Opaque		Transparent			
KWh/year	Wall (U-Value=$0.3W/m^2.^0C$)		Double Clear (g_h=0.63,g_c=0.27)		Triple Low-e (g_h=0.5,g_c=0.2)	
	Winter	Summer	Winter	Summer	Winter	Summer
Conduction	-33	1	-530	-99	-245	-46
Solar Radiation	0	0	215	26	171	20
Total	-33	1	-315	-73	-74	-26

5.6 Sensitivity analysis to the compensation level

The compensation level expresses what fraction of the annual energy imports to the building is to be offset with exports. In the "standard" NZEB definition this has a value of 100%, but it can be higher the case of plus-energy buildings, or lower in the case of partial NZEBs. This parameter also allows to deal with cases when part of the electricity imported from the grids comes from renewables and it is only intended to offset the non-renewable part (off-site NZEB). For each one of the climates and price scenarios five levels of compensation were considered, ranging from 0 to 200 %, with a step of 50%, considering a maximum of 80% of the roof area available for PV covering. The scenarios analyzed are shown in Table 5.16 and they include all climates and all price scenarios with 0, 50, 100, 150 and 200% compensation.

Table 5.16: Scenarios Analysis

Climate Scenarios			Electricity Purchased Price Scenario		
			SP=230%BP	SP=BP	SP=50%BP
Lisbon Iraklion Stockholm	Compensation Level	0%	•	•	•
		50%	•	•	•
		100%	•	•	•
		150%	•	•	•
		200%	•	•	•

5.6.1 Impact of Compensation Level on the Economic Indicators

This subchapter studies the impact of different compensation levels on the economic indicators (LLCC, LIC). The graphs below (Figure 5.23 to 5.31) show the relation between the compensation level for the life cycle cost of the lowest life cycle cost solution (LCC of LLCC) and the initial cost of the lowest initial cost solution (IC of LIC), as obtained from the simulations performed.

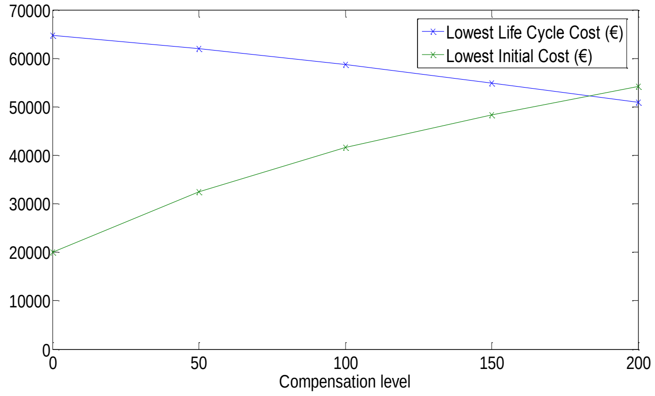


Figure 5.23: Impact of compensation level on economics (SP=BP- Lisbon)

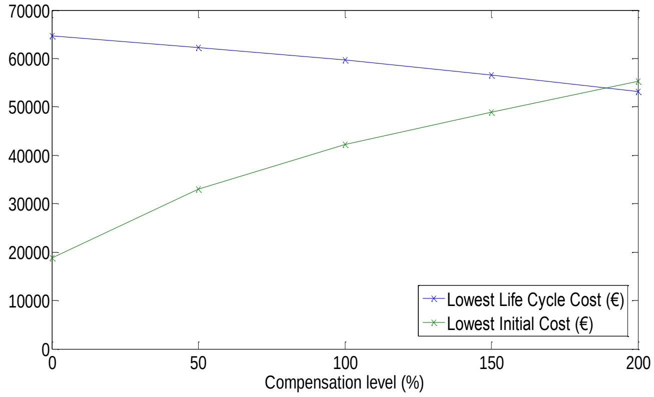


Figure 5.24: Impact of compensation level on Economics (SP=BP-Iraklion)

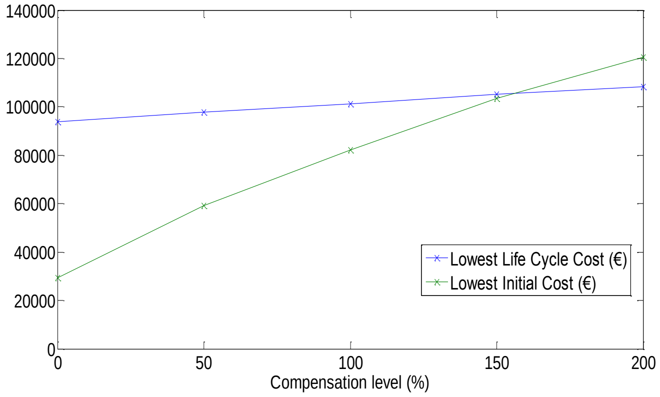


Figure 5.25: Impact of compensation level on economics (SP=BP-Stockholm)

The results from the above graphs (Figures 5.23, 5. 24) show that in the SP=BP scenario, for the climates of Lisbon and Iraklion, as the level of compensation increases, the lowest IC also increases while the lowest LCC decreases. This increase in the LIC could be explained either by the fact that, more energy efficient solutions are being chosen or by the fact that more PV is used (see chapter 5.6.2); consequently, in this case the lowest LCC decreases. For the climate of Stockholm, what is observed, is that both the lowest IC and LCC increase. Even though this is not the same case as for the climates of Lisbon and Iraklion, one could understand this variation since the IC for PV placement in all climates is the same but the energy export (depending on the solar radiation available in each location) is different. As a result, in the long run (25 years' time) in the climates of Lisbon and Iraklion it can turn out to be profitable while Stockholm does not.

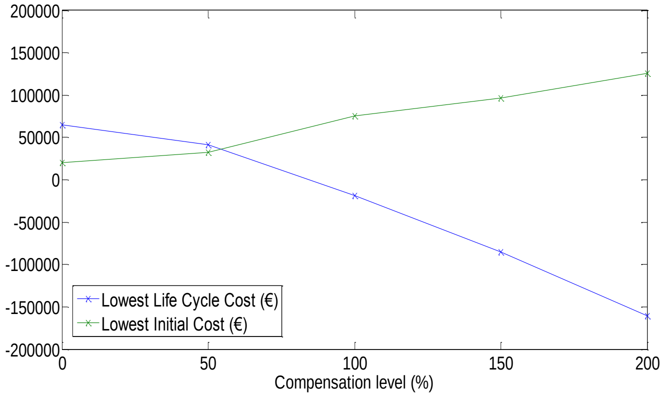


Figure 5.26: Impact of compensation level on economics (SP=230%BP- Lisbon)

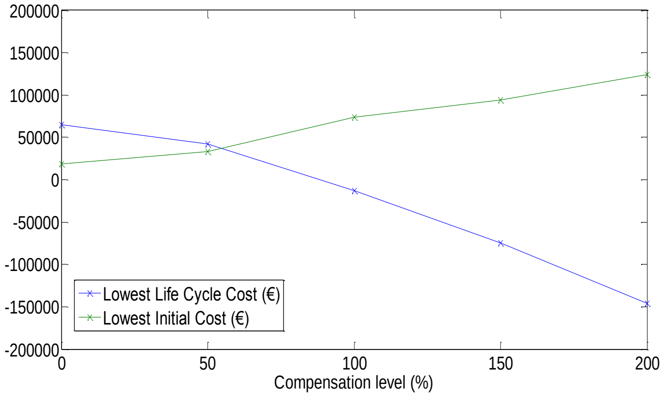


Figure 5.27: Impact of compensation level on economics (SP=230%BP- Iraklion)

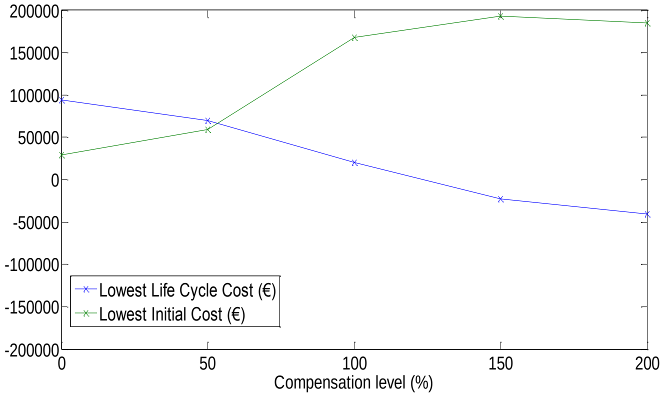


Figure 5.28: Impact of compensation level on economics (SP=230%BP- Stockholm)

The results from figures 5.26, 5.27 and 5.28 show that in the SP=230%BP scenario-the lowest LCC decreases and the lowest IC increases with the compensation level. As expected there is a positive life-cycle cash flow (negative life cycle cost) when financial incentives are present.

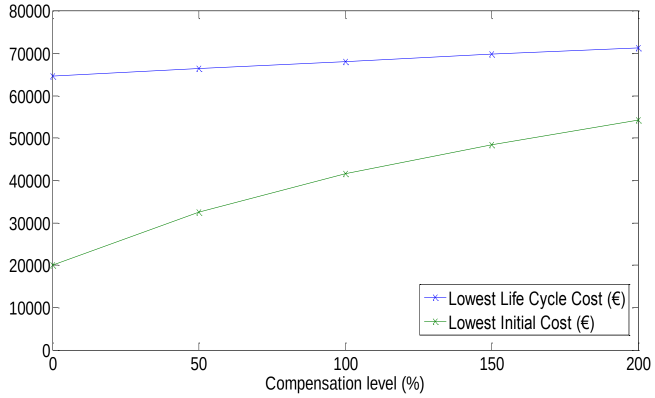


Figure 5.29: Impact of compensation level on economics (SP=50%BP- Lisbon)

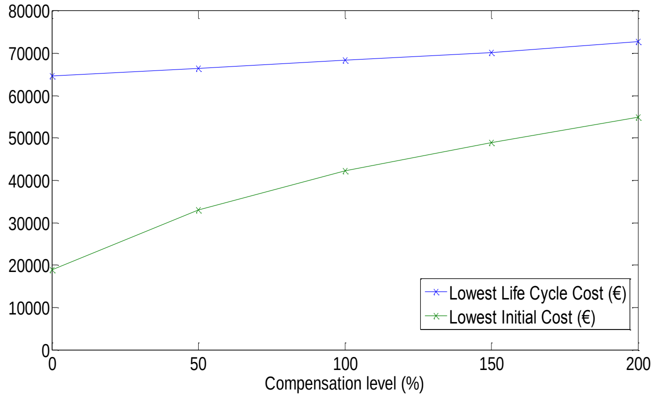


Figure 5.30: Impact of compensation level on economics (SP=50%BP-Iraklion)

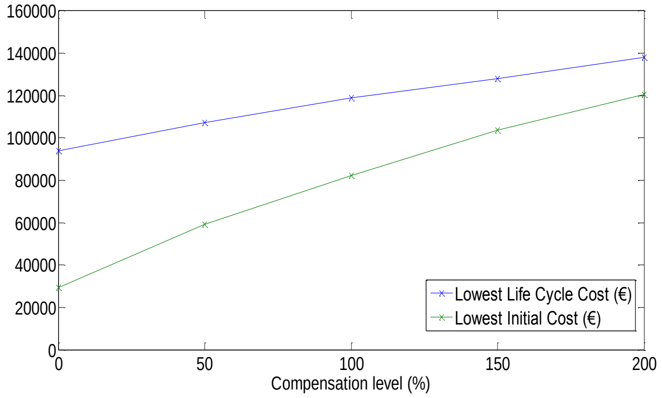


Figure 5.31: Impact of compensation level on economics (SP=50%BP- Stockholm)

The results from the above graphs (Figures 5.29, 5. 30 and 5.31) show that in the SP=50%BP scenario for all climates, as the compensation level increases, both the lowest IC and the lowest LCC increase. This is explained by the fact that more PV is used (see chapter 5.6.2) and as a result the lowest LCC increase. In this case though, the energy export does not turn out to be profitable in the long run (25 years' time) for none of the climates.

Since in the scenario with the SP=230%BP there is a positive cash flow over the project life cycle, it is interesting to know how quickly the initial investment is recovered. Consequently, the length of the time required to recover the costs of the investment, known as payback period, was computed for this sell-price scenario. Table 5.17 shows the results obtained.

Table 5.17: Payback Period for the SP=230%BP tariff scenario

		Compensation level	LLCC (€)	IC of LLCC (€)	LIC (€)	LCC of the LIC (€)	Payback Period
SP=230%BP	Lisbon	200	-160386	214663	126074	-128408	13
		150	-85445	123524	96264	-68653	13
		100	-18425	79430	75667	-15703	19
		50	41535	35544	32497	43041	-
		0	64688	32886	20016	75598	-
	Iraklion	200	-146146	212731	124057	-117251	13
		150	-74243	107560	93890	-59589	13
		100	-13238	77160	73622	-10791	20
		50	41931	37036	32992	44222	-
		0	64664	33156	18839	75198	-
	Stockholm	200	-40582	199014	185213	-32544	20
		150	-22414	196975	192923	-18023	22
		100	20345	192412	168127	24169	-
		50	70128	59964	59261	79733	-
		0	93963	36685	29272	111927	-

As it can be observed from the table 5.17, increasing the compensation level decreases the payback period. When the compensation level is equal to 0% or 50% (in the case of Stockholm, even 100%), the initial investment cannot be recovered, for any climate scenario.

When moving from 100% compensation to 150%, the payback period changes significantly. However, from 150% to 200% compensation the payback period has no significant change. The reason for this different behavior seems to be that in the latter case the payback becomes essentially determined by the payback period of the PV systems, while for low compensation levels the intrinsic efficiency of the building plays a more important role. More specifically, in the case of Stockholm the design variables 'chosen' are highly efficient since the maximum PV area allowed for compensation is 80% and as a result the efficiency on the demand side has to increase to offset the compensation level. For the cases of Lisbon and Iraklion however this is not the case since the PV area required is by far less than the maximum PV area allowed (see chapter 5.5) so there is no need to increase the energy efficiency (represented by the design variables choice) while there is still profit.

5.6.2 Impact of compensation level on the design choices

This part of the work analyses the impact of variations of the compensation level on the LLCC and LIC design choices. The scenarios analyzed are the same ones as in Table 5.16 of chapter 5.6. The design variables of the economic optimal design solutions are presented in tables 5.18, 5.19 and 5.20 while table 5.21 is complementary and shows the percentage of the area of the roof that is covered with PV. The results were computed first in conditions of the central scenario in terms of sell-price, i.e., with SP=BP then for the alternative scenario where SP=230%BP and finally for the second alternative scenario where SP=50%BP.

