Universiteit Utrecht

Actual energy use vs. design energy use

“Comparison between actual and design energy use for the residential sector in Greece, the Netherlands and the United Kingdom. – An exploratory study”

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Abstract

The built environment is one of the biggest energy consumers. Therefore, various methods have been created to estimate and calculate the energy consumption during the lifetime of buildings. However, the actual energy use differs substantially from the design energy use. For this reason, this thesis aims to study the gap between actual and design energy use. Due to the great share of residential buildings in the building sector this research is focused only on residential buildings.

The research revealed five categories of reasons behind the gap. These are a) occupants' characteristics, b) occupants' behavior, c) technical aspects of building, d) knowledge of the industry, e) calculation processes. Each of these categories contains a number of reasons with the most outstanding being i) the age of the occupants ii) the heating habits of the occupants iii) the correct installations iv) the understanding of technologies and building methods v) the assumptions used in the models. A closer look to the residential sector of Greece, the United Kingdom and the Netherlands showed that there is a significant lack of research and thus data on this topic. Nevertheless, the available data showed that the residential sector, in the United Kingdom and the Netherlands, exhibits the same reasons that lead to the gap between actual and design energy use. The reasons that have been confirmed for the two countries are falling into the categories c) technical aspects of the building and d) knowledge of the industry.

Further research in the areas of a) occupants' characteristics, b) occupants' behavior, c) technical aspects of building, d) knowledge of the industry, e) calculation processes is recommended. In order to bring the design energy use closer to the actual energy use statistical data are required which will reveal the main reasons behind the gap in each country. Therefore, data bases which will contain the design calculations as well as the tests and monitoring results are required. The focus of the policy makers should be on three groups, the designers, the constructors, and the occupants. While the possible improvements include less complex designs, better education of the constructors on the heat losses and detailed guidelines to the occupants for efficient use of the building and conscious use of energy.

Acknowledge

First of all I would like to express my gratitude to my supervisors, for their support and for the exceptional collaboration of the past few months. Special thanks go to Melchert Duijve, for his advice, his guidance and especially for his help regarding the collection of data. Further, I would like to thank Prof. Malcolm Bell from Leeds Metropolitan University, for his advice and for providing the necessary data for the United Kingdom, as well as the people in BouwTransparant, for providing me with the necessary data for the Netherlands.

Last but not least, I would like to thank my family for their ever-lasting support and for giving me the opportunity to be in this place now.

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1. Introduction

In order to solve the severe environmental problems, such as global warming, resulting from Greenhouse gas (GHG) emissions of anthropogenic origin, the European Union has set targets to reduce its GHG emissions. According to these targets the European Union should achieve, among others, 20% energy efficiency by 2020 (European Commision, 2011). Having this in mind and the fact that buildings currently represent a great share of the final energy use, (Figure 2); it becomes clear that the energy performance of buildings is important to achieve these targets by 2020. Across the world the building industry and the built environment are some of the biggest energy consumers. Buildings not only consume energy and materials during their construction phase but they also consume a great amount of energy during their lifetime (Schoonvelde, 2010).

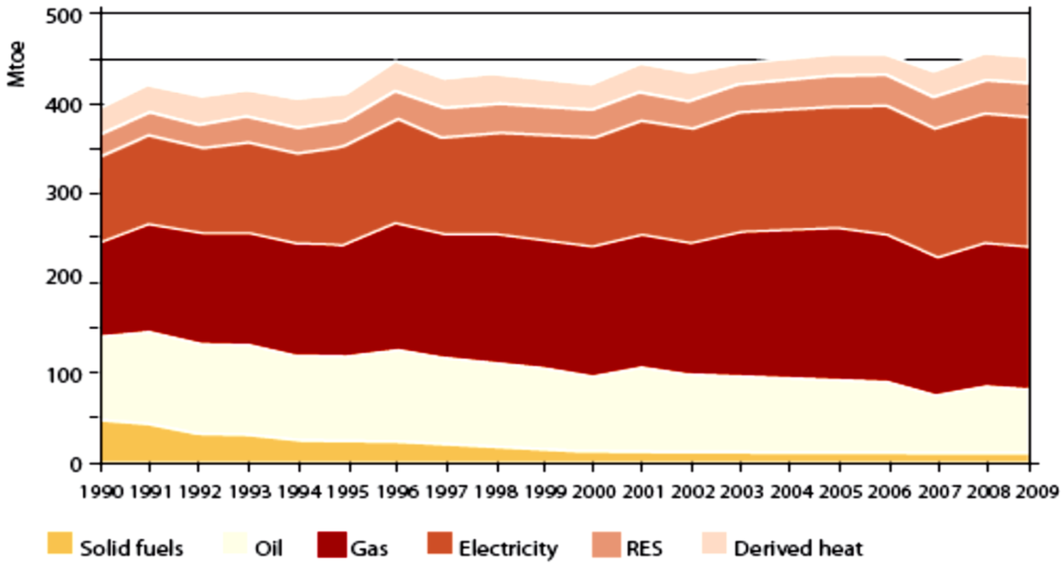

Figure 1: Historical energy consumption in building sector for EU27, Switzerland and Norway (Atanasiu, et.al., 2011)

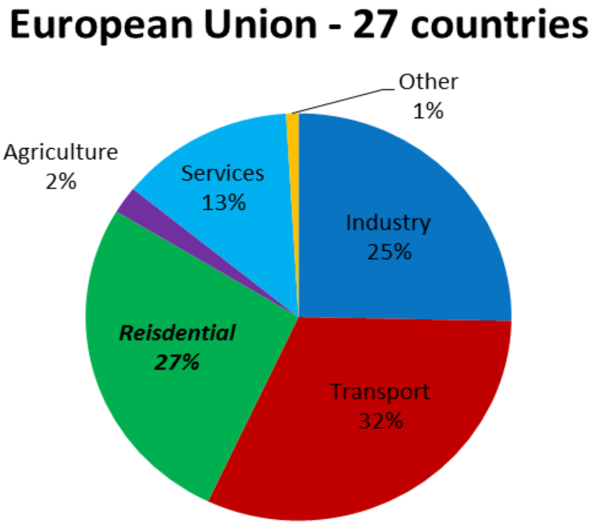

Figure 2: Percentage representation of the final energy consumed in each sector in 2010 in European Union (27 countries) (European Statistics, 2012 f)

As it can be seen from Figure 1 and Figure 2, buildings use a substantial amount of energy that has been increasing throughout the decades. The energy performance of a building depends on its physical characteristics, such as the age and the thermal properties (of materials used for the construction, windows surface etc.), but also on the behavior of the people who use the building such as temperature preferences, lighting preferences etc. (Bell, 2010; de Groot, et al., 2008; Sardianou, 2008; Sunikka Blank & Galvin, 2012).

Since the nineties the built environment has attracted the attention of the experts due to its great potential for energy saving. Therefore the energy efficiency of the buildings has been studied, standards have been set and Energy Conservation Measures have been proposed (Agentschap NL, 2012; Department of Energy and Climate Change, UK, 2011; Minister of Finance & Minister of Environment,Energy and Climate Change, 2010; Pan & Garmston, 2012, a). Moreover, a wide range of policies have been developed and adopted by individual Member States, but also by the European Union. Examples of policies in a European level are, the Energy-Related Products Framework Directive 09/125/EC, the End-use Energy Efficiency and Energy Services Directive 32/2006/EC and the Labeling Framework Directive 2010/30/EU (Atanasiu, et al., 2011). Examples of policies in a national level are the financial programs of each Member State; for instance, in the United Kingdom the Energy supplier obligations, in France The sustainable development account and in Germany The loans and subsidies from the reconstruction credit institute, KfW (Atanasiu, et al., 2011). This policy framework aimed at increasing energy efficiency within buildings by using the standards for new constructions and promoting the renovation of existing buildings.

Nowadays, the efficiency standards for new buildings are higher than the previous decades. For instance, in the United Kingdom the quantity of efficient buildings increased by 40% as against before 2002 (Department of Energy and Climate Change UK, 2012). In the Netherlands the efficient buildings have increased by 50% since 1995 (ODYSSEE-MURE, 2011). However, the energy consumption presents only a small decrease as it can be seen in Figure 3. This is due to the fact that the construction rate of new buildings is low compared to the number of existing buildings. Also the number of buildings that undergo major renovation, and therefore need to comply with the new regulations, is not significant. Therefore, the number of energy inefficient buildings is much higher than the number of energy efficient buildings.

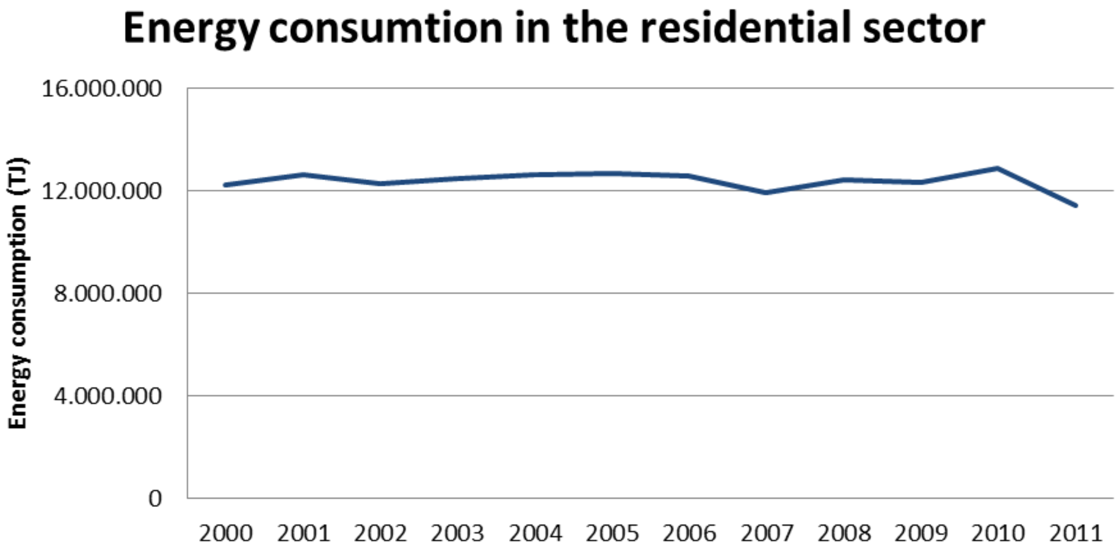

Figure 3: Historical energy consumption in the residential sector in European Union (27 countries) (European Statistics, 2013)

Furthermore, new and renovated buildings also face another important issue which is the significant difference between the estimated energy use before the construction of the building and the actual energy use during its use phase. This difference results from the fact that the actual energy consumption of the building is highly influenced by the behavior of the occupants[1] where the estimated (design) energy use is based mainly on the characteristics of the building and its own efficiency[2], while the occupants are taken into account as a standardized behavior.