Table 5.18: Design variable values of the LCC optimal solution in the SP=BP scenario

		Lisbon					Iraklion					Stockholm				
	SP=BP	Compensation Level (%)														
		0	50	100	150	200	0	50	100	150	200	0	50	100	150	200
Insulation	8cm				•	•			•		•					
	15cm	•	•	•			•	•		•		•	•	•	•	•
Infiltration	High					•				•	•					
	Medium	•	•	•	•		•	•	•			•	•	•	•	•
Ventilation	Natural	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Windows	Single Glazed Clear (Al)			•	•	•			•	•	•					
	Triple Glazed low-e(Al)	•	•				•	•								
	Triple Glazed low-e (Al+TB)											•	•	•	•	•
Shading	Outside	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Glazed Area	10%	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Orientation	South	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Heating System	RCHP	•	•	•	•	•	•	•	•	•	•					
	RCHP Class A											•	•	•	•	•
Cooling System	RCHP			•	•	•			•	•	•	•		•	•	•
	RCHP class A	•	•				•	•					•			
DHW System	Heat Pump		•	•	•	•		•	•	•	•					
	Heat Pump & SC	•					•					•	•	•	•	•
Lighting	High Efficiency	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Appliances	Average Efficiency	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
PV Module	High Efficiency	-	•	•	•	•	-	•	•	•	•	-	•	•	•	•

As it can be seen from table 5.18, for the climates of Lisbon and Iraklion, the design choices tend to become somewhat less energy efficient as the compensation level increases. An explanation for this can be found in table 5.18 where it can be observed that the roof area covered by PV increases and results in design choices with decreased efficiency. However, even though it could be assumed that it would be more efficient to invest on PV placement than an increase on the efficiency, the fact that for both climates of Lisbon and Iraklion and for the 0% and 50% of compensation levels the glazing chosen is the triple low-e and then when compensation turns to 100%, 150% and 200% the glazing chosen is the single clear seemed strange. For this reason, the simulation tool was inputted with the fixed lowest LCC design options in all variables, and then, the windows variable was put in the ‘sweep’ mode. This allowed assessing the influence of this design variable on the LLCC. The effect of the variation of the window type in the output showed that the single glazed clear glazing solution is indeed the cheapest one in terms of LCC. More specifically, when the design choice is indeed the single glazed clear the LLCC is equal to 58787€ while for the double glazed clear, double glazed clear with TB, double glazed low-e with TB, triple glazed clear, triple glazed clear with TB, triple glazed low-e and triple glazed low-e with TB the LLCC becomes correspondingly 59827€, 59697€, 59438€, 59833€, 60781€, 59455€ and 60400€.

Furthermore, for the climate of Stockholm the design choices of the LLCC optimal solution remain almost the same while the compensation level increases.

Table 5.19 presents the design variable values of the LCC optimal solution for the SP=230%BP scenario. As it can be seen, for the climates of Lisbon and Iraklion and for the compensation level of 0% the design choices tend to be more efficient in comparison to greater compensation levels. This can be explained by the fact that in the absence of compensation, a good level of energy efficiency is economically justified in LCC terms. However, when introducing PV and paying its production generously, it becomes financially more sensible to have a lot of PV production which needs a higher point of energy density to enable it and therefore decreases the buildings intrinsic efficiency.

Furthermore, for the climate of Stockholm and the compensation levels equal or greater than 100%, it can be observed that, the design choices efficiency is significantly decreased compared to the other levels of compensation. In this case, the roof area covered by PV is saturated (80% of the roof area) but the cash flow is positive for the LCC optimal solution.

Table 5.19: Design variable values of the LCC optimal solution in the SP=230%BP scenario

SP=230%BP		Lisbon					Iraklion					Stockholm				
		Compensation Level (%)														
		0	50	100	150	200	0	50	100	150	200	0	50	100	150	200
Insulation	3cm			•	•	•			•	•	•					
	8cm		•					•								
	15cm	•					•					•	•	•	•	•
Infiltration	High		•	•	•	•		•	•	•	•			•		
	Medium	•					•					•	•		•	•
Ventilation	Natural	•	•	•			•	•	•	•		•	•	•	•	•
	MV				•	•					•					
Windows	Single Glazed Clear (Al)		•	•	•	•		•	•	•	•					
	Double Glazed clear (Al)															•
	Double Glazed low-e (Al+TB)													•	•	
	Triple Glazed low-e (Al)	•					•						•			
	Triple Glazed low-e (Al+TB)											•				
Shading	Inside			•	•	•			•	•	•					
	Outside	•	•				•	•				•	•	•	•	•
Glazed Area	10%	•	•	•	•		•	•	•	•		•	•	•	•	•
	40%					•					•					
Orientation	Other			•	•	•			•	•	•					
	South	•	•				•	•				•	•	•	•	•
Heating System	Boiler			•	•	•			•	•	•					
	Electric radiator		•					•						•	•	
	RCHP	•					•									•
	RCHP class A											•	•			
Cooling System	RCHP		•	•	•	•		•	•	•	•	•	•	•	•	•
	RCHP class A	•					•									
DHW System	Storage Gas			•	•	•			•	•	•					
	Storage electricity							•						•		•
	Heat Pump		•										•		•	
	Heat Pump & SC	•					•					•				
Lighting	High Efficiency	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Appliances	Average Efficiency	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
PV Module	High Efficiency	-	•	•	•	•	-	•	•	•	•	-	•	•	•	•

Table 5.20 shows the design variable values of the LCC optimal solution for the SP=50%BP electricity price scenario. As it can be seen, for all climate scenarios and compensation levels the efficiency of the design choices is high and doesn't present significant variations when moving between different percentages of compensation.

Table 5.20: Design variable values of the LCC optimal solution in the SP=50%BP scenario

SP=50%BP		Lisbon					Iraklion					Stockholm				
		Compensation Level (%)														
		0	50	100	150	200	0	50	100	150	200	0	50	100	150	200
Insulation	15cm	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Infiltration	Medium	•	•	•	•	•	•	•	•	•	•	•	•			
	Low													•	•	•
Ventilation	Natural	•	•	•	•	•	•	•	•	•	•	•	•			
	MVHR													•	•	•
Windows	Double Glazed low-e (Al+TB)				•											
	Triple Glazed low-e (Al)	•	•	•		•	•	•	•	•	•					
	Triple Glazed low-e (Al+TB)											•	•	•	•	•
Shading	Outside	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Glazed Area	10%	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Orientation	Other										•					
	South	•	•	•	•	•	•	•	•	•		•	•	•	•	•
Heating System	RCHP	•	•		•		•	•	•	•						
	RCHP Class A			•		•					•	•	•	•	•	•
Cooling System	RCHP Class A	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
DHW System	Heat Pump & SC	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Lighting	High Efficiency	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Appliances	Average Efficiency	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
PV Module	High Efficiency	-	•	•	•	•	-	•	•	•	•	-	•	•	•	•

Table 5.21: Roof are covered by PV for all climate and electricity price scenarios and for all compensation levels

		PV area (m^2)								
Climate		Lisbon			Iraklion			Stockholm		
Electricity price scenario		SP=BP	SP=230%BP	SP=50%BP	SP=BP	SP=230%BP	SP=50%BP	SP=BP	SP=230%BP	SP=50%BP
Compensation level	0%	-	-	-	-	-	-	-	-	-
	50%	3%	8%	3%	3%	9%	3%	11%	12%	11%
	100%	8%	29%	5%	9%	28%	5%	21%	79%	15%
	150%	14%	47%	8%	14%	43%	8%	32%	79%	23%
	200%	21%	76%	10%	21%	75%	10%	43%	79%	31%

5.7 Sensitivity analysis to the influence of design variables

This chapter presents a sensitivity analysis that was done for all climates for the SP=BP price scenario. More specifically, the simulation tool was inputted with the (fixed) LLCC design options in all variables, and then, one at a time, each variable was put in the “sweep” mode. This allowed to assess the influence of each design variable on the LLCC, on the corresponding IC and on the Total Final Energy (TFE). The effect of the variation of each design variable in the output is shown in table 5.22.

Table 5.22: Sensitivity Analysis

Design Variables		Maximum Difference (%)								
		Life Cycle Cost			Initial Cost			Final Energy		
		Lisbon	Iraklion	Stockholm	Lisbon	Iraklion	Stockholm	Lisbon	Iraklion	Stockholm
Insulation	15cm	-	1%	-	-	2%	-	-	-11%	-
	8cm	0%	-	10%	-1%	-	11%	12%	-	24%
	3cm	9%	9%	39%	9%	10%	44%	45%	28%	82%
Infiltration	Medium	-	-	-	-	-	-	-	-	-
	High	1%	2%	17%	0%	1%	19%	16%	13%	39%
	Low	-	-	-	-	-	-	-	-	-
Ventilation	Natural	-	-	-	-	-	-	-	-	-
	MVHR	23%	23%	17%	31%	31%	21%	6%	5%	9%
	MV	15%	14%	17%	19%	19%	19%	9%	7%	19%
Windows	Single Glazed Clear (Al)	-	-	13%	-	-	14%	-	-	30%
	Triple Glazed low-e (Al)	1%	1%	1%	3%	3%	1%	-10%	-9%	3%
	Triple Glazed Clear (Al+TB)	1%	3%	3%	3%	6%	3%	-10%	-6%	6%
	Triple Glazed Clear (Al)	3%	2%	3%	6%	3%	3%	-8%	-5%	9%
	Double Glazed low-e (Al+TB)	1%	1%	2%	3%	3%	2%	-9%	-8%	5%
	Doublen Glazed Clear (Al+TB)	2%	1%	6%	3%	3%	6%	-6%	-5%	13%
	Double Glazed Clear (Al)	2%	2%	11%	3%	3%	11%	-2%	-2%	24%
	Triple Glazed low-e(Al+TB)	3%	2%	-	6%	5%	-	-11%	-10%	-
Shading	Outside	-	-	-	-	-	-	-	-	-
	Inside	4%	3%	2%	3%	3%	1%	6%	8%	1%
Glazed Area	10% of Useful Area	-	-	-	-	-	-	-	-	-
	20% of Useful Area	24%	24%	19%	27%	28%	21%	9%	9%	4%
	40% of Useful Area	73%	73%	55%	84%	85%	63%	29%	27%	13%
Orientation	South	-	-	-	-	-	-	-	-	-
	Other	1%	1%	2%	2%	2%	2%	5%	4%	3%
Heating System	RCHP	-	-	7%	-	-	11%	-	-	22%
	RCHP Class A	2%	1%	-	0%	-1%	-	-7%	-8%	-
	Boiler	8%	9%	59%	15%	17%	79%	44%	45%	152%
	Condensing Boiler	6%	6%	50%	12%	14%	68%	36%	38%	131%
	Electric Radiator	4%	5%	45%	9%	11%	61%	33%	34%	120%
Cooling System	RCHP	-	-	-	-	-	-	-	-	-
	RCHP Class A	1%	0%	1%	0%	-2%	1%	-6%	-7%	-1%
DHW System	Heat Pump	-	-	1%	-	-	4%	-	-	12%
	Storage Electricity	6%	6%	9%	10%	10%	15%	24%	22%	31%
	Storage Gas	12%	12%	15%	18%	18%	22%	42%	39%	45%
	Tankless Condensing	9%	9%	10%	12%	12%	15%	24%	22%	31%
	Tankless Gas	8%	8%	12%	13%	13%	18%	31%	28%	36%
	Heat Pump & SC	2%	2%	-	-2%	-2%	-	-20%	-18%	-
	Storage Electricity & SC	2%	3%	8%	-1%	1%	10%	-12%	-10%	18%
	Storage Gas & SC	9%	9%	14%	8%	8%	18%	6%	7%	33%
	Tankless Condensing & SC	6%	5%	9%	3%	3%	11%	-12%	-10%	19%
	Tankless Gas &SC	5%	5%	10%	3%	3%	14%	-5%	-4%	24%
Lighting	High Efficiency	-	-	-	-	-	-	-	-	-
	Average Efficiency	13%	13%	7%	1%	1%	1%	4%	3%	1%
Appliances	Average Efficiency	-	-	-	-	-	-	-	-	-
	High Efficiency	16%	15%	10%	4%	4%	3%	-10%	-9%	-2%
PV Module	High Efficiency	-	-	-	-	-	-	-	-	-
	Average Efficiency	4%	5%	6%	5%	6%	7%	0%	0%	0%

The maximum influence of each design variable optimum solution on the Lowest Life Cycle Cost (LLCC), Initial Cost (IC) & Total Final Energy (TFE) resulting from the tables below, is also presented in the graphs of Figures 5.32, 5.33 and 5.34, while table 5.23 summarizes the top-bottom 3 design variables influence on the economic indicators (LLCC, IC) and on the energy performance (TFE). The results of this assessment supported the option of neglecting a certain number of design variables (see chapter 5.2).