Research has been done on the energy use of the buildings, both commercial and residential buildings (Atanasiu, et al., 2011), and the factors that determine the energy use are identified (Dall'O, et al., 2012; de Groot, et al., 2008; Fokaides, et al., 2011; Guerra Santin, 2010; Santamouris, et al., 2001; Sardianou, 2008; Tigchelaar, et al., 2011; van Raaij & Verhallen, 1983). However, little has been done concerning the gap between the calculated, pre-construction, design energy consumption and the actual, measured during the use phase, energy consumption.

1.1. Problem definition

The built environment is one of the biggest consumers of energy (Atanasiu, et al., 2011). Buildings represent 40% of the total energy consumption in Europe (Atanasiu, et al., 2011). Therefore, various methods have been created to estimate and calculate the energy consumption during the lifetime of the buildings. However, the actual energy use differs substantially from the design energy use. This difference is due to behavioral reasons and different lifestyles of the inhabitants but also due to inaccurate assumptions (behavior of residents, thermal properties of material etc.) and variations from the design (Bell, 2010; Guerra Santin, 2010; Sunikka Blank & Galvin, 2012). For this reason this thesis researches the various factors that determine the actual energy consumption of a building as well as the differences with the design energy use. The aim is to identify the reasons behind this gap, the magnitude of the problem in the three countries (Greece, the Netherlands and the United Kingdom) and the available options to close the gap.

Main question

Which factors contribute to the observed difference between actual and design energy use and what options are there to minimize this difference?

This thesis will be carried out in steps and each one of them should give the answer to one of the following sub-questions. Answering these sub-questions will lead to the answer of the main question.

Sub-questions

1. *Which factors determine the actual energy use of a household?*
2. *What is the actual energy consumption of residential buildings in Greece, the Netherlands and the United Kingdom?*
3. *Which factors are missing or differ between design and actual energy use?*
4. *What are the similarities and the differences between these countries?*
5. *What are the possible options to close the gap between design and actual energy use?*

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[1] More information on the relation between energy use and user’s found behavior can be: (de Groot, et al.,

[2] More information on the calculation methods for the design energy use can be found: (Agentschap NL, 2012; Department of Energy and Climate Change UK, 2012; Minister of Finance & Minister of Environment,Energy and Climate Change, 2010)

2. Methodology

In this chapter the methodology used to answer the research question is described and the boundaries of this research are specified.

The methodology of this thesis has been based on literature review, preliminary studies and case studies. Moreover, contact with experts in this field was made, in order to gain more insight information and unpublished data. Due to shortage of academic literature in this field, great shares of data were retrieved from other sources such as statistical databases and institutions working in the built environment. This research takes into account all the aspects of buildings' life that can affect the energy use i.e. the regulations, the calculations, the design, the construction, the use.

The research started with literature review of the legislations for each country in order to retrieve the regulations and calculation methods that are currently into force. This provided the necessary proof that the differences in the calculation procedures are not essential and that the results from the different countries can be compared. European and National Statistics have been use to retrieve the necessary data on the energy consumption of the residential sector in each country. The possible reasons behind the gap were collected from literature review and categorized based on which phase of the buildings' life they can be observed. For the needs of this research the buildings' life is separated into three phases:

i) *"design-calculation" phase:* starts with the design of the building and finishes with the completion of the calculations for the predicted energy use
ii) *"construction" phase:* starts with the beginning of the construction and finishes when the building is ready to be occupied
iii) *"use" phase:* starts at the moment that the residents move into the building and continues until the point that some alteration is made to the building by the residents. After the alteration takes place the building is different from the original design and therefore it is not possible to compare actual and predicted energy use anymore.

The reasons behind the gap were further categorized based on their nature. Five categories are defined:

a) *occupants' characteristics*
b) *occupants' behavior*
c) *technical aspects of building*
d) *knowledge of the industry*
e) *calculation processes*

In order to make the problem more comprehensive to its full extent a conceptual model has been developed. The model gives a schematic representation of the relations among the problem of the gap, the phases of the buildings' life and the reasons that cause this problem.

The nature of this research required the use of case studies which deal with the building performance after the construction but also with the calculation of the performance during the design. These case studies were provided by Prof. Malcolm Bell (for the United Kingdom) and by BouwTransparant (for the Netherlands). Due to limited availability of case studies and therefore numerical data the analysis is mainly qualitative. Each case study was examined separately and the reasons causing the gap were collected. Then they were categorized in the same way as the reasons retrieved from the literature review. The performance differences of the case studies were also collected in order to create a sample of the performance gap. The percentage representations of the performance differences were calculated using the following equation:

$$\frac{actual\ energy\ use - predicted\ energy\ use}{predicted\ energy\ use} * 100\%$$

The nature of the data for the Netherlands made it possible to do a statistical analysis. From this analysis the most observed reasons creating the gap have been determined. It should be noted that the houses that have been constructed according to the design are not taken into account since they do not exhibit variations from the predicted energy use. Moreover, the most common source for the energy difference among heating, ventilation, lighting, summer comfort etc. has been determined. After the analysis of the case studies the results for each country were formulated. The results from each country were compared with the results from the other countries but also with the results from the literature review. This comparison verified the reasons behind the gap that have been retrieved earlier from the literature.

The recommendations are formulated based on the research results and consist proposals which can help to overcome the issues that cause the gap between actual and design energy use.

2.1. Boundaries

Due to the great share of residential buildings in the building sector and the amount of energy that they consume, this thesis is focused on the residential sector only. In order to have a more general view on this topic the residential sector of three different European countries is investigated. Greece and the Netherlands have been chosen based on their geographical location, South and North, which results in different climatic conditions. The third country, United Kingdom, also from the North, has been chosen in order to have a comparison between countries with similar climate. The climate in Greece is Mediterranean, with hot, dry summers and cool, wet winters. The Netherlands has a maritime climate, with cool summers and mild winters. Similar to the climate of the Netherlands is the climate of the United Kingdom with slightly more precipitation throughout the year.

3. Results

The results will be presented in six sections. Section 3.1 describes the current situation in the building sector as well as a presentation of the design and the actual energy use in the three countries. Section 3.2 presents an overview of the factors that affect the energy consumption in residential buildings and cause the gap between design and actual energy use. The size of the gap between estimated and measured energy consumption for the United Kingdom, the Netherlands and Greece are discussed in Sections 3.3, 3.4, 3.5 respectively. The last part, Section 3.6, presents a comparison between the three countries.

3.1. The current situation in the building sector

In this section the current state of the building sector in Europe is presented and basic terms, such as the design and the actual energy use, are explained.

In Europe buildings vary remarkably, from large commercial offices to terraced single family houses. In general they can be divided into residential and non-residential buildings, which consist of different types of buildings. The residential sector is the largest part of the building stock in the EU, as it can be seen in Figure 4. It represents approximately 75% of the total floor space, that is 25 billion m^2 useful floor space or 30.528 km^2 gross floor space (Atanasiu, et al., 2011). However, for each country the share of the residential buildings is different. A schematic representation of the floor space distribution between residential and non-residential sector, for each European country, is shown in Figure 5 (Atanasiu, et al., 2011).

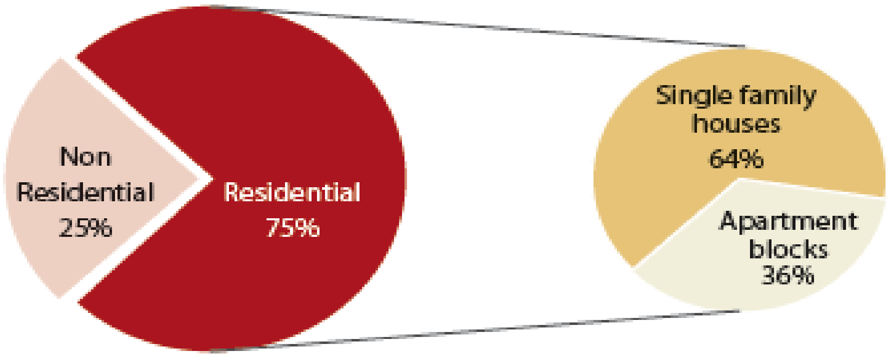

Figure 4: Proportion of residential floor space in EU (Atanasiu, et al., 2011)

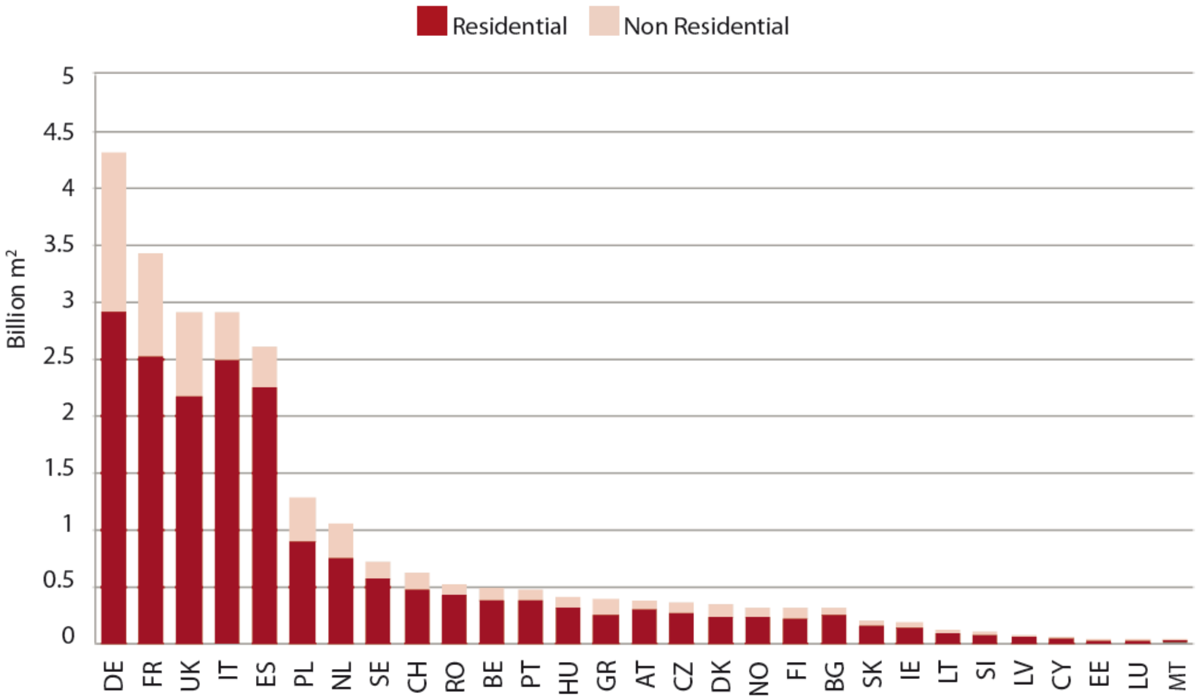

Figure 5: Floor space distribution between residential and non-residential sector for each European country (Atanasiu, et al., 2011)

In Europe the energy efficiency of the residential buildings is so poor, that it makes this sector one of the most significant energy consumers as well as a significant CO_2 emission source (Atanasiu, et al., 2011). This created the necessity to set standards for new buildings, but also for existing buildings. The regulations and the standards, that have been formed, in each country separately and in the EU in general, force the constructors to use new and improved materials and technologies in new buildings and existing buildings which undergo major renovations.

3.1.1. Design energy use

In this research the design and the actual energy use of the residential buildings are examined. The term "design energy use" refers to the amount of energy that the building would consume, according to estimations made by architects and engineers. The design energy use is determined before the building is constructed and does not take into account appliances and activities which are not related to the operation of the building. Despite the fact that the EU has a directive concerning the energy performance of buildings (Energy Performance of Building Directive - EPBD), it also allows each Member state to decide which methodology they will use. Therefore, the legislation and the calculations differ between the countries. For the three countries that are considered here the calculation methods are as follows.

Greece

The Greek housing stock is relatively old with the majority of the dwellings constructed between 1960 and 2000, as it is presented in Figure 6. Nevertheless, the legislation concerning efficiency in buildings is quite new in Greece since before the EU Directive there were no measures concerning the energy use or the energy performance of buildings.

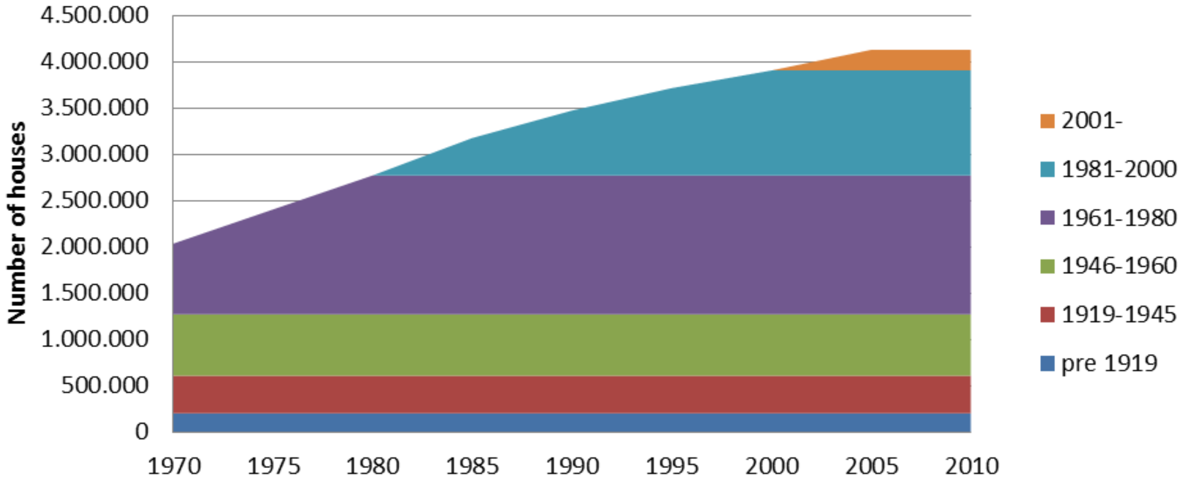

Figure 6: Housing stock distribution by age in Greece (Hellenic Statistics, 2008)

After the EU directive (EPBD) the Greek government formulated the law No. 3661/2008 "Measures to reduce energy consumption in buildings and other provisions" in order to incorporate the European directive to the national legislation (President of the Hellenic Republic, 2008). The Greek government also formulated the regulation No Δ6/Β/οικ.5825 "Regulation for the energy efficiency of buildings", which contains the methodology of calculating the energy performance of buildings (Minister of Finance & Minister of Environment,Energy and Climate Change, 2010). According to the Greek regulation, the energy efficiency of the dwelling is determined using the methodology of primary energy consumption[3]. The calculations take into consideration the following factors:

- number of residents

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[3] The emission factors as well as the transformation factors to primary energy for the different energy sources are determined in the legislation.

- the desired indoor conditions (temperature, moisture, ventilation)[4]
- the climatic conditions of the region (see Figure 7)
- geometrical characteristics of the dwelling's exterior shell and its orientation
- thermal characteristics of the building materials
- technical characteristics of the heating and cooling systems
- characteristics of mechanical and natural ventilation of the dwelling
- characteristics of the hot water supply system
- artificial lighting
- natural lighting
- renewable energy technologies, if applicable

In the Greek regulation a "reference building" is defined which has the same geometrical characteristics, position, orientation and use as the investigated one (Minister of Finance & Minister of Environment,Energy and Climate Change, 2010). The reference building meets the minimum legal requirements and has predetermined technical characteristics for heating, cooling, lighting, ventilation and hot water. The building under investigation satisfies the legal requirements if it complies with the minimum standards presented in the Greek regulation (Article 8) and with one of the following criteria:

1. The total primary energy consumption, of the investigated building, is equal or smaller than the primary energy consumption of the reference building.
2. The investigated building has the same technical characteristics, for the exterior shell and the various installed systems, as the reference building.

The calculations take into account the climatic conditions of the region the building belongs to. Therefore, in the Greek regulation, the country is divided into four climatic zones according to the heating degree-days of each region. Moreover, the regulation sets different insulation (U-values) requirements for each of these zones. The insulation level is increasing from the warmer to the coldest regions. In Figure 7, the climatic zones are presented from the warmer to the coldest. It should be noted, however, that all the places with altitude greater than 500m fall into the next coldest zone than the region they belong to (Minister of Finance & Minister of Environment,Energy and Climate Change, 2010).

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[4] The calculations for the design energy use take into account standardized indoor conditions and occupants behavior (Minister of Finance & Minister of Environment,Energy and Climate Change, 2010)

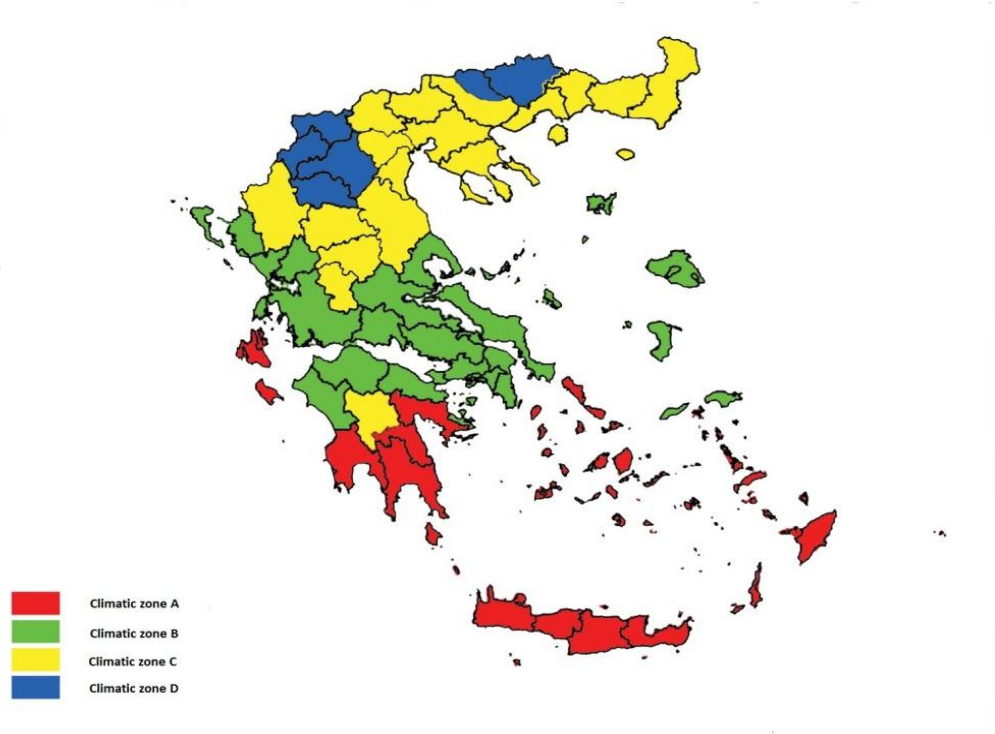

Figure 7: The four climatic zones in Greece from the warmest to the coldest. (Minister of Finance & Minister of Environment,Energy and Climate Change, 2010)

United Kingdom

In the United Kingdom the first regulations appeared in the sixties and seventies and they concerned with health and safety issues. From the late nineties onwards, the building requirements have been improved and focused more on the energy performance and CO_2 emission reduction of buildings.