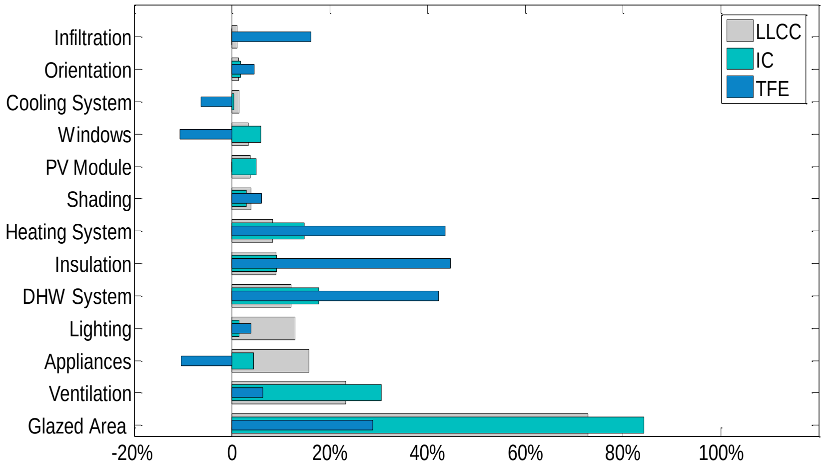


Figure 5.32: Maximum Influence of the design variables (Lisbon)

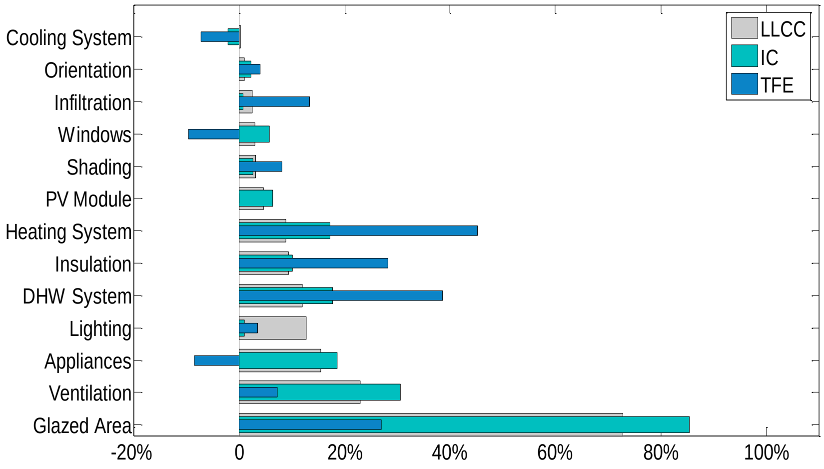


Figure 5.33: Maximum influence of the design variables (Iraklion)

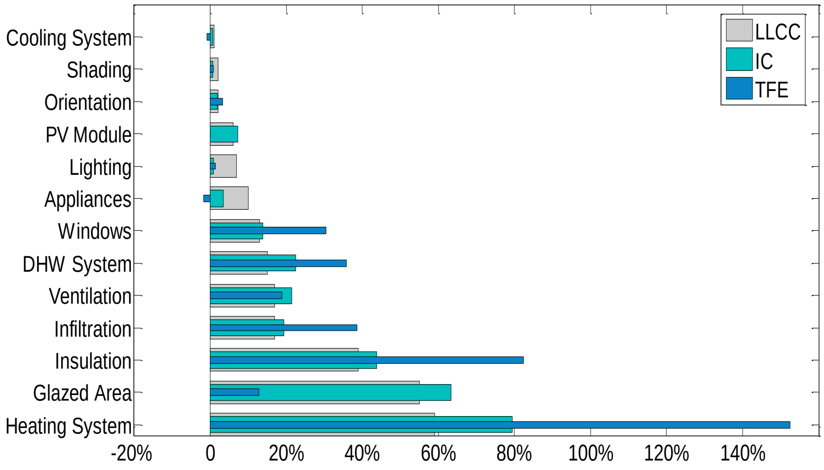


Figure 5.34: Maximum Influence of the design variables (Stockholm)

Table 5.23: Top- Bottom hierarchy of influence of design variables

Design Variables Influence			
	Lowest Life Cycle Cost		
	Lisbon	Iraklion	Stockholm
Maximum (top 3)	1.Glazed Area	1.Glazed Area	1.Heating System
	2.Ventilation	2.Ventilation	2.Glazed Area
	3.Appliances	3.Appliances	3.Insulation
Minimum (bottom 3)	11.Cooling System	11.Infiltration	11.Orientation
	12.Orientation	12.Orientation	12.Shading
	13.Infiltration	13.Cooling System	13.Cooling System
	Initial Cost		
Maximum (top 3)	1.Glazed Area	1.Glazed Area	1.Heating System
	2.Ventilation	2.Ventilation	2.Glazed Area
	3.DHW System	3.Appliances	3.Insulation
Minimum (bottom 3)	11.Lighting	11.Cooling System	11.Lighting
	12.Cooling System	12.Lighting	12.Shading
	13.Infiltration	13.Infiltration	13.Cooling System
	Total Final Energy		
Maximum (top 3)	1.Insulation	1.Heating System	1. Heating System
	2.Heating System	2.DHW System	2.Insulation
	3.DHW System	3.Insulation	3.Infiltration
Minimum (bottom 3)	11.Shading	11.Ventilation	11.Lighting
	12.Orientation	12.Orientation	12.Shading
	13.Lighting	13.Lighting	13.Cooling System

The design variables hierarchy regarding their impact on the energy performance, for the climate of Stockholm, concluded that the top 3 variables with maximum influence are the type of heating system, level of thermal insulation and air infiltration, while the efficiency of lighting, the type of shading and the type of cooling system have the smallest impact. For the climate of Lisbon the rank order found the variables: level of thermal insulation, type of heating system and type of DHW system in the top of the hierarchy and the: type of shading, the building orientation and efficiency of lighting at the bottom of the rank order. Finally, for the city of Iraklion the type of heating & DHW system as well as the level of thermal insulation variables, have the largest influence in contrast with the type of ventilation, building orientation and efficiency of lighting that have the lowest influence.

Furthermore, the design variables with the highest impact on the optimal LCC building design for Stockholm were found to be the type of heating system, the glazed area and the level of thermal insulation while the building orientation, type of shading, and type of cooling system seem to have the lowest influence. For both Lisbon & Iraklion, the glazed area, type of ventilation and appliances seem to have the largest impact while the type of cooling system, building orientation and level of air infiltration have minimum impact.

Finally, regarding the initial cost, the top 3 design variables with the highest impact on the optimal economic building design for Stockholm were ranked as follows: type of heating system, glazed area and the level of thermal insulation. The variables: efficiency of lighting, type of shading and type of cooling system were ranked last. Moreover, for the climate of Lisbon variations in the glazed area, type of ventilation system and type of DHW system influence the most the initial cost while the efficiency of lighting, the type of cooling system and the level of air infiltration have a minimized impact. Finally, for Iraklion the top 3 ranked variables include the: glazed area, the type of ventilation system and the appliances while the bottom 3 ranked ones are the type of cooling system, efficiency of lighting and level of air infiltration.

5.8 Sensitivity analysis to limits of roof area available for installing PV

This part of the work studies the impact of the area available for PV installation upon the economic indicators. The scenarios analyzed include all climates and all price scenarios for the cases that area for PV installation is: i) unlimited; ii) limited to 80% of the roof area; limited to 40% of the roof area. In all cases the study is made considering 100% compensation.

Figures 5.35, 5.36 and 5.37 show the influence of limits on the PV covering upon the LCC of the LLCC and the LIC of IC optimum design solutions. The first important observation is that for the SP=BP and the SP=50%BP scenarios the roof area of the optimal solutions never reaches 40% and therefore the roof area limitation does not have any impact.

It can also be observed that, for the climate of Stockholm and for the SP=230%BP price scenario, introducing limits to the PV area causes the LIC to decrease and the LLCC to increase. This happens because for this scenario the economical optimal solutions would require about 170% of the roof area (figure 5.38) and therefore introducing a limit will cause a penalty in terms of economic-efficiency. On the other hand, less PV area implies less initial cost, hence the lowering of the LIC.

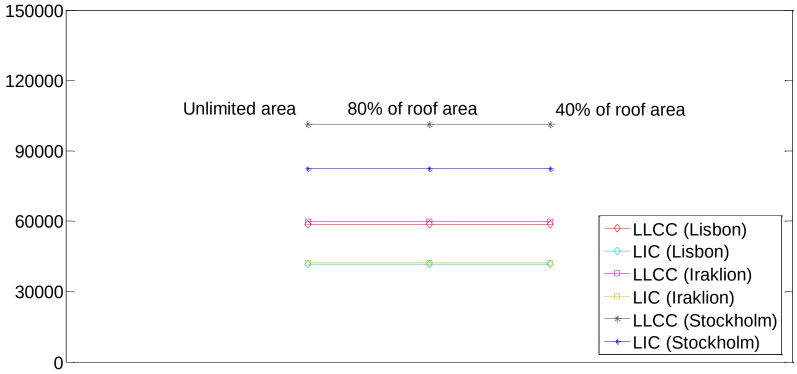


Figure 5.35: Impact of limits on the PV area upon the economic indicators for the SP=BP scenario

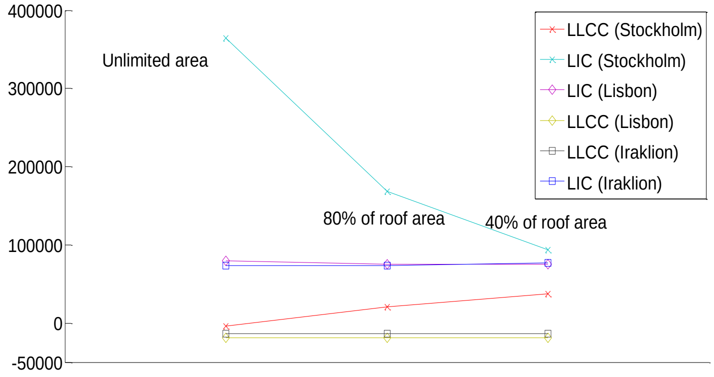


Figure 5.36: Impact of limits on the PV area upon the economic indicators for the SP=230%BP scenario

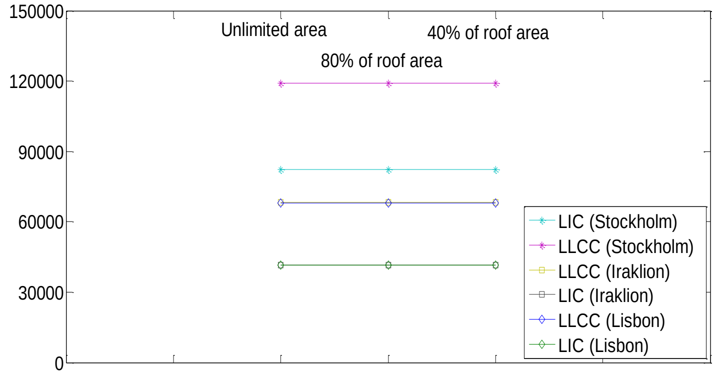


Figure 5.37: Impact of limits on the PV area upon the economic indicators for the SP=50%BP scenario

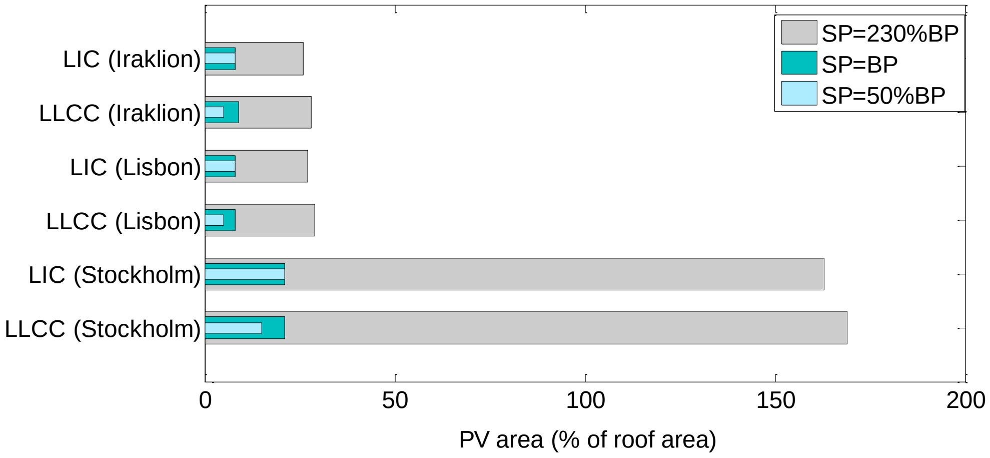


Figure 5.38: PV area needed for 100% compensation, depending on the climate and price scenarios.

Following, the impact of the available PV area on the design choices is presented. The design variables of the LLCC choices in each of the PV-limit area scenarios are presented in tables 5.24, 5.25 and 5.26.

As it can be seen from table 5.25, reducing the available area leads to more energy efficient design solutions. This applies for the climate of Stockholm and the SP=230%BP price scenario. For the same price scenario but for the climates of Lisbon and Iraklion, the case is not the same since the maximum PV area as shown in previous chapter, is more than enough to offset the energy use and compensation is reached with less efficient design solutions since there is still a life cycle economic benefit resulting from the integration of the PV modules.

According to table 5.24, a decrease on the available PV covering area doesn't influence the design solutions as regards the climates of Lisbon , Iraklion and Stockholm and for the SP=50%BP scenario.

Finally, what can be noted from table 5.26 is that for all climates and for the SP=50%BP electricity price scenario, no variations are observed in the design choices when moving from unlimited, to 80% and to 40% roof area for PV covering .

Table 5.24: Impact of PV area limit on design choices (SP=BP)

		Lisbon			Iraklion			Stockholm		
SP=BP					PV area					
		unlimited	80%	40%	unlimited	80%	40%	unlimited	80%	40%
Insulation	8cm				•	•	•			
	15cm	•	•	•				•	•	•
Infiltration	Medium	•	•	•	•	•	•	•	•	•
Ventilation	Natural	•	•	•	•	•	•	•	•	•
Windows	Single Glazed Clear (Al)	•	•	•	•	•	•			
	Triple Glazed low-e (Al+TB)							•	•	•
Shading	Outside	•	•	•	•	•	•	•	•	•
Glazed Area	10%	•	•	•	•	•	•	•	•	•
Orientation	South	•	•	•	•	•	•	•	•	•
Heating Equipment	RCHP	•	•	•	•	•	•			
	RCHP Class A							•	•	•
Cooling Equipment	RCHP	•	•	•	•	•	•	•	•	•
DHW System	Heat Pump	•	•	•	•	•	•			
	Heat Pump & SC							•	•	•
Lighting	High Efficiency	•	•	•	•	•	•	•	•	•
Appliances	Average Efficiency	•	•	•	•	•	•	•	•	•
PV Module	High Efficiency	•	•	•	•	•	•	•	•	•

Table 5.25: Impact of PV area limit on design choices (SP=230%BP)

SP=230%BP		Lisbon			Iraklion			Stockholm		
					PV area					
		unlimited	80%	40%	unlimited	80%	40%	unlimited	80%	40%
Insulation	3cm	•	•	•	•	•	•	•		
	8cm									•
	15cm								•	
Infiltration	High	•	•	•	•	•	•	•	•	
	Medium									•
Ventilation	Natural	•	•	•	•	•	•	•	•	•
Windows	Single Glazed Clear (Al)	•	•	•	•	•	•	•		
	Double Glazed Clear (Al+TB)								•	
	Triple Glazed low-e (Al+TB)									•
Shading	Inside	•	•	•	•	•	•			
	Outside							•	•	•
Glazed Area	10%	•	•	•	•	•	•	•	•	•
	40%									
Orientation	Other	•	•	•	•	•	•	•		
	South								•	•
Heating System	Boiler	•	•	•	•	•	•	•		
	Electric radiator								•	
	RCHP									•
Cooling System	RCHP	•	•	•	•	•	•	•	•	•
DHW System	Storage Gas	•	•	•	•	•	•	•		
	Storage Electricity								•	•
Lighting	High Efficiency	•	•	•	•	•	•	•	•	•
Appliances	Average Efficiency	•	•	•	•	•	•	•	•	•
PV Module	High Efficiency	•	•	•	•	•	•	•	•	•

Table 5.26: Impact of PV area on design choices (SP=50%BP)

SP=50%BP		Lisbon			Iraklion			Stockholm		
					PV area					
		unlimited	80%	40%	unlimited	80%	40%	unlimited	80%	40%
Insulation	15cm	•	•	•	•	•	•	•	•	•
Infiltration	Medium	•	•	•	•	•	•			
	Low							•	•	•
Ventilation	Natural	•	•	•	•	•	•			
	MVHR							•	•	•
Windows	Triple Glazed low-e (Al)	•	•	•	•	•	•			
	Triple Glazed low-e (Al+TB)							•	•	•
Shading	Outside	•	•	•	•	•	•	•	•	•
Glazed Area	10%	•	•	•	•	•	•	•	•	•
Orientation	South	•	•	•	•	•	•	•	•	•
Heating System	RCHP Class A	•	•	•	•	•	•	•	•	•
Cooling System	RCHP Class A	•	•	•	•	•	•	•	•	•
DHW System	Heat Pump & SC	•	•	•	•	•	•	•	•	•
Lighting	High Efficiency	•	•	•	•	•	•	•	•	•
Appliances	Average Efficiency	•	•	•	•	•	•	•	•	•
PV Module	High Efficiency	•	•	•	•	•	•	•	•	•

5.9 Impact of including Small Wind Turbines as an electricity generation option

This final subchapter of the results of this case-study analyzes a scenario with the wind turbines included as a microgeneration design option. All climate and electricity price scenarios are analyzed for this purpose, while the area available for the deployment of renewables is considered unlimited. The analysis that follows includes the graphs that show the relation between the lowest life cycle and the related initial costs, a sensitivity analysis for the SP=BP scenario and an overview of the best design options and considers the optimal combination of design solutions that deviate at most 20% from the LLCC.