From Figure 8, one can see that there is a vast amount of old buildings in the United Kingdom. Therefore, the regulations were focused on the improvement of the energy performance of existing buildings. However, regulations also exist for new constructions.

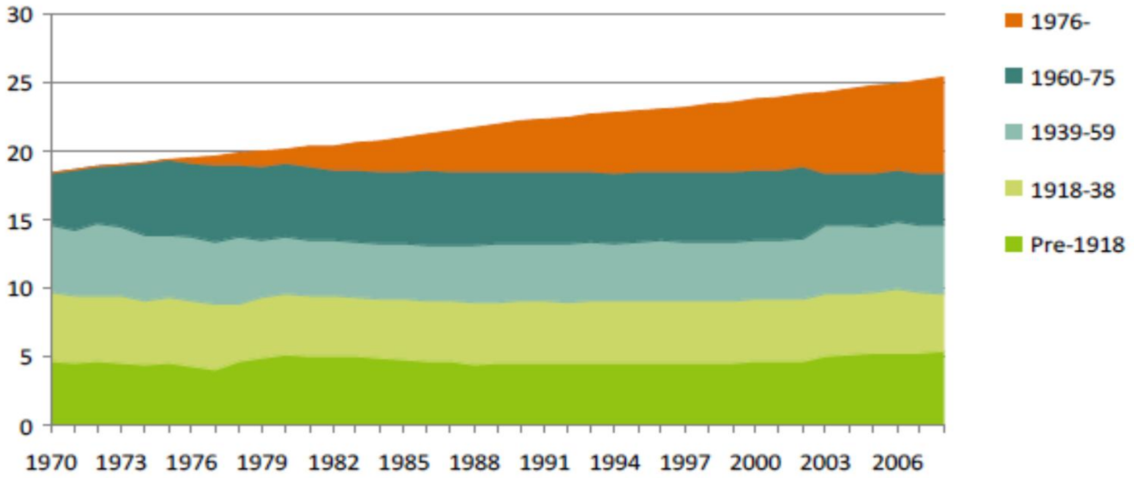

Figure 8: Housing stock distribution by age in United Kingdom (millions of houses) (Palmer & Cooper, 2011)

The Building Regulations in England and Wales contain 14 technical parts. Among them there is a part which is dealing with the efficiency requirements in the built environment. This part is Part L "Conservation of fuel and power" which consists of (Pan & Garmston, 2012, a)*:*

- Part L1A (new dwellings)
- Part L1B (existing dwellings)
- Part L2A (new buildings other than dwellings)
- Part L2B (existing buildings other than dwellings)

According to Part L1A, for new buildings, the methodology used to determine the energy performance of the dwelling is the standard assessment procedure (SAP). The calculation consists of a number of factors which affect the energy consumption such as (Department of Energy and Climate Change, UK, 2011):

- thermal characteristics of the material used for the construction of the dwelling
- ventilation characteristics of the building and the installed ventilation equipment
- efficiency of the heating system
- solar gains through openings of the dwelling
- energy source used for heating, lighting, ventilation and hot water
- energy consumption for space cooling (if there is one)
- applied renewable energy technologies

The SAP methodology calculates the energy consumption, the related costs and the corresponding CO_2 emissions but it does not set any standards (Department of Energy and Climate Change, UK, 2011). The UK government has also identified a notional[5] dwelling which has the same size and shape as the new dwelling but it is built in compliance with the legal standards. The compliance with the energy efficiency requirements is denoted by achieving five criteria (Pan & Garmston, 2012, a):

1. The Dwelling Emission Rate (DER) must be better than the Target CO_2 Emission Rate (TER) which is the emission rate of the notional building.
2. The dwelling design must meet a set of minimum limits as concerns the U-values[6], air permeability[7], fixed services and fixed lighting.
3. It should be demonstrated that the solar gains are limited in the design in order to avoid overheating of the new building.
4. The consistency of performance between the "as-designed" and "as-built" dwelling must be demonstrated through the consistency of performance of the dwelling and the DER.
5. Operating instructions for the efficient operation and maintenance of fixed services should be provided to the occupants.

The calculations are independent from characteristics related to the occupants of the dwelling (Pan & Garmston, 2012, a).

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[5] The "notional dwelling" is also referred to as the "reference dwelling"

[6] U-value is a measure of how well building elements (wall, floor, roof etc.) transfer heat. This means that the higher the U-value the worse the thermal performance of the element. In other words a low U-value indicates a high level of insulation. The value is expressed in W/mK.

[7] Air-permeability is the air leakage through gaps, holes and cracks in the buildings envelop which are not always visible. It can affect the performance of the building. This means that a more air tight building uses less energy for heating.

The Netherlands

The first policy measures appeared in the seventies and comprehensive legislation for reduction in energy use in buildings exists since the nineties (Schoonvelde, 2010). The housing stock is also relatively old with the majority of the dwellings being constructed from 1960 to 2000, as it is presented in Figure 9.

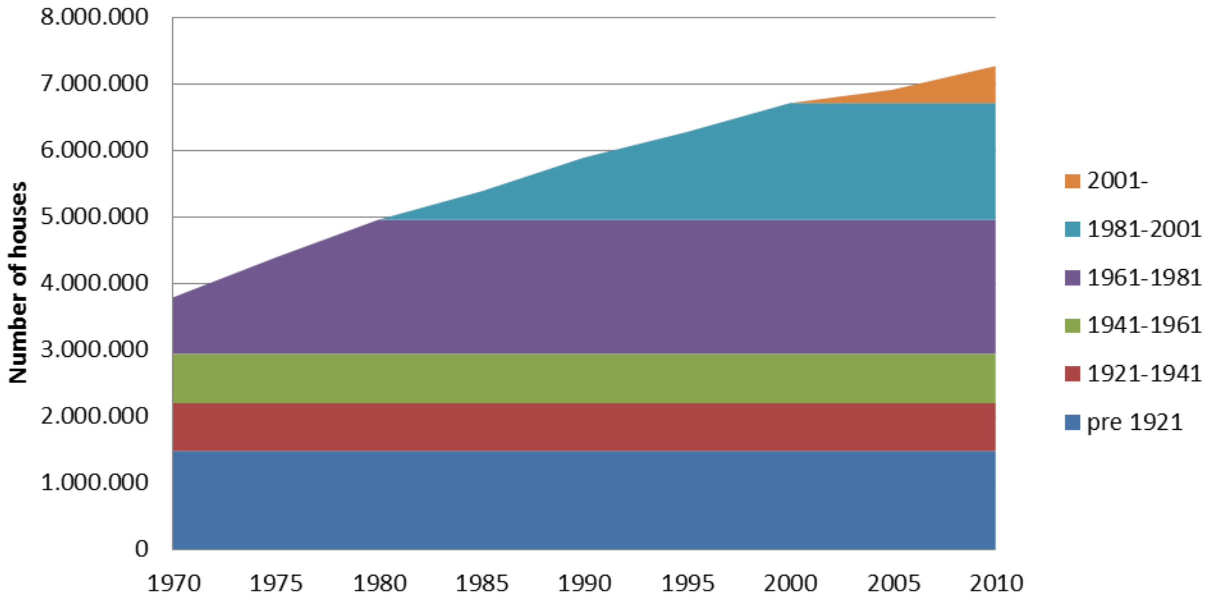

Figure 9: Housing stock distribution by age in the Netherlands (Centraal Bureau voor Statistics, 2012)

From the beginning of 21st century and after the Kyoto protocol, energy savings became a primary concern. The Dutch legislation is extensive and very similar to the European Union (EU) norms since the Netherlands had a significant influence on the development of EU norms (Schoonvelde, 2010). Nowadays, and after various methods used earlier, the determination of the energy performance of dwellings is based on the Energy Performance Coefficient (EPC) calculations. The energy performance coefficient is a dimensionless number which represents the theoretical energy use of a building. The calculation for the EPC consists of two parts: the actual energy characteristics of the building and the assumptions about consuming habits and outdoor climate.

The energy characteristics of the building can be presented as follows (Agentschap NL, 2012):

- The orientation of the building (orientation in relation to the sun)
- The structure and the thermal characteristics of the exterior shell (walls, floor, roof, windows, connections between the different parts, air leaks through the shell)
- The mechanical and electronic installations of the building (equipment for heating/cooling, hot water, ventilation, lighting)

The assumptions about the typical energy consumption behavior of the occupants contain assumptions for:

- Heating/cooling preferences
- Ventilation
- Lighting preferences
- Use of hot water

- Presence at home

However the energy consumption that results from equipment (such as refrigerators, computers, televisions etc.) and activities (like cooking, washing etc.) which are connected to the use phase of the building are not related to the building operation and are not taken into account when the energy performance coefficient is calculated (Schoonvelde, 2010). Since the performance of the dwellings is presented with a single dimensionless number the Dutch government has set standards for new buildings, i.e. a maximum value for the EPC which will be decreased in the coming years. Thus for a new building, to be in compliance with the requirements, its EPC value must be equal or lower than the existing standards[8].

3.1.2. Actual energy use

The "actual energy use" refers to the amount of energy that is consumed when the building is used by the residents. In households energy is mainly consumed for heating, cooling, hot water, cooking and the utilization of appliances. It should be noted that the dominant energy use in households is for space heating. Figure 10 presents the energy use in the residential sector for Greece, the Netherlands and the United Kingdom during the last decade. Figure 11 and Figure 12[9] show the electricity and the heating consumption, respectively, for the same period of time. As it can be seen from Figure 10, the actual energy use is not fixed over the years.

Comparing Figure 11 and Figure 12 it becomes obvious that the fluctuations in energy use represent mainly fluctuations in the heating consumption. Heating consumption can differ substantially each year due to the different weather conditions and therefore the different number of heating degree-days in each year. Moreover, the small increase in the electricity consumption, in Figure 11, can be explained by the use of electrical appliances in the households; either this is an increased number of appliances or the increased use of the existing appliances.

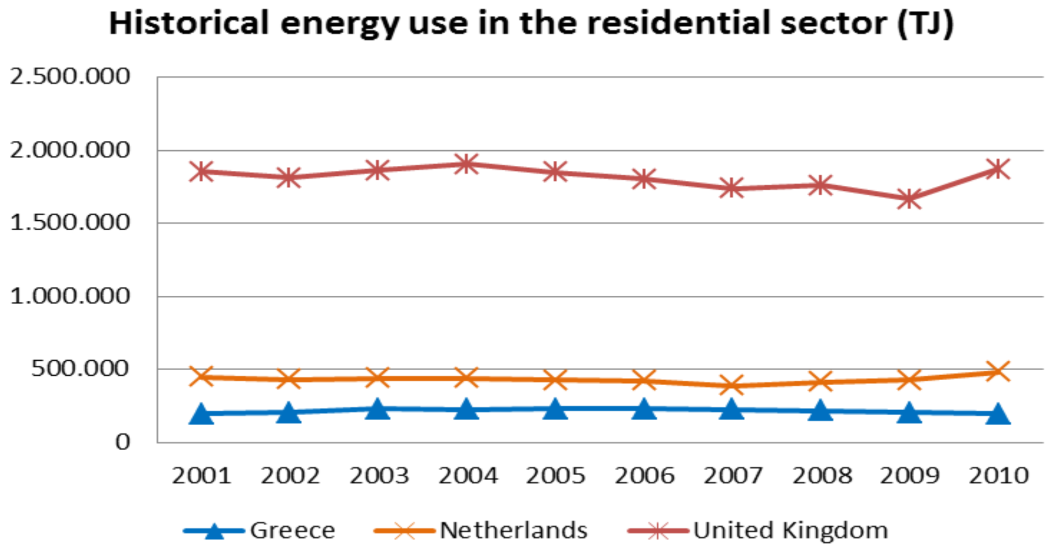

Figure 10: Historical energy use in the residential sector in Greece, the Netherlands and the United Kingdom

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[8] The EPC values, in contrast to the efficiency, represent better performance as they are becoming smaller. For example a dwelling with EPC of 0,6 performs better than one with EPC of 0,8.

[9] Data used in the graphs have been retrieved from (European Statistics, 2012 b; European Statistics, 2012 c; European Statistics, 2012 d; European Statistics, 2012 e)

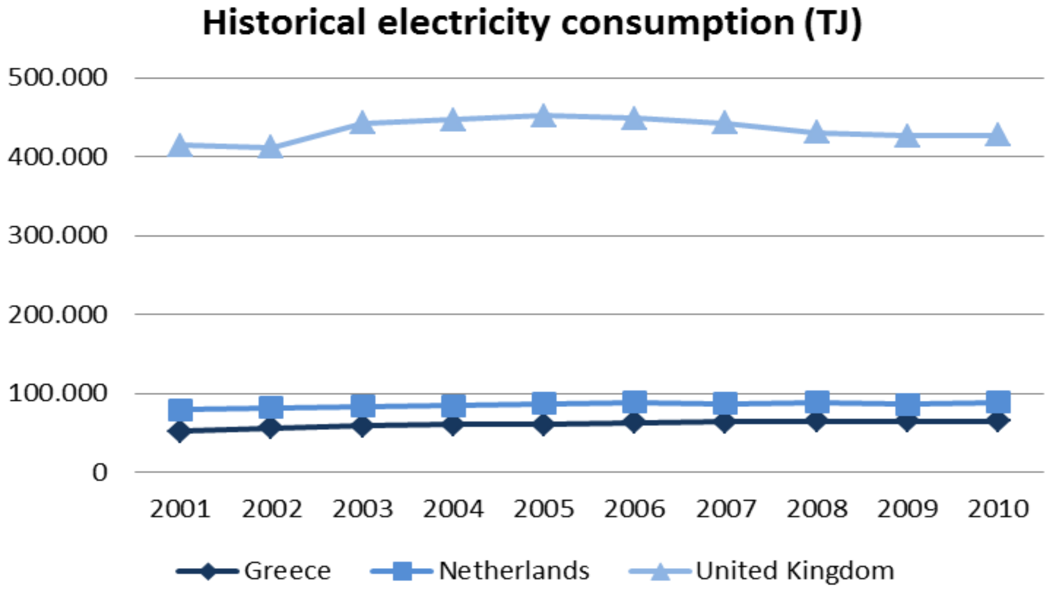

Figure 11: Historical electricity use in the residential sector in Greece, the Netherlands and the United Kingdom

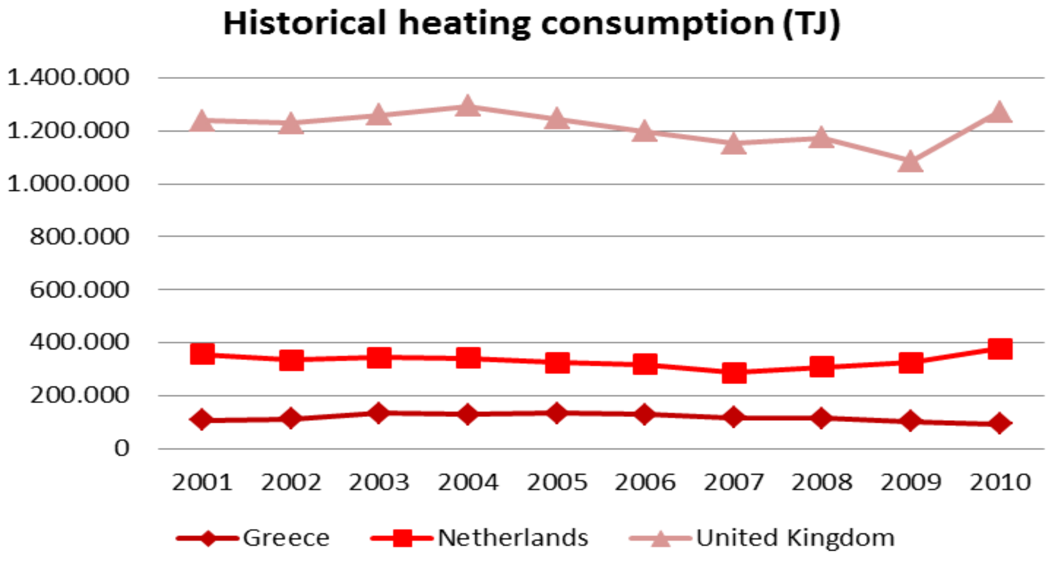

Figure 12: Historical heating consumption in the residential sector in Greece, the Netherlands and the United Kingdom

The actual energy consumption depends on the building characteristics as well as the occupant characteristics and behavior. The building characteristics which can influence the energy use in a household are (Guerra Santin, 2010):

- The type of the dwelling (detached dwelling, maisonette, flat, row dwelling, double dwelling, corner dwelling)
- The size of the building
- The age of the building
- The insulation level of the exterior shell (roof, walls, floors, windows, doors)
- The number of rooms

- The presence of auxiliary rooms (garage, shed, basement)

In addition, the energy consumption is highly dependent on the number, habits and the lifestyle of the residents in each household. There is a number of occupant related parameters that can influence the energy consumption such as (de Groot, et al., 2008):

- Number of occupants
- Age of occupants
- Amount of time that someone is in the house
- Desired indoor temperature
- Frequency of showering and bathing
- Preferred ventilation setting
- Number of appliances (as the size of the family increases the number of appliances also increases),
- Use of available devices
- Willingness to change habits / Motivation to save energy

It has been found that the improved efficiency of a dwelling is not enough to reduce the energy use. An energy intensive lifestyle has a bigger impact on the energy consumption than a very efficient building (de Groot, et al., 2008).

Furthermore, the energy use is also related to the income of the households. Research has shown that there is a positive correlation between income and energy consumption, which means that an increase in the income leads to an increase in the energy use. However, within the same income category, a smaller number of family members means less energy use (de Groot, et al., 2008; Sardianou, 2008). For instance de Groot (2008) states that households with one person consume 20% less energy than households with more members.

The factors that contribute to the calculation of the actual energy consumption have been described. Moreover, from Figure 10, Figure 11 and Figure 12, one can see how much the actual energy consumption in the three countries is. However, at this point another question arises: "What are the annual average electricity and heat consumption of a household in Greece, the Netherlands and the United Kingdom?". The answer to this question will provide a clearer picture of the similarities and differences among a Greek, a Dutch and an English household.