5.9.1 Analysis of solutions in a scenario with SP=BP

An assessment of the analysis of the full space of design solutions in a scenario with SP=BP is presented in figures 5.39, 5.40 and 5.41, in terms of the relation between the LCC and the corresponding Initial Cost (IC). The red spots in the graphs represent the LLCC and the LIC for the range of the solutions displayed.

A comparison between figures 5.39, 5.40 and 5.41 with the coresponding figures 5.5, 5.6 and 5.7 of chapter 5.2 leads to the observation that when allowing wind turbines to be a microgeneration design option while financial incentives are absent they will be chosen over photovoltaics (see table 5.27 of chapter 5.93). In agreement with that, both the LLCC and LIC are lower for all climates.

As happened in section 5.2, in the SP=BP price scenario the cash flow turns negative in the sense that there is not a return of the initial investment in the life cycle of 25 years, regardless the climate. Secondly, for the climates of Lisbon & Iraklion (Figures 5.39 & 5.40), less energy efficient design solutions seem to be chosen as optimal than for the case of Stockholm (Figure 5.41).

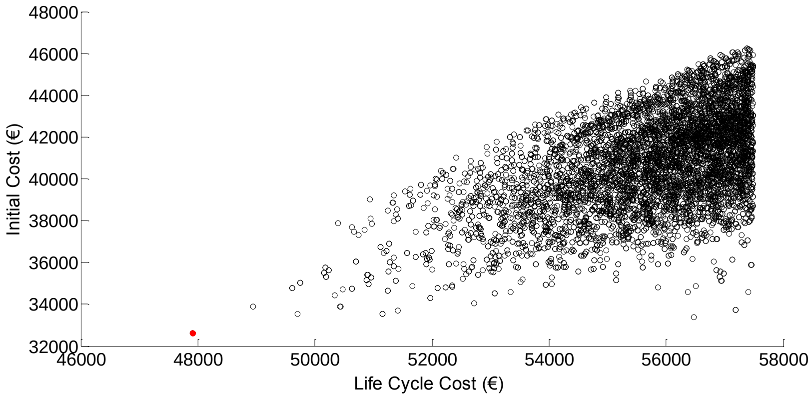


Figure 5.39: Relation between LLCC and IC for the climate of Lisbon with hypothetical SP=BP for the design solutions deviating less than 20% from the lowest LCC

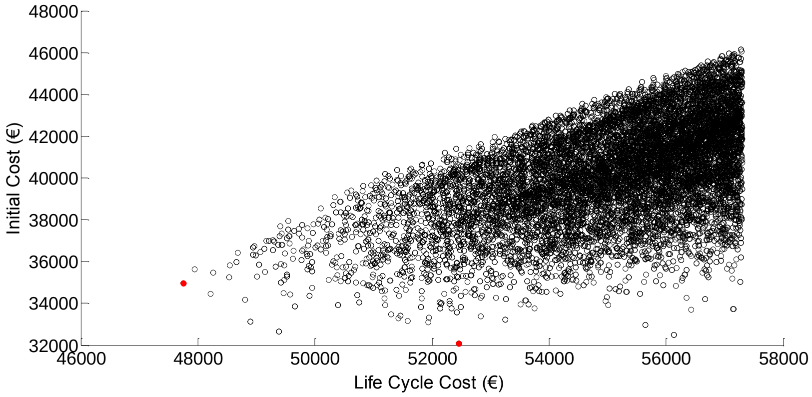


Figure 5.40: Relation between LLCC and IC for the climate of Iraklion with hypothetical SP=BP for the design solutions deviating less than 20% from the lowest LCC

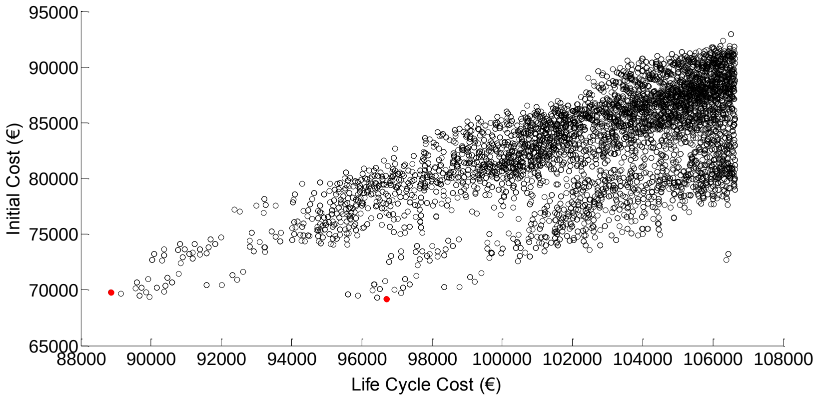


Figure 5.41: Relation between LLCC and IC for the climate of Stockholm with hypothetical SP=BP for the design solutions deviating less than 20% from the lowest LCC

5.9.2 Analysis of solutions in a scenario with SP=230%BP

This chapter analyses solutions in a scenario with SP=230%BP. Figures 5.42, 5.43 and 5.44, show the relation between the LCC and the corresponding IC for the solutions deviating less than 20% from the LLCC. The red spots in the graphs represent the LLCC and the LIC for the range of the solutions displayed.

A comparison between figures 5.42, 5.43 and 5.44 with the corresponding figures 5.11, 5.12 and 5.13 of chapter 5.3 results in the conclusion that when allowing wind turbines to be a microgeneration design choice while financial incentives are present, they will be chosen over photovoltaics (see table 5.27 of chapter 5.9.3).

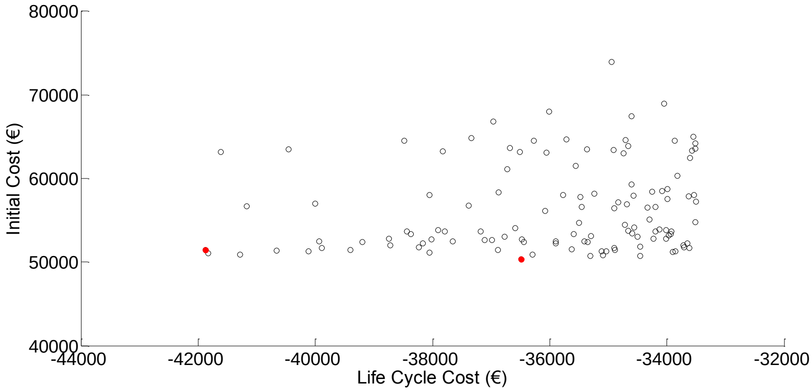


Figure 5.42: Relation between LLCC and IC for the climate of Lisbon with hypothetical SP=230%BP for the design solutions deviating less than 20% from the lowest LCC

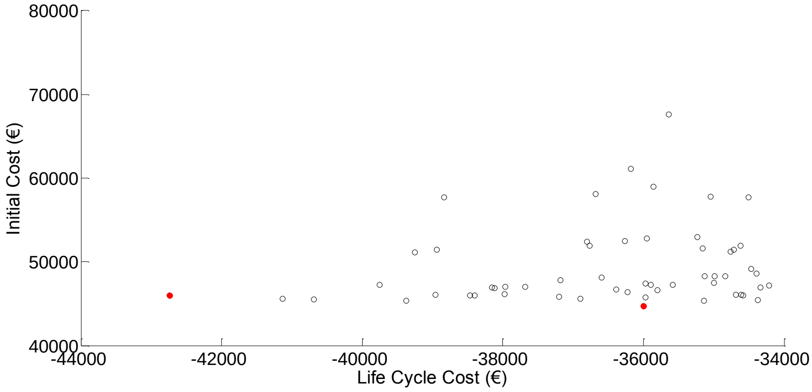


Figure 5.43: Relation between LLCC and IC for the climate of Iraklion with hypothetical SP=230%BP for the design solutions deviating less than 20% from the lowest LCC

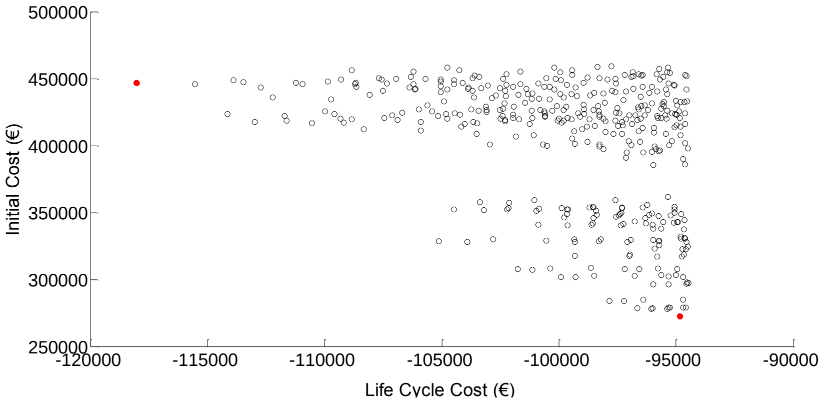


Figure 5.44: Relation between LLCC and IC for the climate of Stockholm with hypothetical SP=230%BP for the design solutions deviating less than 20% from the lowest LCC

5.9.3 Analysis of solutions in a scenario with SP=50%BP

An assessment of the analysis of solutions in a scenario with SP=50%BP is studied in this chapter with the graphs that follow, showing once again the relation between the LCC and the corresponding Initial Cost (IC) (the red spots in the graphs represent the LLCC and the Lowest Initial Cost (LIC) for the range of the solutions displayed) (Figures 5.45, 5.46 and 5.47).

Figures 5.45, 5.46 and 5.47 when compared to the corresponding figures 5.17, 5.18 and 5.19 of chapter 5.4, lead to the conlcusion that when allowing wind turbines to be a microgeneration design choice while financial incentives are absent (SP=50%BP), they will be chosen over photovoltaics (see table 5.27 of chapter 5.9.3) while both the LLCC and LIC are lower for all climates.

Additionally, as in section 5.4, it can be noted that when the electricity price bought is equal to half of the electricity price bought the cash flow is negative. More specifically, in a time period of 25 years there is no payback for all climates. Secondly, for the climates of Lisbon & Iraklion (Figures 5.45 and 5.46) less energy efficient design solutions seem to be chosen as optimal because both the LLCC and the correspondent IC are much lower than in the case of Stockholm (Figure 5.47).

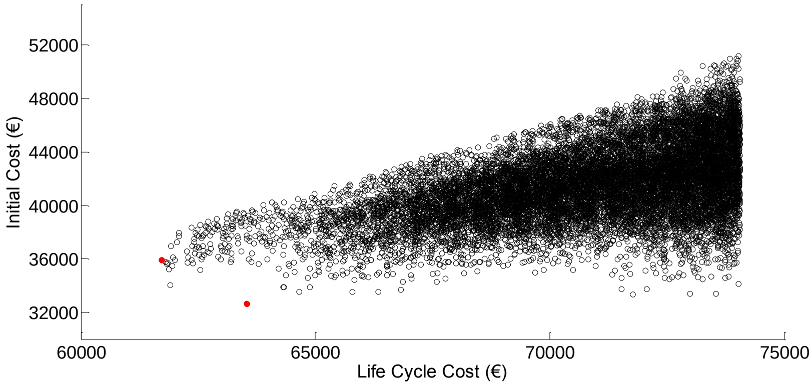


Figure 5.45: Relation between LLCC and IC for the climate of Lisbon with hypothetical SP=50%BP for the design solutions deviating less than 20% from the lowest LCC

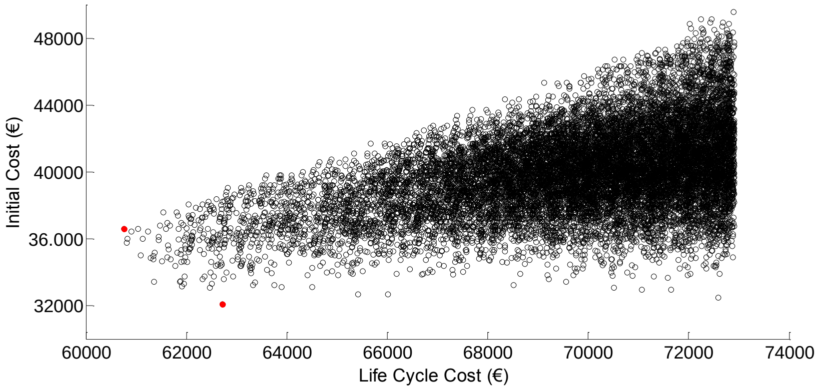


Figure 5.46: Relation between LLCC and IC for the climate of Iraklion with hypothetical SP=50%BP for the design solutions deviating less than 20% from the lowest LCC

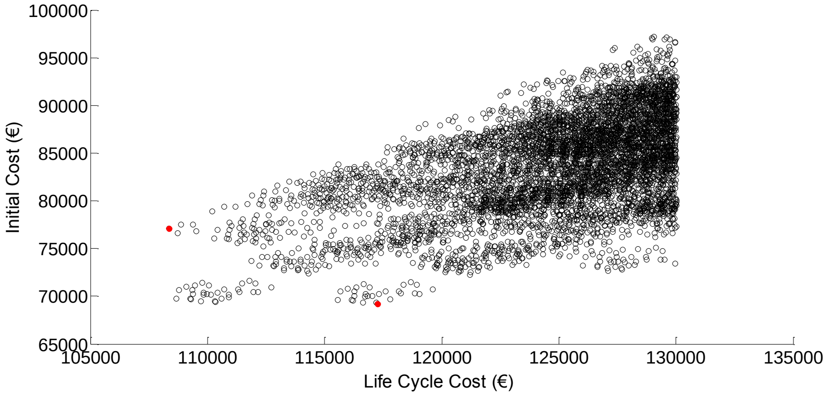


Figure 5.47: Relation between LLCC and IC for the climate of Stockholm with hypothetical SP=50%BP for the design solutions deviating less than 20% from the lowest LCC

A third main conclusion that derives from an overview of the LCC versus IC graphs for all climates and all electricity price scenarios (‘cloud’ graphs of chapters 5.9.1, 5.9.2 and 5.9.3) is that the LLCC increases when the price of electricity sold decreases. This is primarily because the electricity sold is paid at lower price, even if the amount of electricity sold is also changing. Furthermore, in the SP=BP and SP=50%BP scenarios, the design variables tend to be more energy efficient and thus a more expensive solution in terms of initial cost.

Table 5.27 serves for the comparison of the LLCC and LIC in both cases when the microgeneration choice is either PV or WT; it summarizes the LLCC and LIC for all climate contexts and sell-buy price scenarios, for the case when there is no limit put to the area available for WT placement while the available area for PV placement is considered to be limited up to 80% to the roof area.

Table 5.27: LLCC & LIC values for PV versus WT microgeneration options

Climate	Microgeneration Option	PV		WT	
	Sell-Buy Price Scenario	LLCC (€)	LIC (€)	LLCC (€)	LIC (€)
Lisbon	SP=BP	58787	41582	47907	32627
	SP=230%BP	-18425	75667	-41877	50359
	SP=50%BP	68035	41582	61716	32627
Iraklion	SP=BP	59669	42245	47750	32071
	SP=230%BP	-13238	73622	-42738	44720
	SP=50%BP	68340	42245	60755	32071
Stockholm	SP=BP	101211	82285	88864	69209
	SP=230%BP	20345	168127	-118043	272666
	SP=50%BP	119021	82285	108355	69209

As it can be seen from the table 5.27, for all the electricity sell-buy price scenarios the WT is the chosen over PV for the LLCC design choice. In accordance, both the LLCC and LIC are lower in the case when WT is a possibility of design choice with the exception of the LIC for the SP=230%BP scenario in Stockholm which has a much higher LIC. It was verified that in this case the software choses a very inefficient building to justify the installation of a very high number of WTs.

5.9.4 Sensitivity analysis to the influence of design variables

This part of the analysis includes a sensitivity analysis for all climates for the SP=BP price scenario. More specifically, variations starting from the best design choices (LLCC) were studied in order to study the influence of each design variable on the LLCC, the corresponding IC and the Total Final Energy (TFE). The impact of changes in design variables upon the outputs is shown in table 5.28 that follows.

Table 5.28: Variation of optimum design variables

Design Variables		Maximum Difference (%)								
		Life Cycle Cost			Initial Cost			Final Energy		
		Lisbon	Iraklion	Stockholm	Lisbon	Iraklion	Stockholm	Lisbon	Iraklion	Stockholm
Insulation	8cm	-	-	12%	-	-	13%	-	-	23%
	3cm	11%	6%	34%	13%	8%	38%	26%	15%	80%
	15cm	5%	9%	-	8%	11%	-	10%	40%	-
Infiltration	high	-	5%	19%	-	6%	22%	-	22%	38%
	medium	5%	-	-	9%	-	-	13%	-	-
	low	-	-	-	-	-	-	-	-	-
Ventilation	Natural	-	-	-	-	-	-	-	-	-
	MVHR	39%	39%	21%	57%	53%	27%	5%	5%	9%
	MV	26%	26%	15%	38%	35%	18%	7%	10%	18%
Windows	Single Glazed Clear (Al)	-	9%	12%	-	12%	13%	-	3%	26%
	Triple Glazed low-e (Al)	7%	4%	-	13%	6%	-	9%	10%	-
	Triple Glazed Clear (Al+TB)	5%	5%	1%	10%	7%	1%	8%	8%	2%
	Triple Glazed Clear (Al)	6%	2%	6%	10%	4%	7%	6%	6%	6%
	Double Glazed low-e (Al+TB)	4%	3%	0%	7%	5%	0%	5%	10%	2%
	Double Glazed Clear (Al+TB)	5%	2%	7%	9%	3%	7%	9%	6%	9%
	Double Glazed Clear (Al)	4%	-	7%	7%	-	7%	6%	-	20%
	Triple Glazed low-e (Al+TB)	2%	6%	1%	4%	9%	1%	2%	12%	3%
Shading	Outside	-	-	-	-	-	-	-	-	-
	Inside	13%	13%	1%	16%	15%	0%	5%	6%	1%
Glazed Area	10% of Useful Area	-	-	-	-	-	-	-	-	-
	20% of Useful Area	38%	38%	24%	51%	49%	29%	5%	8%	7%
	40% of Useful Area	90%	91%	66%	117%	115%	78%	18%	25%	22%
Orientation	South	-	-	-	-	-	-	-	-	-
	Other	12%	12%	0%	17%	16%	0%	5%	6%	3%
Heating System	RCHP	-	9%	9%	-	7%	14%	-	25%	23%
	RCHP Class A	5%	14%	-	4%	10%	-	11%	30%	-
	Boiler	14%	12%	53%	29%	18%	75%	65%	8%	154%
	Condensing Boiler	14%	12%	41%	29%	18%	59%	54%	3%	132%
	Electric Radiator	14%	-	40%	27%	-	58%	49%	-	122%
Cooling System	RCHP	-	-	-	-	-	-	-	-	-
	RCHP Class A	4%	3%	1%	3%	2%	1%	4%	5%	1%
DHW System	Heat Pump	-	-	1%	-	-	5%	-	-	12%
	Storage Electricity	10%	10%	7%	17%	16%	13%	19%	17%	30%
	Storage Gas	10%	10%	13%	17%	16%	21%	33%	30%	43%
	Tankless Condensing	13%	13%	8%	19%	18%	14%	19%	17%	30%
	Tankless Gas	10%	10%	7%	17%	16%	13%	24%	22%	35%
	Heat Pump & SC	9%	9%	-	7%	6%	-	15%	14%	-
	Storage Electricity & SC	7%	7%	5%	6%	6%	8%	9%	8%	18%
	Storage Gas & SC	19%	19%	12%	24%	22%	16%	5%	5%	31%
	Tankless Condensing & SC	10%	10%	7%	9%	8%	9%	9%	7%	18%
	Tankless Gas &SC	8%	8%	12%	7%	6%	16%	4%	3%	23%
Lighting	High Efficiency	-	-	-	-	-	-	-	-	-
	Average Efficiency	26%	14%	8%	17%	0%	0%	3%	2%	1%
Appliances	Average Efficiency	-	-	-	-	-	-	-	-	-
	High Efficiency	23%	23%	12%	11%	10%	5%	7%	4%	2%
Microgeneration System	WT 2.4KW	-	-	-	-	-	-	-		-
	WT 1.8KW	7%	30%	6%	10%	20%	7%	0%	0%	0%
	WT 400W	89%	107%	114%	131%	126%	145%	0%	0%	0%
	PV Module(High.Eff)	25%	53%	15%	36%	51%	19%	0%	0%	0%
	PV module (Av.Eff)	30%	59%	22%	44%	60%	28%	0%	0%	0%

The maximum influence of each design variable optimum solution on the Lowest Life Cycle Cost (LLCC), Initial Cost (IC) & Total Final Energy (TFE), resulting from the table 5.28, is presented in the graphs below (Figure 5.48, 5.49 and 5.50), while table 5.29 summarizes the top-bottom 3 design variables influence on the economic indicators (LLCC, IC) and on the energy performance (TFE).

Compared to the results of subchapter 5.7, there were some minor changes in the hierarchy of design variables taken from different aspects (economically and energetically related). More specifically, the design variables hierarchy regarding their impact on the energy performance, for the climate of Stockholm, included the type of heating system, level of thermal insulation and type of DHW system in the first three places and the efficiency of lighting, type of shading and type of cooling system in the three last. Furthermore, for the climate of Lisbon the rank order shows that the type of heating system, type of DHW system and the level of thermal insulation come first in the hierarchy while the building orientation, the type of cooling system and the efficiency of lighting. Finally for Iraklion the variables: level of thermal insulation, type of heating and DHW system have the largest impact while the type of cooling system, the appliances, and the efficiency of lighting have a reduced influence.

The three top variables with the highest impact on the optimal LCC economic building design for Stockholm were the type of microgeneration system, the glazed area and the type of heating system while the type of shading, the type of cooling system and the building orientation had the lowest influence. For Lisbon the glazed area, the type of microgeneration system and the type of ventilation system influence the most while the type of window, the level of air infiltration and the type of cooling system influence the least. Finally, for Iraklion the optimal LCC was found to be significantly influenced by variations in the type of microgeneration system, the glazed area and the type of ventilation system while design variables like the type of windows, the level of air infiltration and the type of cooling system don’t affect the LCC.

Finally, in reference to the initial cost the design variables with the highest impact on the optimal economic building design for Stockholm are the type of microgeneration system, the glazed area and the type of heating system while the type of cooling system, the building orientation and type of lighting are ranked last. Moreover, for the climate of Lisbon the variables with significant influence are the type of microgeneration system, the glazed area and the type of ventilation system while the appliances, the level of air infiltration and the type of cooling system do not have the minimum impact. Finally, for Iraklion the rank order puts the type of microgeneration system, the glazed area and the type of ventilation in the top 3 places while the level of air infiltration, the type of lighting and the type of cooling system come last.

Tables 5.30, 5.31 and 5.32 summarize the best design solutions choices for all climates and all electricity price scenarios. Regardless the price or climate scenario (SP=BP & SP=50%BP) wind turbines are selected over PV. Once again, design choices tend to be more efficient provided that the electricity price sold is equal or half of the electricity price sold for all climates though this is not the case when SP=230%BP.

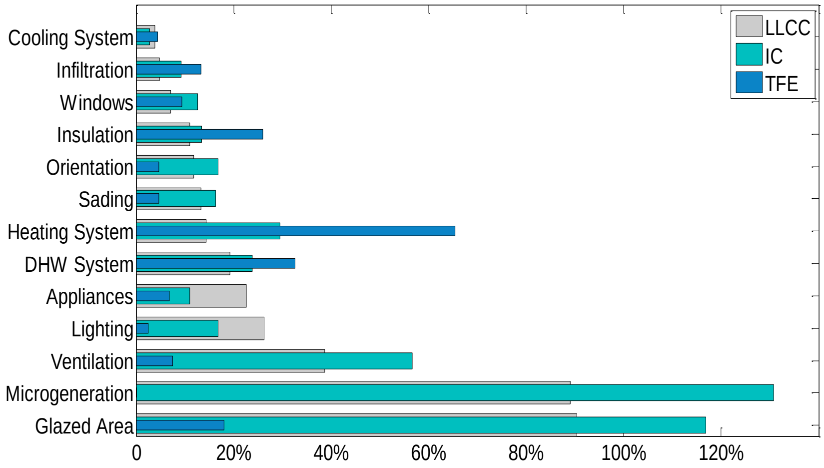


Figure 5.48: Maximum influence of the design variables (Lisbon)

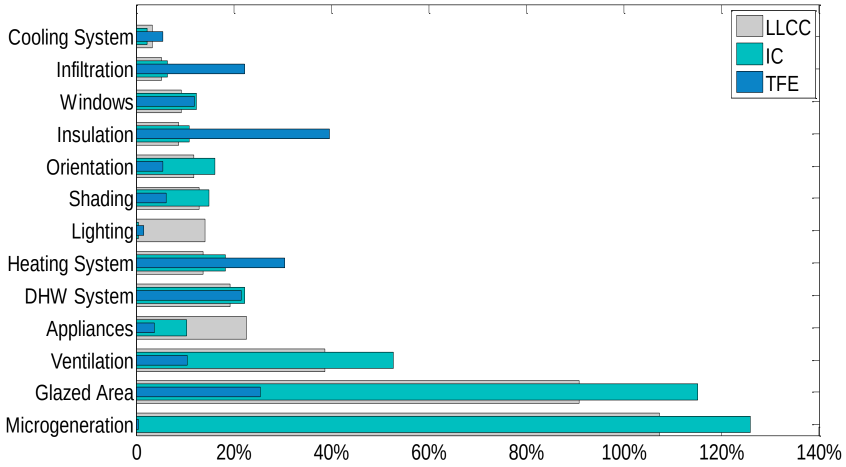


Figure 5.49: Maximum influence of the design variables (Iraklion)

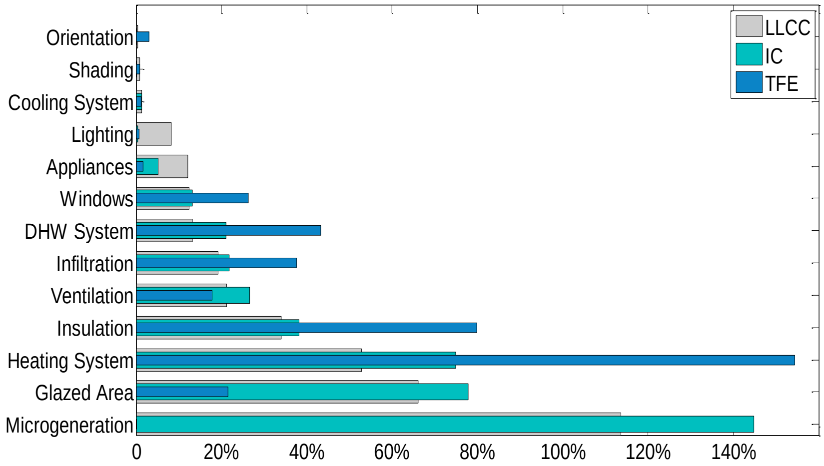


Figure 5.50: Maximum influence of the design variables (Stockholm)