According to the European statistics, the electricity consumption in households in 2008 for the Netherlands is 24.798 GWh (89.273 TJ), for the United Kingdom is 119.800 GWh (431.280 TJ) and for Greece is 18.126 GW*h* (65.254 TJ) (European Statistics, 2012 e). The energy used for heating in households in the same year for the Netherlands is 308.449 TJ, for the United Kingdom is 1.174.115 TJ and for Greece is 115.193 TJ (European Statistics, 2012 b; European Statistics, 2012 c; European Statistics, 2012 d). After taking into account the number of households[10] in each country, the annual electricity and energy use for heating for a household has been calculated and presented in the next figures.

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[10] The number of households in 2008 has retrieved from the national statistics of each country: CBS (the Netherlands), ONS (United Kingdom), EL.STAT. (Greece)

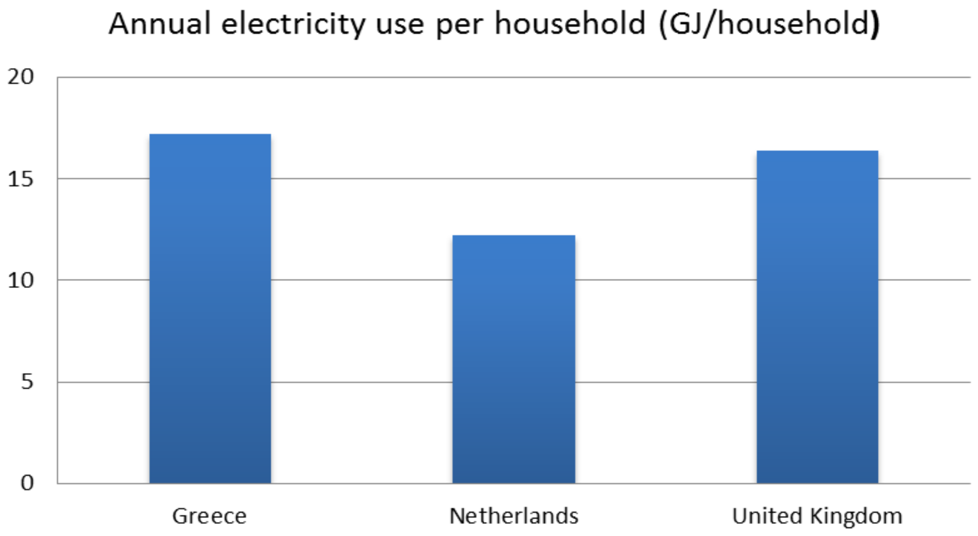

Figure 13: Average annual electricity consumption per household in the three countries (2008).

Figure 13 presents the average electricity consumed by a household in 2008 for the three countries under investigation. As it can be seen households in Greece and the United Kingdom consume much more electricity than in Netherlands. This results, probably, from the use of air conditioning and electric heating. In United Kingdom 8-9% of the households use electric heating (Owen, 2011). In Greece a substantial amount of households, especially at the islands, use electric heat during the winter and during the summer air conditioners are extensively used across the country. This leads to increased electricity consumption.

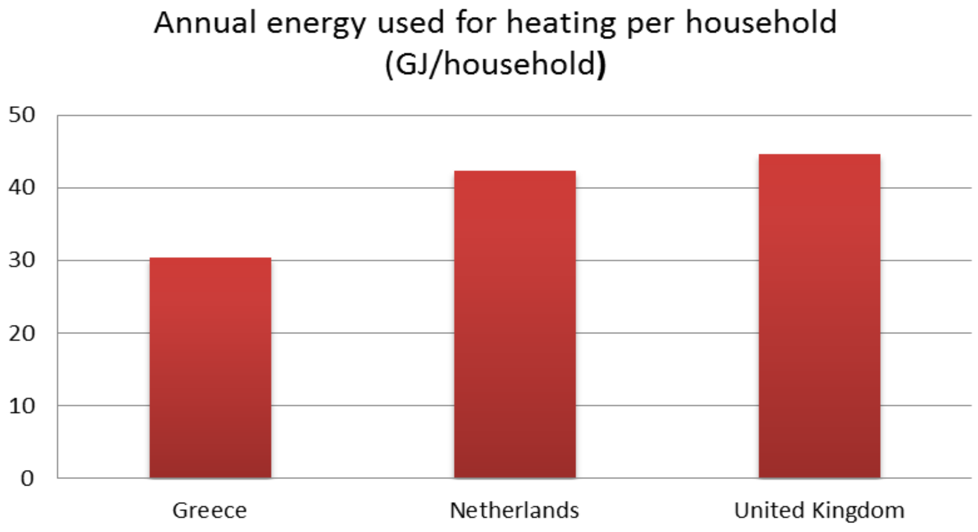

Figure 14: Average annual energy used for heating per household in the three countries (2008)

Similar to the electricity consumption, the energy use for heating exhibits differences between the three countries, as it can be seen in Figure 14. These differences can be explained by the weather conditions in that year in the three countries. As it can be seen in Table 1, in 2008, Greece had the least heating degree-days while the United Kingdom had the most. This means that the United Kingdom, in that year, had the most severe winter followed by the Netherlands and Greece.

Therefore, due to warmer winter, compared to the other two countries, Greek household used less energy for heating than a household in the other two countries.

Table 1: Number of heating degree-days in each country for a series of years (European Statistics, 2012 a)

Country	Heating Degree-days per year								
	2001	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**
Greece	1539	1490	1713	1545	1624	1685	1489	1434	1449
Netherlands	2721	2596	2759	2805	2658	2574	2424	2694	2727
United Kingdom	3093	2884	2880	2881	2879	2814	2818	3043	2990

In conclusion, the "design energy use" depends mostly on the dwelling characteristics and even though the legislation, in each of the three countries, takes into account a standardized occupant behavior, this usually does not correspond to the actual occupancy. For the "actual energy use" the dwelling characteristics and the occupant's behavior are of the same importance. This means that factors such as the type, the age and the insulation of a dwelling have a significant contribution to the energy consumption; but also factors such as the indoor temperature, the ventilation rate and the time at home contribute to the energy consumption.

3.2. Reasons behind the gap

In this section the reasons behind the gap between design and actual energy use are examined. Among the causes are different behavioral variables that influence the energy use in households, technical parameters of the construction as well as theoretical issues with the calculation methods. The reasons are presented based on which phase of the buildings' life they occur. In addition a schematic representation of the problem is given at the end of this section.

"Use" phase

From the analysis of literature review, it has been found that the importance of the occupants' influence on the energy consumption has been increasing over time (de Groot, et al., 2008; Guerra Santin, 2010). While Brounen et al. (2011) concluded that the occupants have a greater contribution to the energy use than the physcal characteristics of the buildings. The occupant factor has two parts: the first one is the characteristics of the occupants e.g. number, age and the second part is the occupants' behavior e.g. heating habits, ventilation habits, use of appliances. The number of household members, their age and their income are strongly connected to the energy requirement of a household. Vringer (2005) concludes that there is a strong positive correlation between energy consumption and income. This means that an increase in the income will, most probably, be followed by an increase in energy use. However, the income does not indicate the level of energy use since there are significant differences within the same income category. This means that the consumption pattern of a household is more important than the income. The variation within the same income category can also be partially explained by the family size and their age.

Sardianou (2008) focused on residential demand for space heating since it dominates the households' energy consumption and her results are in agreement with these from Vringer. Namely, the factors that can influence the heating demand are the number and the age of the residents as well as their income. In line with the previous, the results from Guerra-Santin's research (2010) showed that the presence of elderly persons in a household leads to more hours of heating and less hours of ventilation. In addition, the presence of children appeared to be the reason for less ventilation but not for more heating demand. Furthermore, the education level found not to be connected with the energy use.

Moreover, and apart from the occupant characteristics, occupant behavior is also important for the energy consumption. de Groot et al. (2008) found that the most influential, behavior related, parameters are the heating and ventilation habits, the amount of time someone is in the house, shower and bath frequency as well as the way of using the available devices. For instance, families with one or more children have higher frequency of bathing which lead to higher demand for hot water. The increase in the family members increases the possession of appliances which leads to higher electricity consumption. As concerns the occupant's behavior Guerra-Santin (2010) concludes that the number of hours with heating on at the maximum temperature has a stronger effect on the energy consumption than the higher temperature setting.

"Construction" phase

Up to now factors originating from the use-phase of the buildings have been discussed, which influence the energy consumption and can be the reason for the gap between predicted and measured consumption. However, there are also some other reasons behind this gap which are more technical. As it is reported by Sunikka-Blank and Galvin (2012), the way the building was designed to perform might be different from the way it is built in practice. For example, the insulation or the heat losses may be regulated differently than designed, or the installation of energy control devices might be wrong.

There are also issues in the building industry that cause this gap between design and actual energy use. As Bell (2010) concluded, the understanding of the technology is not sufficient for the production of energy efficient houses. He also argued that, even though the science behind the buildings is well established, and there are some people who understand the principles, for the majority the understanding of the details of the building performance in relation to the technologies and the ways of building is poor. The methods of calculating the design and the actual energy use are not well developed. Additionally, before the introduction of policies concerning the efficiency of the houses, the building industry has never been asked to achieve energy targets or to prove the energy performance of its products.

Furthermore, the energy performance is insufficiently considered in the design process and the control of the design is poor. The design is not connected with the calculations and the modeling and there are weak mechanisms for proving that the models reflect what is built. While the construction faces difficulties from insufficient design information, the various processes, that are included in the construction, are not able to ensure that the required standards are achieved because of their low level of detail. The feedback mechanisms, between construction and design, are underdeveloped and there is an underlying assumption that modeling results are the same as practice. This leads to lack of knowledge about what works and what does not and consequently to really small improvements in energy performance (Bell, 2010).

"Design-Calculation" phase

In addition to the above, there are some more theoretical reasons causing this gap. As Sunikka-Blank and Galvin (2012) stated, since the pre-construction energy use is calculated based on standardized methods, it is possible that the assumptions built into these methods are inaccurate or wrong; e.g. ventilation losses or standard indoor temperature. Other assumptions that are used in the models are the performance of the building materials. However, these assumptions are usually based on laboratory performance tests and they are not in agreement with the actual performance (Bell, 2010). In conjunction with the previous, the construction sector might have problems with complying with the building energy regulations. Pan and Garmston (2012, b) studied the compliance with the building energy regulations and they concluded that the compliance is influenced by constructors' knowledge and experience, building control, building method, type of building and project size. As concerns the building type, they found that new flats were more likely to comply with the regulations than new houses. Also the probability of compliance is increasing from mid-floor flats to ground-floor flats and it is greater for top-floor flats. It should be noted, however, that the authors do not make a clear distinction in why flats are in better compliance than the houses. Moreover, the detached houses have the lowest probability followed by the end-terrace and semi-terrace houses, whereas the mid-terrace houses have the highest probability for compliance. As concerns the size of the construction, the results suggested that larger projects were more probably in compliance with the regulations than the smaller ones.

In conclusion, the reasons behind the gap can be separated in five categories. These are a) the occupants' characteristics, b) the occupants' behavior, c) technical aspects of building, d) knowledge of the industry, e) calculation processes. Each category contains a number of reasons; however, some of them stand out. For instance, the age of occupants and the heating habits dominate the first two categories. Whereas the correct installations, the understanding of technologies and building methods, as well as the assumptions in the models are among the most important factors for the last three categories. The categories and the corresponding factors can be found in Table 2.

Table 2: The five categories of reasons behind the gap and the corresponding factors in each category

Phase of Buildings' life	Categories	Reasons
"Use" phase	*Occupants' characteristics*	Number of occupants
		Age of the occupants
		Income of occupants
	Occupants' behavior	Heating preferences
		Ventilation preferences
		Time at home
		Shower/bath frequency
		Use of appliances
"Construction" phase	*Technical aspects of the building*	Different U-values
		Incorrect installation
		Building differ from design
	Knowledge of the industry	Understanding of the design
		Understanding of the technologies
		Experience of the constructors
		Control of the construction
"Design-Calculation" phase	*Calculation processes*	Standardized occupant behavior
		Use of nominal instead of actual efficiencies

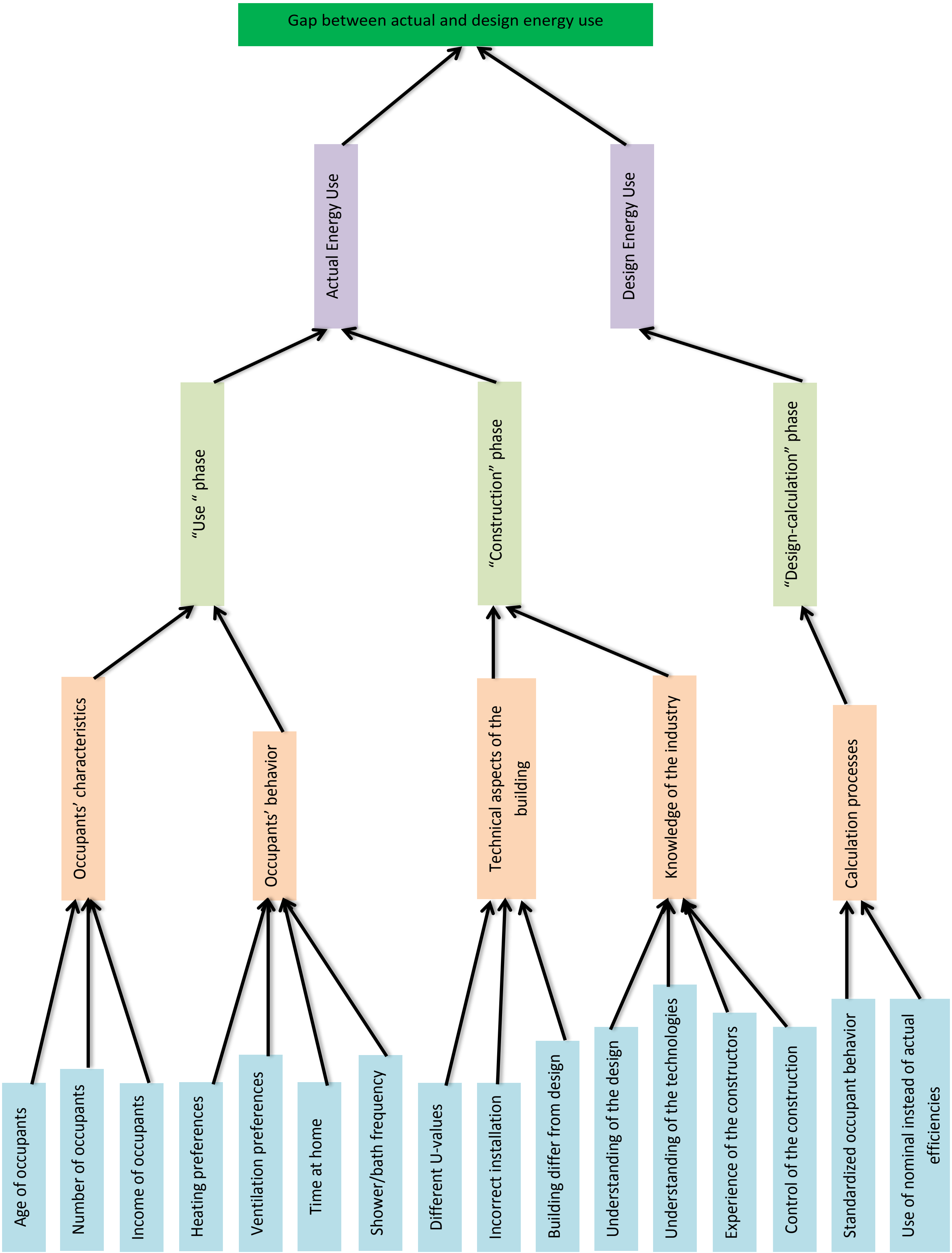

Figure 15: Schematic representation of the problem of the gap and the reasons behind it

Figure 15 presents a schematic representation of the problem of the gap as well as the reasons behind this problem. The representation starts from the problem itself "Gap between actual and design energy use" and by doing one step back at the time it unfolds the problem to its full extent. Thus the problem is presented fist and then the aspects of the problem are presented: "Actual energy use" and "Design energy use". The phases of the buildings' life that these aspects are related to are then presented, followed by the categories of reasons that fall into each phase. The representation is completed with the reasons that are contained in each category.

3.3. United Kingdom

In the United Kingdom, the size of the gap is unknown. The difference between expected and achieved energy performance of a building is in the range of -10% – 120% (Bell M., personal communication, October 11, 2012, see also Appendix). However, the size of the case studies and the collected data is too small and it is not possible to extrapolate them to the whole country and of course they do not constitute statistical data. Therefore, the aim of their presentation here is to give a preliminary insight to the problem and highlight the need for further research.

In total 34 tests have been carried out, but the number of buildings is smaller since most of them were tested before and after the intervention. A very general representation of the results can be seen in Figure 16 where the predicted heat losses, from the building's envelope, are displayed next to the measured heat losses, from the building's envelope. The difference between these two values is presented in Figure 17 as a percentage. Figure 17 is a preliminary representation of the gap between predictions and measurements (Stafford, et al., 2012).

It should be noted that, the heat loss coefficient, as well as the performance gap, can be affected by different factors such as the size and the type of the building (Stafford, et al., 2012). Moreover, attention should be paid to the four negative results. The two with the highest negative value are tests conducted on existing buildings. Therefore there is great uncertainty on the predicted values since the materials used, the building method and the thermal bridging calculations were unknown. The other two negative results came after physical intervention. The small values of the results in combination with the corresponding uncertainty of the test make these results to be considered as zero. This means that the dwellings, after the intervention, had the same performance with the "as-

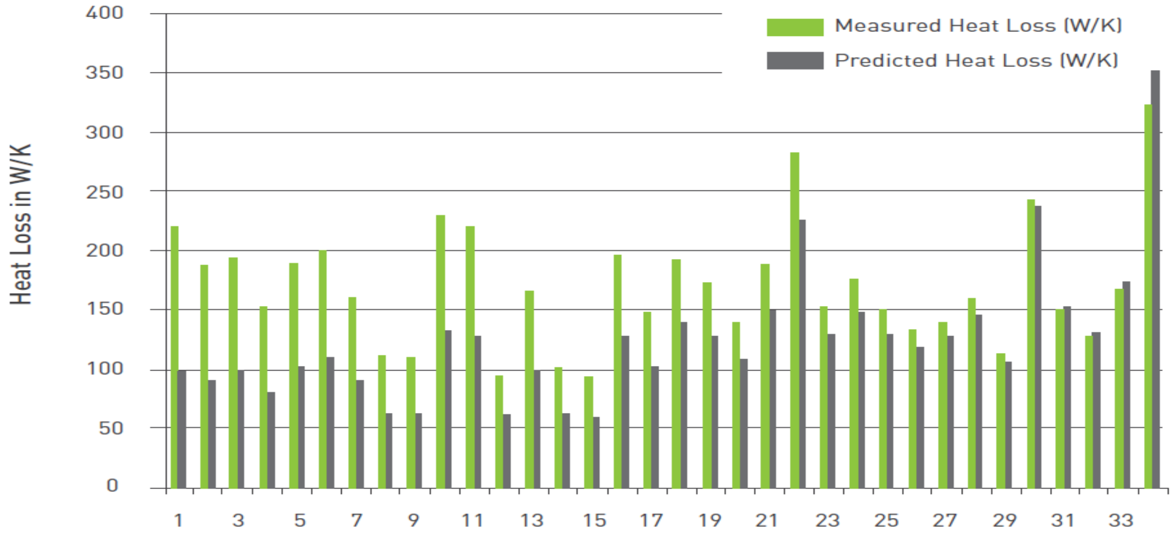

Figure 16: Comparison between predicted and measured heat loss for the tested houses (Stafford, et al., 2012)

designed” performance (Stafford, et al., 2012).