Table 5.29: Top- Bottom hierarchy of influence

Design Variables Influence			
	Lowest Life Cycle Cost		
	Lisbon	Iraklion	Stockholm
Maximum (top 3)	1.Glazed Area	1.Microgeneration	1.Microgeneration
	2.Microgeneration	2.Glazed Area	2.Glazed Area
	3.Ventilation	3.Ventilation	3.Heating System
Minimum (bottom 3)	11.Windows	11.Windows	11.Shading
	12.Infiltration	12.Infiltration	12.Cooling System
	13.Cooling System	13.Cooling System	13.Orientation
	Initial Cost		
Maximum (top 3)	1.Microgeneration	1.Microgeneration	1.Microgeneration
	2.Glazed Area	2.Glazed Area	2.Glazed Area
	3.Ventilation	3.Ventilation	3.Heating System
Minimum (bottom 3)	11.Appliances	11.Infiltration	11.Cooling System
	12.Infiltration	12.Lighting	12.Orientation
	13.Cooling System	13.Cooling System	13.Lighting
	Total Final Energy		
Maximum (top 3)	1.Heating System	1.Insulation	1.Heating System
	2.DHW System	2.Heating System	2.Insulation
	3.Insulation	3.DHW System	3.DHW System
Minimum (bottom 3)	11.Orientation	11.Cooling System	11.Lighting
	12.Cooling System	12.Appliances	12.Shading
	13.Lighting	13.Lighting	13.Cooling System

Table 5.30: Design Options of LLCC solution (SP=BP)

SP=BP		Lisbon	Iraklion	Stockholm
			Unlimited area	
Insulation	8cm	•	•	•
	15cm			•
Infiltration	High	•		
	Medium		•	•
Ventilation	Natural	•	•	•
	MVHR			
Windows	Single Glazed Clear (Al)	•		
	Double Glazed Clear (Al)		•	
	Triple Glazed low-e (Al)			•
Shading	Outside	•	•	•
Glazed Area	10%	•	•	•
Orientation	South	•	•	•
Heating System	Electric Radiator		•	
	RCHP	•		
	RCHP Class A			•
Cooling System	RCHP	•	•	•
DHW System	Heat Pump	•	•	
	Heat Pump & SC			•
Lighting	High Efficiency	•	•	•
Appliances	Average Efficiency	•	•	•
Microgeneration	WT 2.4KW	•	•	•

Table 5.31: Design Options of LLCC solution (SP=230%BP)

SP=230%BP		Lisbon	Iraklion	Stockholm
			Unlimited area	
Insulation	3cm	•	•	•
Infiltration	High	•	•	•
Ventilation	Natural	•	•	
	MV			•
Windows	Single Glazed Clear (Al)	•	•	•
Shading	Outside	•	•	•
Glazed Area	10%	•	•	
	40%			•
Orientation	Other	•	•	•
Heating System	Boiler	•	•	•
Cooling System	RCHP	•	•	•
DHW System	Storage Gas	•	•	
	Tankless Gas			•
Lighting	High Efficiency	•	•	•
Appliances	Average Efficiency	•	•	•
Microgeneration	WT 2.4kW	•	•	•

Table 5.32: Design Options of LLCC solution (SP=50%BP)

SP=50%BP		Lisbon	Iraklion	Stockholm
			Unlimited area	
Insulation	8cm	•		
	15cm		•	•
Infiltration	Medium	•	•	
	Low			•
Ventilation	Natural	•	•	
	MVHR			•
Windows	Triple Glazed low-e	•	•	
	Triple Glazed low-e (Al+TB)			•
Shading	Outside	•	•	•
Glazed Area	10%	•	•	•
Orientation	South	•	•	•
Heating System	RCHP	•	•	
	RCHP Class A			•
Cooling System	RCHP			•
	RCHP Class A	•	•	
DHW System	Heat Pump		•	
	Heat Pump & SC	•		•
Lighting	High Efficiency	•	•	•
Appliances	Average Efficiency	•	•	•
Microgeneration	WT 2.4KW	•	•	•

6 Case study 2: high rise building

This chapter provides a second application example of the methodology and tool described in chapter 4. In this case a high-rise building was analyzed to gain insights on the viability of a high-rise NZEB in different climate contexts, as well as to assess the influence of significant variations in the costs of PV modules.

6.1 Case study description

The building chosen to serve as case study is part of the manual of application of the RCTTE (Portuguese Government 2006) and represents a semi-detached block of flats with six floors and four dwellings per floor (two dwellings of T1 and another two of T2 typology), intended exclusively for housing. It also has two garage levels at the basement but these are not explicitly considered for the present analysis. The total heated floor area is 1700 m^2 and the building is originally located in Lisbon, Portugal (Figures 6.1 & 6.2).

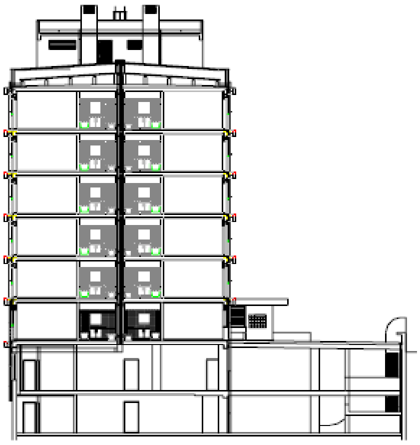


Figure 6.1: A side cut view of the high-rise case study building (ADENE, et al. 2007)

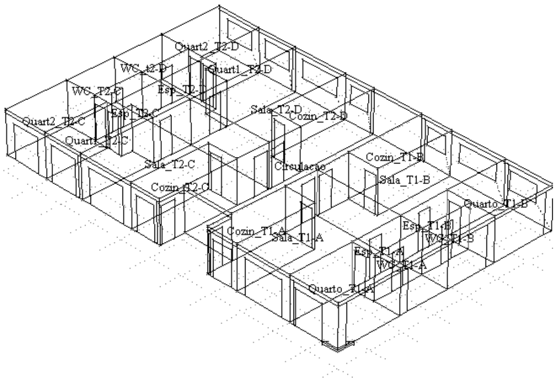


Figure 6.2: 3-d wireframe representation of the building floor plan (Leal, Ferreira e Oliveira Fernandes 2008)

The application involved first inputting the mandatory inputs (useful area, shape factor, adjacent area, floor to floor height, roof area and internal area, number of dwellings).The fixed inputs related to the costs were maintained as those already presented in the tables 5.3, 5.4, 5.5 and 5.6 of chapter 5.1.

In order to assess the impact of building height in the design configuration, 6 different building “typologies” were established, based on the number of floors considered and ranging from just the ground floor (floor 0) to the full size of the building (floor 0 + 5 floors = 6 floors). The main characteristics of the different building typologies related to the total building height variations are shown in table 6.1.

Table 6.1: Different building typologies

Building Geometry	Floors included					
	0	0+1	0+2	0+3	0+4	0+5
Useful area (m^2)	243	486	730	973	1216	1459
Shape factor (m^2/m^3)	1	0.64	0.51	0.45	0.41	0.39
Floor to floor height (m)	2.5	2.5	2.5	2.5	2.5	2.5
Adjacent area (m^2)	243	243	243	243	243	243
Roof area (m^2)	243	243	243	243	243	243
Internal area (m^2)	59	109	159	210	260	310
Number of dwellings	4	8	12	16	20	24

As in chapter 5, several climate scenarios were considered for the analysis: the cold winter climate of Stockholm (Sweden), the Atlantic climate of Lisbon (Portugal), the Mediterranean climate of Iraklion (Crete, Greece). The climate of Venice (Italy), with 2420 HDD and 520 CDD, was also introduced for reasons that will be explained later in chapter 6.2.

Finally, for all combinations of the above building typologies and climates, a sensitivity analysis to the cost of PV was conducted, considering a hypothetical scenario where the cost of the PV modules (both average and highly efficient) drops to half compared to its initial cost.

6.2 Impact of Building height considering solar thermal

This part of the work studies the implications on the design choices as well as on the economic indicators of altering the number of floors and therefore the building height. Tables 6.2, 6.3, 6.4 and 6.5 present the design choices and the economic indicators of the LLCC solution while increasing the number of floors from 1 (floor 0) to the maximum possible total building height (expressed in terms of number of floors; the highlighted parts of the tables, in italic , point up the changes of the design choices when compared to the design choices of the low rise building - 1 floors) The electricity price scenario that is adopted is the central one that considers the price of electricity sold equal to the price of the electricity bought. The number of occupants considered for each floor is 10 (three in each T2 plus 2 in each T1). Furthermore, it is considered that there is a limit to the fraction of the roof that can be occupied by the solar PV panels, set to 80% of the roof area. This is because usually the roofs need to accommodate also other mechanical installations (antennas, solar thermal collectors, lift engines, etc.)

As it can be observed, for the climates of Lisbon & Iraklion consumption can be offset within the 80% roof area for up to the 0+6 floors height. However, the optimal combination of choices of the design variables results in choosing a storage electricity DHW equipment and a solar collector as the optimal DHW equipment. If it were assumed that 2.7 m^2 of thermal solar is needed for each dwelling, then in that case 75.6m^2 of roof area would be needed to be occupied by solar thermal. Considering that the roof area is 243m^2 and the PV panels cover a 75% of the roof area, there wouldn't be enough space for the solar collectors. Even if there are in the market more efficient thermal solar collectors , which would require less roof area for the same energy collected, it can be concluded that for the climates of Lisbon and Iraklion the limit for NZEB design within the building footprint and placing the collectors only in the roof is 0+5 floors.

Table 6.2: Design choices and economic indicators of the LLCC for the climate of Lisbon

Design Choices & Economic Indicators	Lisbon						
	Low rise (0)	High rise (0+1)	High rise (0+2)	High rise (0+3)	High rise (0+4)	High rise (0+5)	High rise (0+6)
LLCC (€)	115165	217487	320375	422569	547407	868917	1011090
IC of LLCC (€)	79793	147523	215827	283442	347225	454276	527496
LLCC (€/m^2)	474	448	439	434	450	596	693
IC of LLCC (€/m^2)	328	304	296	291	286	311	362
Insulation	15cm	15cm	15cm	15cm	15cm	15cm	15cm
Infiltration	Medium	Medium	Medium	Medium	Medium	Medium	Medium
Ventilation	Natural	Natural	Natural	Natural	Natural	Natural	Natural
Windows	Sngl_Glz_Clr	Sngl_Glz_Clr	Sngl_Glz_Clr	Sngl_Glz_Clr	Sngl_Glz_Clr	Sngl_Glz_Clr	Sngl_Glz_Clr
Shading	Outside	Outside	Outside	Outside	Outside	Outside	Outside
Glazed Area	10% of Useful Area	10% of Useful Area	10% of Useful Area	10% of Useful Area	10% of Useful Area	10% of Useful Area	10% of Useful Area
Orientation	South	South	South	South	South	South	South
Heating Equipment	RCHP	RCHP	RCHP	RCHP	RCHP	RCHP	RCHP
Cooling Equipment	RCHP	RCHP	RCHP	RCHP	RCHP	RCHP	RCHP
DHW Equipment	Heat Pump	Heat Pump	Heat Pump	Heat Pump	*Storage Electricity & SC*	*Storage Electricity & SC*	*Storage Electricity & SC*
Lighting	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency
Appliances	Average Efficiency	Average Efficiency	Average Efficiency	Average Efficiency	Average Efficiency	*High Efficiency*	*High Efficiency*
PV Module	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency
Useful Heating Needs (KWh/m^2/yr)	27	19	16	15	14	16	18
Useful Cooling Needs (KWh/m^2/yr)	13	12	12	12	12	9	10
DHW Final Needs (KWh/yr)	8043	16087	24130	32174	0	0	0
Roof area covered by PV (%)	21	40	60	78	75	65	75

Table 6.3: Design choices and economic indicators of the LLCC for the climate of Iraklion

Design Choices & Economic Indicators	Iraklion						
	Low rise (0)	High rise (0+1)	High rise (0+2)	High rise (0+3)	High rise (0+4)	High rise (0+5)	High rise (0+6)
LLCC (€)	116633	220960	324247	429812	553680	874002	1017368
IC of LLCC (€)	80926	150460	218963	287064	352361	458018	532236
LLCC (€/m^2)	480	455	444	442	455	599	697
IC of LLCC (€/m^2)	333	310	300	295	290	314	365
Insulation	15cm	15cm	15cm	15cm	15cm	15cm	15cm
Infiltration	Medium	Medium	Medium	Medium	Medium	Medium	Medium
Ventilation	Natural	Natural	Natural	Natural	Natural	Natural	Natural
Windows	Sngl_Glz_Clr	Sngl_Glz_Clr	Sngl_Glz_Clr	Sngl_Glz_Clr	Sngl_Glz_Clr	Sngl_Glz_Clr	Sngl_Glz_Clr
Shading	Outside	Outside	Outside	Outside	Outside	Outside	Outside
Glazed Area	10% of Useful Area	10% of Useful Area	10% of Useful Area	10% of Useful Area	10% of Useful Area	10% of Useful Area	10% of Useful Area
Orientation	South	South	South	South	South	South	South
Heating Equipment	RCHP	RCHP	RCHP	RCHP	RCHP	RCHP	RCHP
Cooling Equipment	RCHP	RCHP	RCHP	*RCHP class A*	*RCHP*	RCHP	RCHP
DHW Equipment	Heat Pump	Heat Pump	Heat Pump	Heat Pump	*Storage Electricity & SC*	Storage Electricity & SC	*Storage Electricity & SC*
Lighting	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency
Appliances	Average Efficiency	Average Efficiency	Average Efficiency	Average Efficiency	Average Efficiency	*High Efficiency*	*High Efficiency*
PV Module	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency
Useful Heating Needs (KWh/m^2/yr)	23	16	14	13	12	11	15
Useful Cooling Needs (KWh/m^2/yr)	16	15	14	14	14	7	12
DHW Final Needs (KWh/yr)	8043	16087	24130	32174	0	0	0
Roof area covered by PV (%)	22	38	60	79	77	66	77

Table 6.4: Design choices and economic indicators of the LLCC for the climate of Stockholm

Design Choices & Economic Indicators	Stockholm						
	Low rise (0)	High rise (0+1)	High rise (0+2)	High rise (0+3)	High rise (0+4)	High rise (0+5)	High rise (0+6)
LLCC (€)	180368	323233	593221	**Unfeasible within PV area<80% of roof area**			
IC of LLCC (€)	136913	238561	383736				
LLCC (€/m^2)	742	665	813				
IC of LLCC (€/m^2)	563	491	526				
Insulation	15cm	15cm	15cm				
Infiltration	Medium	Medium	*Low*				
Ventilation	Natural	Natural	*MVHR*				
Windows	Trpl_Glz_Le_TB	Trpl_Glz_Le_TB	Trpl_Glz_Le_TB				
Shading	Outside	Outside	Outside				
Glazed Area	10% of Useful Area	10% of Useful Area	10% of Useful Area				
Orientation	South	South	South				
Heating Equipment	RCHP Class A	RCHP Class A	RCHP Class A				
Cooling Equipment	RCHP	RCHP	RCHP				
DHW Equipment	Storage Electricity & SC	Storage Electricity & SC	Storage Electricity & SC				
Lighting	High Efficiency	High Efficiency	High Efficiency				
Appliances	Average Efficiency	Average Efficiency	*High Efficiency*				
PV Module	High Efficiency	High Efficiency	High Efficiency				
Useful Heating Needs (KWh/m^2/yr)	123	87	50				
Useful Cooling Needs (KWh/m^2/yr)	2	3	3				
DHW Final Needs (KWh/yr)	4182	8366	12549				
Roof area covered by PV (%)	43	72	75				

Regarding the climate of Stockholm what can be noted here is that, the maximum number of floors viable for a high rise NZEB, if the PVs can only be installed in up to 80% of the roof area is limited to two floors. Thus, since the difference between Lisbon and Stockholm was considerable, it was considered necessary to introduce a new location to assess the intermediate space. The results regarding the climate of Venice are shown in table 6.5 from where it can be observed that a high rise NZEB appears to be feasible up to 0+3 floors. In both Stockholm and Venice climates, efficiency measures as well as available roof area for PV cover are exhausted after exceeding these limits. These limits would most likely be different with the possibility of installing collectors (thermal or PV) in the façades, but this possibility is not addressed in this study.

Table 6.5: Design choices and economic indicators of the LLCC for the climate of Venice

Design Choices & Economic Indicators	Venice						
	Low rise (0)	High rise (0+1)	High rise (0+2)	High rise (0+3)	High rise (0+4)	High rise (0+5)	High rise (0+6)
LLCC (€)	139226	258631	378641	564546	**Unfeasible within PV area<80% of roof area**		
IC of LLCC (€)	102834	187316	271459	403988			
LLCC (€/m^2)	573	354	519	580			
IC of LLCC (€/m^2)	423	257	372	415			
Insulation	15cm	15cm	15cm	15cm			
Infiltration	Medium	Medium	Medium	*Low*			
Ventilation	Natural	Natural	Natural	*MVHR*			
Windows	Trpl_Glz_Le	Trpl_Glz_Le	*Trpl_Glz_Le_TB*	*Trpl_Glz_Le_TB*			
Shading	Outside	Outside	Outside	Outside			
Glazed Area	10% of Useful Area	10% of Useful Area	10% of Useful Area	10% of Useful Area			
Orientation	South	South	South	South			
Heating Equipment	RCHP Class A	RCHP Class A	RCHP Class A	RCHP Class A			
Cooling Equipment	RCHP	RCHP	*RCHP Class A*	*RCHP class A*			
DHW Equipment	Heat Pump	Heat Pump	Heat Pump	Storage Electricity & SC			
Lighting	High Efficiency	High Efficiency	High Efficiency	High Efficiency			
Appliances	Average Efficiency	Average Efficiency	Average Efficiency	Average Efficiency			
PV Module	High Efficiency	High Efficiency	High Efficiency	High Efficiency			
Useful Heating Needs (KWh/m^2/yr)	57	26	30	17			
Useful Cooling Needs (KWh/m^2/yr)	9	6	9	12			
DHW Final Needs (KWh/yr)	4043	8086	12129	4165			
Roof area covered by PV (%)	30	56	80	79			

Regarding the economic indicators and according to tables 6.2, 6.3, 6.4 and 6.5, the results show that both the LLCC and the corresponding IC increase while increasing the number of floors, for all climates. To be noted that while the roof area is still not saturated, increasing the number of floors decreases the costs per m^2.However, when the roof area becomes saturated, increasing the number of floors starts to increase the cost per m^2.

Furthermore, it is also observed from tables 6.2, 6.3, 6.4 and 6.5, that adding another floor generates little difference in the design options in the case when there is still more roof area to be occupied by PV. However, when the roof area occupied by PV is already close to the 80% the changes on the design choices become considerable.

6.3 Sensitivity to the cost of PV

This chapter addresses the influence of variations on the cost of the PV modules, on the economic indicators and on the design choices. This study was made because of the reported observations that the costs of PV have been decreasing and will keep decreasing in the mid-term future (IEA 2010). The assessment was made by introducing an alternative scenario where the costs of PV are half of what they are in the reference scenario. The reference scenario considers the values of 600€/m^2 and 800€/m^2 for the average and highly efficient PV module respectively; the new scenario added reduces these costs into half resulting to 300€/m^2 and 400€/m^2 for the average and highly efficient PV modules respectively.

The results of economic indicators and design choices are shown in the tables 6.6, 6.7 and 6.8; the parts in italic show the differences in the LLCC design choices between the scenario with the initial PV module costs and the new PV module cost scenario.

As far as the influence in the design choices is concerned, what can be observed is that when the cost of PV is reduced to half, compared to the initial PV price, the design choices tend to be less energy-efficient. This happens for all climate contexts and all building typologies.

Regarding the influence on the economics, the results show that, as expected, when the PV module cost decrease then both the LLCC and the corresponding IC decrease. More specifically, as regards the climates of Lisbon & Iraklion, what can be observed is that, the LLCC decrease ranges from around 19% for the low rise building, the high rise with one floor (0+1) and the high rise with two floors; to around 18% for the three floor high rise building (0+3); to around 14% for the four floor (0+4) high rise building and around 8% for the five floor high rise building. For the climate of Stockholm, the LLCC decrease ranges from around 26% for the low-rise building to around 22% for the high rise (0+1) and to around 12% for the high rise (0+2). The IC of the LLCC decrease is around 29%, 30%, 30%, 26% 22% and 16% for the low rise, high rise (0+1), high rise (0+2), high rise (0+3) high rise (0+4) and high rise (0+5) buildings respectively regarding both the climates of Lisbon and Iraklion. Finally, for the case of Stockholm the decrease in IC of the LLCC becomes 30% and 29% and 12% respectively for the low rise, one floor high rise (0+1) and two floors high rise buildings.

As far as the area occupied by PVs is concerned, what can be noted is that while decreasing the PV cost, the roof area covered by PV increases. Concomitantly, the LLCC decreases, and the energy export increases. This seems to be all due to the fact that with low costs of PV it becomes cheaper to install PV than to invest in intrinsic energy efficiency – the same market distortion that had already been identified when considering feed-in tariffs.

Table 6.6: Design choices and economic indicators of the LLCC for the climate of Lisbon

Design Choices & Economic Indicators	Lisbon											
	Low rise(0)		High rise(0+1)		High rise(0+2)		High rise(0+3)		High rise(0+4)		High rise(0+5)	
	PV(600/800)	PV(300/400)	PV(600/800)	PV(300/400)	PV(600/800)	PV(300/400)	PV(600/800)	PV(300/400)	PV(600/800)	PV(300/400)	PV(600/800)	PV(300/400)
LLCC (€)	115165	92973	217487	175758	320375	258391	422569	346169	547407	472342	868917	798833
IC of LLCC (€)	79793	56502	147523	103983	215827	151331	283442	207042	347225	271300	454276	379549
LLCC (€/m^2)	474	383	448	362	439	354	434	356	450	388	596	548
IC of LLCC (€/m^2)	328	233	304	214	296	207	291	213	286	223	311	260
Insulation	15cm	*8cm*	15cm	*8cm*	15cm	*8cm*	15cm	15cm	15cm	*8cm*	15cm	*8cm*
Infiltration	Medium	*High*	Medium	*High*	Medium	*High*	Medium	Medium	Medium	Medium	Medium	*High*
Ventilation	Natural	Natural	Natural	Natural	Natural	Natural	Natural	Natural	Natural	Natural	Natural	Natural
Windows	Sngl_Glz_Clr	Sngl_Glz_Clr	Sngl_Glz_Clr	Sngl_Glz_Clr	Sngl_Glz_Clr	Sngl_Glz_Clr	Sngl_Glz_Clr	Sngl_Glz_Clr	Sngl_Glz_Clr	Sngl_Glz_Clr	Sngl_Glz_Clr	Sngl_Glz_Clr
Shading	Outside	Outside	Outside	Outside	Outside	Outside	Outside	Outside	Outside	Outside	Outside	Outside
Glazed Area	10% of Useful Area	10% of Useful Area	10% of Useful Area	10% of Useful Area	10% of Useful Area	10% of Useful Area	10% of Useful Area	10% of Useful Area	10% of Useful Area	10% of Useful Area	10% of Useful Area	10% of Useful Area
Orientation	South	South	South	South	South	South	South	South	South	South	South	South
Heating Equipment	RCHP	RCHP	RCHP	RCHP	RCHP	RCHP	RCHP	RCHP	RCHP	RCHP	RCHP	RCHP
Cooling Equipment	RCHP	RCHP	RCHP	RCHP	RCHP	RCHP	RCHP	RCHP	RCHP	RCHP	RCHP	RCHP
DHW Equipment	Heat Pump	Heat Pump	Heat Pump	Heat Pump	Heat Pump	Heat Pump	Heat Pump	Heat Pump	Storage Electricity & SC	Storage Electricity & SC	*Storage Electricity & SC*	*Storage Electricity & SC*
Lighting	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency
Appliances	Average Efficiency	Average Efficiency	Average Efficiency	Average Efficiency	Average Efficiency	Average Efficiency	Average Efficiency	Average Efficiency	Average Efficiency	Average Efficiency	High Efficiency	High Efficiency
PV Module	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency
Useful Heating Needs (KWh/m^2/yr)	27	50	19	36	16	31	15	15	14	14	16	16
Useful Cooling Needs (KWh/m^2/yr)	13	12	12	11	12	10	12	12	12	12	9	9
DHW Final Needs (KWh/yr)	8043	8043	16087	16087	24130	24130	32174	32174	0	0	0	0
Roof area covered by PV (%)	21	25	40	46	60	66	78	78	75	78	65	77

Table 6.7: Design choices and economic indicators of the LLCC for the climate of Iraklion

Design Choices & Economic Indicators	Iraklion											
	Low rise(0)		High rise(0+1)		High rise(0+2)		High rise(0+3)		High rise(0+4)		High rise(0+5)	
	PV(600/800)	PV(300/400)	PV(600/800)	PV(300/400)	PV(600/800)	PV(300/400)	PV(600/800)	PV(300/400)	PV(600/800)	PV(300/400)	PV(600/800)	PV(300/400)
LLCC (€)	116633	94012	220960	177848	324247	260567	429812	352742	553680	476506	874002	803090
IC of LLCC (€)	80926	57022	150460	105227	218963	158552	287064	214253	352361	274182	458018	381678
LLCC (€/m^2)	480	387	455	366	444	357	442	363	455	392	599	550
IC of LLCC (€/m^2)	333	235	310	217	300	217	295	220	290	225	314	262
Insulation	15cm	*8cm*	15cm	*8cm*	15cm	*8cm*	15cm	*8cm*	15cm	*8cm*	15cm	*8cm*
Infiltration	Medium	*High*	Medium	*High*	Medium	*High*	Medium	Medium	Medium	Medium	Medium	*High*
Ventilation	Natural	Natural	Natural	Natural	Natural	Natural	Natural	Natural	Natural	Natural	Natural	Natural
Windows	Sngl_Glz_Clr	Sngl_Glz_Clr	Sngl_Glz_Clr	Sngl_Glz_Clr	Sngl_Glz_Clr	*Sngl_Glz_Clr*	Sngl_Glz_Clr	Sngl_Glz_Clr	Sngl_Glz_Clr	Sngl_Glz_Clr	Sngl_Glz_Clr	Sngl_Glz_Clr
Shading	Outside	Outside	Outside	Outside	Outside	Outside	Outside	Outside	Outside	Outside	Outside	Outside
Glazed Area	10% of Useful Area	10% of Useful Area	10% of Useful Area	10% of Useful Area	10% of Useful Area	10% of Useful Area	10% of Useful Area	10% of Useful Area	10% of Useful Area	10% of Useful Area	10% of Useful Area	10% of Useful Area
Orientation	South	South	South	South	South	South	South	South	South	South	South	South
Heating Equipment	RCHP	RCHP	RCHP	RCHP	RCHP	*Electric Radiator*	RCHP	RCHP	RCHP	RCHP	RCHP	RCHP
Cooling Equipment	RCHP	RCHP	RCHP	RCHP	RCHP	RCHP	*RCHP class A*	RCHP	*RCHP*	RCHP	RCHP	RCHP
DHW Equipment	Heat Pump	Heat Pump	Heat Pump	Heat Pump	Heat Pump	Heat Pump	Heat Pump	Heat Pump	*Storage Electricity & SC*	Storage Electricity & SC	Storage Electricity & SC	*Storage Electricity & SC*
Lighting	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency
Appliances	Average Efficiency	Average Efficiency	Average Efficiency	Average Efficiency	Average Efficiency	Average Efficiency	Average Efficiency	Average Efficiency	Average Efficiency	Average Efficiency	High Efficiency	High Efficiency
PV Module	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency
Useful Heating Needs (KWh/m^2/yr)	23	43	16	31	14	27	13	11	12	15	11	26
Useful Cooling Needs (KWh/m^2/yr)	16	16	15	14	14	13	14	14	14	14	7	9
DHW Final Needs (KWh/yr)	8043	8043	16087	16087	24130	24130	32174	32174	0	0	0	0
Roof area covered by PV (%)	22	25	38	46	60	80	79	80	77	80	66	77

Table 6.8: Design choices and economic indicators of the LLCC for the climate of Stockholm

Design Choices & Economic Indicators	Stockholm					
	Low rise(0)		High rise (0+1)		High rise(0+2)	
	PV(600/800)	PV(300/400)	PV(600/800)	PV(300/400)	PV(600/800)	PV(300/400)
LLCC (€)	180368	133921	323233	253082	593221	519591
IC of LLCC (€)	136913	95617	238561	168114	383736	309662
LLCC (€/m^2)	742	551	665	521	813	712
IC of LLCC (€/m^2)	563	393	491	346	526	424
Insulation	15cm	15cm	15cm	15cm	15cm	15cm
Infiltration	Medium	Medium	Medium	Medium	Low	Low
Ventilation	Natural	Natural	Natural	Natural	MVHR	MVHR
Windows	Trpl_Glz_Le_TB	*Trpl_Glz_Le*	Trpl_Glz_Le_TB	*Trpl_Glz_Le*	Trpl_Glz_Le_TB	*Trpl_Glz_Le*
Shading	Outside	Outside	Outside	Outside	Outside	Outside
Glazed Area	10% of Useful Area	10% of Useful Area	10% of Useful Area	10% of Useful Area	10% of Useful Area	10% of Useful Area
Orientation	South	South	South	South	South	South
Heating Equipment	RCHP Class A	RCHP Class A	RCHP Class A	RCHP Class A	RCHP Class A	RCHP Class A
Cooling Equipment	RCHP	RCHP	RCHP	RCHP	RCHP	RCHP
DHW Equipment	Storage Electricity & SC	*Heat Pump*	Storage Electricity & SC	Storage Electricity & SC	Storage Electricity & SC	Storage Electricity & SC
Lighting	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency
Appliances	Average Efficiency	Average Efficiency	Average Efficiency	Average Efficiency	High Efficiency	High Efficiency
PV Module	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency
Useful Heating Needs (KWh/m^2/yr)	123	127	87	91	50	54
Useful Cooling Needs (KWh/m^2/yr)	2	2	3	3	3	3
DHW Final Needs (KWh/yr)	4182	4447	8366	8366	12549	12549
Roof area covered by PV (%)	43	52	72	73	75	78

7 Conclusions

Net zero energy buildings are becoming an important policy option in many countries and regions of the world. There are now some examples of NZEBs already built, which show that they are achievable. However, the bibliographic review performed in the first phase of this work showed that little effort has been made to prove that the design choices adopted, were, besides effective, also efficient (close to the optimal) from an economical point of view or a systematic assessment of the design of the buildings.

This study addressed a methodology and a new tool, precisely with the goal of assisting in the choice of economically- efficient NZEB solutions, right from the early design stage and without compromising the environmental performance in any way. The methodology and its correspondent tool can be used for any residential building in any part of the world, to identify the lowest life cycle cost and /or lowest initial cost design solutions, considering the local climate, the endogenous energy resources and the local economic conditions that lead to a null energy (made in terms of final energy) annual balance.

This chapter summarizes the results of this study, presented and discussed thoroughly in the previous chapters. Subchapter 7.1, presents the main findings and is followed by subchapter 7.2, which is a reference to the implication of real practices and concludes with subchapter 7.3 and the future opportunities for research.

7.1 Main findings

Findings regarding the economic space of NZEB solutions

In order to obtain indications on the economic space of NZEB solutions, the relation between the LCC and the corresponding IC was assessed for two case studies covering all the range of possible design solutions.

It was found that, as a general trend, the most expensive NZEB design solution in terms of initial cost was at least 3 times more expensive than the cheapest design solution. The same at least about 3:1 ratio, was generally observed in terms of life cycle cost. This result clearly illustrates the importance of an economic analysis at the early design stage of NZEBs in order to reach the energy goals with economic efficiency.

The general trend observed is that, in the absence of feed in tariffs, the more costly solutions in terms of initial cost are also more costly in terms of life cycle. Thus, investing more on energy efficiency saves initial investment on PV, which tends to be costly.

Findings regarding the influence of the climatic context

Assessing the influence of different climate contexts in the economic-efficient design of NZEBs, indicated that the ‘optimal’ design solutions for mild winter climates can be significantly cheaper than for cold winter climates, as in the latter more energy efficient solutions are required and also because of the low solar radiation more PV area is required for the offset which tends to be more costly.

Though the solutions are more expensive for colder climates, the importance of an economic optimization is even higher since it was found that the ratio between the worst and the best solution is about 6:1 whereas for the milder ones it was 3:1.both in terms of IC and LCC.

Findings regarding the influence of fuel and electricity buy and sell prices

Studying the influence of fuel and electricity buy and sell prices concluded that, when the electricity sell prices are increased (e.g. through feed in tariffs) the economic optimal solutions become less energy efficient. This seems to happen because in that case it is more cost effective to invest on PV to receive the generous economic compensation than to invest on energy efficiency. This is potentially perverse effect of feed in tariffs that should be avoided with adequate regulation. Conversely, lower sell- price energy tariffs tend to lead to higher energy efficient solutions

Moreover, in the low sell price scenarios no trade off trends between the IC and LCC were observed, while with feed in tariffs, there can be significant trade off trends. This happens because less efficient buildings require more offset microgeneration equipment, which in general are expensive in terms of initial cost.

Finally, when financial incentives are absent, there is no return in the initial investment as regards a 25 years life cycle. This is the normal situation of a non-NZEB residence, which also has a positive life-cycle cost of considerable value. However in climates with high yearly solar radiation e.g. Lisbon and Iraklion in the SP=BP price scenario the total LCC of an NZEB building can be lower than that of an non-NZEB building as can be observed on figures 5.23 and 5.24 of chapter 5.

Findings regarding the influence of the compensation level

In order to assess the influence of the compensation level (fraction of the annual energy imports to the building offset with exports) upon the economic indicators, the relation between the former, was studied, for the LCC of LLCC and the IC of LIC as obtained from the simulations performed.

The LIC was found to increase and the LLCC to decrease as the compensation level increased, either because solar radiation is high or because there are feed in tariffs to assist it; when the energy export is not profitable both economic indicators increase as the compensation level increases.

Moreover, for high compensation levels if the roof area available becomes fully occupied then the increasing the compensation level can only be achieved by increasing the energy efficiency of the building as it can be seen from table 5.21 of chapter 5.

Findings regarding the hierarchy of influence of the design variables

The hierarchy of influence of the design variables was assessed through a sensitivity analysis conducted for all climate contexts and for the SP=BP price scenario.

The design variables with the highest impact on the optimal LCC building design for Stockholm were found to be the type of heating system, the glazed area and the level of insulation while the building orientation, the type of shading, and the type of cooling system seem to have the lowest influence. For both Lisbon & Iraklion, the glazed area, the type of ventilation and the appliances seem to have the largest impact while the type of cooling system, the building orientation and the level of air infiltration have minimum impact.

As regards the initial cost, the top 3 design variables with the highest impact on the optimal economic building design for Stockholm were ranked as follows: type of heating system, glazed area, and level of thermal insulation. The variables: type of lighting, type of shading and type of cooling system were ranked last. Moreover, for the climate of Lisbon variations in the glazed area, type of ventilation system and type of DHW system influence the most the initial cost while the type of lighting, type of cooling system and level of air infiltration have a minimized impact. Finally, for Iraklion the top 3 ranked variables include the: glazed area, the type of ventilation system and the appliances while the bottom 3 ranked ones are the type of cooling system, the type of lighting and the level of air infiltration.

In the case that WTs were considered as a reliable design option, the three top variables with the highest impact on the optimal LCC economic building design for Stockholm were the type of microgeneration system, the glazed area and the type of heating system while the type of shading, the type of cooling system and the building orientation had the lowest influence. For Lisbon the glazed area, the type of microgeneration system and the type of ventilation system influence the most while the type of window, the level of air infiltration and the type of cooling system influence the least. Finally, for Iraklion the optimal LCC was found to be significantly influenced by variations in the type of microgeneration system, the glazed area and the type of ventilation system while design variables like the type of windows, the level of air infiltration and the type of cooling system have little effect upon the LCC.

Finally, in reference to the initial cost the design variables with the highest impact on the optimal economic building design for Stockholm are the type of microgeneration system, the glazed area and the type of heating system while the type of cooling system, the building orientation and type of lighting are ranked last. Moreover, for the climate of Lisbon the variables with significant influence are the type of microgeneration system, the glazed area and the type of ventilation system while the appliances, the level of air infiltration and the type of cooling system have minimum impact. Finally, for Iraklion the rank order puts the type of microgeneration system, the glazed area and the type of ventilation in the top 3 places while the level of air infiltration, the type of lighting and the type of cooling system come last.

Findings regarding the influence of limitation on the area available for PV installation

The simulation carried out to assess the influence of limitation on the area available for PV installation revealed that in the case of low rise buildings in mild climates may not make any effect neither on the economic indicators nor on the ‘optimal’ design solutions because the limit is not reached. For high-rise or for low-rise buildings in cold climates it may be reached and then starts having an influence on the optimal design solutions. In the latter case the observed effects are an increase in the efficiency of the buildings, an increase in the LLCC and a decrease in the LIC.

Findings regarding the impact of considering WT as a reliable design option

Concerning now the scenario where wind turbines were considered and evaluated as a microgeneration design option, it was found that when available it was always selected as the microgeneration ‘optimal’ design solution for all climates and price scenarios considered. In agreement with that, both the LLCC and LIC are lower in the case when WT is a possibility than when the mocrogeneration options are restricted to PV, with the exception of the LIC for the SP=230%BP scenario in Stockholm which has a much higher LIC. It was verified that in this case the software choses a very inefficient building to justify the installation of a very high number of WTs whose production would be highly profitable in a generous feed in tariff scenario.

Findings regarding the feasibility of high-rise buildings

The analysis of a high-rise NZEB building in order to gain insights on its´ viability in different climate contexts, found high-rise NZEBs to be feasible within the building footprint for up to 5 floors height, as regards the climates of Lisbon and Iraklion; for the climate of Venice and Stockholm high rise NZEBs reached up to 3 and 2 floors respectively. Although only one building was analyzed, it is clear that the limitation can be significant, especially in the cold climates with low solar radiation. Hypothetically, it could be overcome through the integration of PV in the façades, but this was not addressed.

Regarding now the economic indicators, the results show that both the LLCC and the corresponding IC increase while increasing the number of floors, for all climates. While the roof area is still not saturated, increasing the number of floors decreases the costs per m^2. However, when the roof area becomes saturated, increasing the number of floors starts to increase the cost per m^2.

Finally, while the number of floors increase, the design choices tended to become highly efficient; this occurred after the point that PV compensation reached the maximum limit allowed (80% of the roof area).

Findings regarding the sensitivity to the costs of PV

The analysis on a high-rise NZEB to assess the influence of significant variations in the costs of PV modules showed that, decreasing the PV module cost to half of the initial implemented price, results in less efficient optimal combinations of the design choices since apparently it becomes cheaper to offset the consumption through production of electricity than to decrease the energy needs through energy efficiency. This can be potentially conflicting with other sustainability goals and should be a point of attention from public and regulatory entities as a policy sensitive issue.

7.2 Implications for real practice

The results of this research work suggests possibilities for considerable improvements in the real practice on the following:

- Economic optimization at the early design stage while simultaneously ensuring the energy goals. This is now possible with this tool developed.

- Design of energy pricing policies, especially those regarding the electricity bought from buildings. These have a direct impact upon the optimal design solutions and the economic indicators and can affect the balance between energy efficiency and offset. Feed in tariffs can have a positive effect on the payback period but if caution is not taken an NZEB can be achieved in an economical-optimal way with non energy efficient measures.

- Offsite compensation should not be excluded if it is not intended to create barriers to high-rise buildings, which are known to be beneficial for sustainability in a number of ways (e.g. city compactness etc.). To be noted that this applies even if integration of microgeneration in the façades were possible as it is known that the economic performance of these solutions is heavily affected.

7.3 Future research opportunities

During the development of this work, many issues were identified which although connected, were out of the scope of this work but it would be interesting to address in future research opportunities:

- Expansion of the methodology in order to consider the possibility of thermal solar and PV panels on the vertical walls (façades) of the building. It must be noted that the productivity of thermal PV panels on vertical walls is typically significantly lower than in the optimal inclination, so it is not expected that these solutions would be chosen as economically optimal unless in extreme cases. Nevertheless, it would add to the comprehensiveness of the analysis.

- Introducing the possibility of offsite compensation through the evaluation of the footprint at a broader border, e.g. through a net zero energy community. It has been hinted that this might lead to a more effective adoption of renewable energy technologies (Crawley, et al. 2009) (Azevedo e Leal 2010).

- Expanding the analysis to NZEB communities rather than singular buildings. This could hypothetically open the space for significant cost reduction through economies of scale at the initial investment but also through better maintenance and operation of the systems.

- Studying the impacts of large numbers of NZEBs in the operation and the resulting needs of investment in the electric grid by addressing the stability and management of electrical systems. There is currently a concern from utilities regarding the future large-scale penetration of NZEBs into the grid, in terms of on how this will affect its stability especially since NZEBs do not often offset peak demand (Crawley, et al. 2009).

- Studying the impacts of large numbers of NZEBs in the transportation needs, as a large-scale development of NZEBs could possibly have collateral effects on the transportation. Since the feasibility of small rise NZEBs is clearer than in high-rise NZEB s, this could induce a low-density urban system that places increased challenges to sustainable transportation.

- Introducing behavioral issues into the estimated energy demand evaluation, since the prediction of total home energy use for a specific house becomes highly uncertain due to individual occupant choices and behavior (Norton e Christensen 2008) and occupant’s behavior maybe critical to achieve net zero design goals.

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ANNEX I

Table 1: Inputs and Outputs of the Application Tool

Inputs		Outputs	
		Identifiers of the Design Alternatives	
1	Location	1	Number of the optimal design alternative
2	Useful Area	2	Value of variable: ‘Insulation’
3	Shape Factor	3	Value of variable: ‘Infiltration’
4	Height	4	Value of variable: ‘Ventilation’
5	Adjacent Area	5	Value of variable: ‘Windows’
6	Roof Area	6	Value of variable: ‘Shading’
7	Internal Area	7	Value of variable: ‘Glazed Area’
8	Number of dwellings	8	Value of variable: ‘Orientation’
9	Insulation level	9	Value of variable: ‘Heating Equipment’
10	Inertia	10	Value of variable: ‘Cooling Equipment
11	Leakage Level	11	Value of variable: ‘DHW Equipment
12	Window Type	12	Value of variable: ‘Lighting’
13	Shades	13	Value of variable: ‘Appliances’
14	Glazed Area	14	Value of variable: ‘Microgeneration’
		Results of the Design Alternative	
15	Orientation	15	Life Cycle Cost
16	Ventilation	16	Annual Electricity and/or Gas Bill
17	Heating System	17	Initial Cost
18	Cooling System	18	Useful Heating Needs
19	Occupants	19	Useful Cooling Needs
20	Water Heating System	20	Final Heating Needs
21	Type of Lighting	21	Final Cooling Needs
22	Appliances	22	Total Final Energy
23	Price of Electricity sold	23	Area PV or Number of Wind Turbines
24	Price of Electricity bought		
25	Price of Gas bought		
26	Cost of thermal Insulation		
27	Cost of envelope airtightness		
28	Window Type Cost		
29	Shades Cost		
30	Heating System Cost		
31	Cooling System Cost		
32	Domestic Hot Water System Cost		
33	Mechanical Ventilation Cost		
34	Lamps Cost		
35	Appliances Cost		
36	Photovoltaic Panel Cost		
37	Wind Turbine Cost		
38	Solar Collector Cost		
39	Discount Rate		
40	Lifecycle Years		
41	Type of Microgeneration System		
42	Site Description		
43	Height of Wind Turbine		
44	Percentage of Compensation		