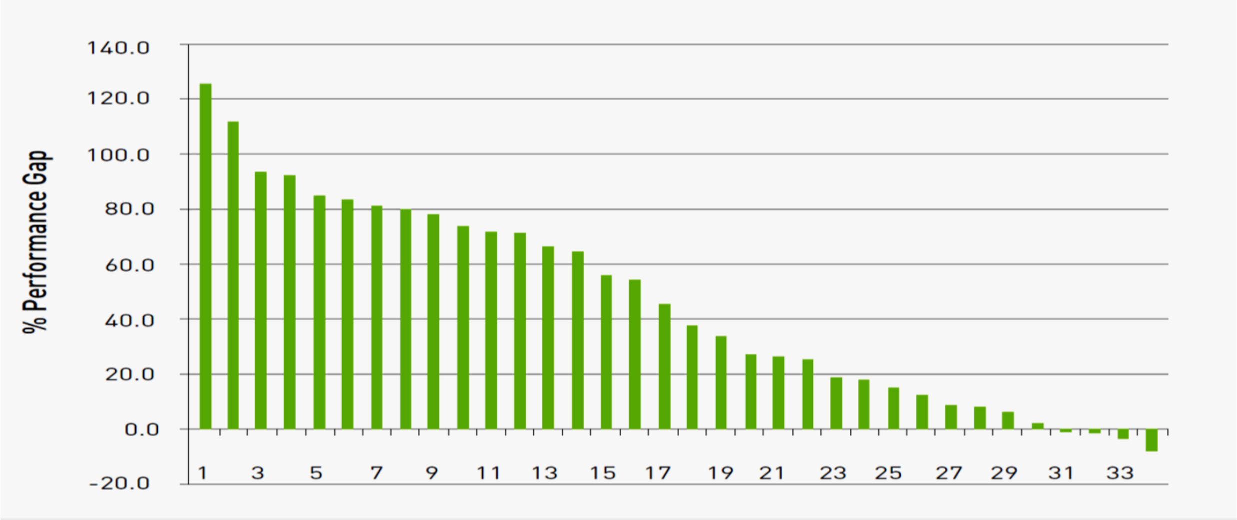

Figure 17: Percentage representation of the gap between predicted and measured heat loss coefficient for the tested houses (34 tests) (Stafford, Bell, & Gorse, 2012)

As mentioned earlier the type and the size of a dwelling can affect its performance. More precisely, the type of the building has a great effect on heat losses through party walls. For instance, a mid-terrace dwelling has two party walls which means higher heat losses due to bypass than for the other types of dwellings. The size of the dwelling has a great effect on air-permeability and the corresponding heat losses. The collected data showed that it is easier to achieve lower air-permeability values in large dwellings (Stafford, et al., 2012).

In order to have a better understanding of the problem the case studies of Elm Tree Mews (new buildings), Stamford Brook (new buildings) and Temple Avenue (existing buildings) are discussed in detail.

3.3.1. New buildings

Elm Tree Mews case study

For Elm Tree Mews the research was conducted by Leeds Metropolitan University from 2007 to 2009 (Bell, et al., 2010; Wingfield, et al., 2011, a). The case study consists of six low energy dwellings (their details can be found in Table 3) and the research includes construction observations, post-construction measurements and monitoring of the dwellings for one year after their occupancy[11] (Bell, et al., 2010; Wingfield, et al., 2011, a) .

Table 3: Dwelling details for the Elm Tree Mews case study (Wingfield, et al., 2011, a)

Dwelling Code	House Type	Occupancy	Tenure
House A	Mid terrace	4 + 1 dog	Rented
House B	Mid terrace	5	Rented
House C	Ground floor flat	1 (intermittent occupation)	Rented
House D	Mid terrace	3 + 1 cat	Part-ownership
House E	Duplex flat	1	Part-ownership
House F	End terrace	n/a	Full sale

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[11] Thermal images can be found in Appendix

The performance of the dwelling is strongly connected to the heat losses through the various construction elements and junctions of the dwelling. In Elm Tree Mews the observations and the measurements showed that the predicted heat losses were not in agreement with the measured heat losses. The predicted heat losses were calculated during the design phase using the nominal U-values and thermal bridging factors which were not achieved during the construction. This resulted to an increase of the actual heat losses compared to the predicted using the nominal values (Bell, et al., 2010; Wingfield, et al., 2011, a). The next tables (Table 4 and Table 5) present the predicted heat losses using the nominal U-values and thermal bridging factors and the calculated heat losses using the "as-built" U-values and thermal bridging factors (for the houses with the best and the worst performance). The differences between these two values and the percentage increase of heat loss are also shown in the same tables. As it can be seen, for most of the construction elements the variations are big, which lead to substantially higher heat losses than predicted. Of crucial importance are the losses through party walls. During the design phase, these losses were not taken into account in spite the fact that in some cases they constitute a significant part of the total losses. (E.g. houses A, B, D)

Table 4: Difference between predicted and actual heat losses for the mid terrace houses in Elm Tree Mews case study (Wingfield, et al., 2011, a)

As-built and nominal fabric heat loss for mid-terrace (Houses A,B,D)			
Heat loss element	**Heat loss using as-built U-values or y-values (W/K)**	**Heat loss using designed U-values or y-values (W/K)**	**Difference between as-built and designed heat loss (W/K)**
External Wall	9.5	5.7	3.8 (+66.7%)
Party Wall	41.4	0.0	41.4
Roof	12.7	9.2	3.5 (+38.5%)
Windows/ Doors	38.5	28.8	9.6 (+33.3%)
Rooflights	2.4	2.4	0.0
Thermal Bridging	24.2	12.9	11.3 (+87.5%)
Floor	7.7	7.7	0.0
TOTAL	136.4	66.7	69.7 (+104.4%)

Table 5: Difference between predicted and actual heat losses for the ground floor flat in Elm Tree Mews case study (Wingfield, et al., 2011, a)

As-built and nominal fabric heat loss for ground floor flat (House C)			
Heat loss element	**Heat loss using as-built U-values or y-values (W/K)**	**Heat loss using designed U-values or y-values (W/K)**	**Difference between as-built and designed heat loss (W/K)**
External Wall	9.6	5.8	3.8 (+66.7%)
Party Wall	6.0	0.0	6.0
Roof	0.0	0.0	0.0
Windows/ Doors	32.0	24.0	8.0 (+33.3%)
Thermal Bridging	15.2	8.1	7.1 (+87.5%)
Floor	10.7	10.7	0.0
TOTAL	73.5	48.5	24.9 (+51.4%)

Apart from the calculations using the "as-built" values, coheating tests[12] were also conducted at the houses. The results of these tests were in good agreement with the calculations using the "as-built" values. For instance, for the end terrace house (House F) the difference between predicted and calculated heat losses was 68,1 W/K and the difference between predicted heat loss and test result was 68,9 W/K. The above results lead to the conclusion that the variations between the test results and the predicted values can be explained by the variation in U-values and thermal bridging factors (Wingfield, et al., 2011, a). Thus, as it is presented in section 3.2, the construction methods and the material use are important contributors to the gap between predicted and actual energy consumption. In section 3.2 factors affecting the energy consumption which are related to the human behavior are also discussed. These factors are in agreement with the results from Elm Tree Mews case study. More precisely, it is found that the number of occupants and the time at home have both positive correlations with the energy consumption. The mid terrace houses (houses A,B and D) had a higher electricity consumption compared to the ground floor flat (house C) and the duplex flat (house E), as one can see in Table 6. This reflects the higher number of occupants in the mid terrace houses compared to the other two as well as the smaller floor area of the flats and the limited time spent at home from their occupants.

Table 6: Average daily electricity consumption in each house in a year and in seasons. (Wingfield, et al., 2011, a)

Mean daily electricity use -annual and by season					
Period	**Mean Daily electricity use (kWh)**				
	House A	**House B**	**House C**	**House D**	**House E**
Annual	12.1	10.3	3.0		
Oct-Apr	12.9	11.0	3.2		
Jul-Aug	10.7	10.5	2.3	11.8	5.0

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[12] The objective of a coheating test is to measure the actual heat loss through the building's fabric. It includes measurements of heat losses through walls, floor, roof, doors, windows and thermal bridges. In order a coheating test to take place first the ventilation system is block to eliminate losses. Then a heating system is installed to the building which is heating it for one or two weeks without disturbances. Then the heat loss through the various elements of the building is measured.

The same conclusion, concerning the number of occupants and the time at home, can be drawn by the heat (Table 7) and hot water consumption (Table 8) for each household (Wingfield, et al., 2011, a). Again the households with the higher occupancy and the bigger floor area (houses A,B and D) have the highest consumption. It should be noted, however, that household B has lower hot water consumption than a similar average household in United Kingdom ("BREDEM-12 Model" row in Table 8); this means that their bath and shower habits are more conscious (Wingfield, et al., 2011, a).

Table 7: Average daily heat consumption in each house in a year and in seasons. (Wingfield, et al., 2011, a)

Mean daily communal heat input -annual and by season					
Period	**Mean Daily heat input from communal main (kWh)**				
	House A	**House B**	**House C**	**House D**	**House E**
Annual	12.2	9.8	2.6		
Oct-Apr	19.2	16.6	4.1		
Jul-Aug	1.1	0.3	0.6	1.1	0.8

Table 8: Average daily hot water consumption in each house in a year and in seasons and comparison with the average household in UK (Wingfield, et al., 2011, a)

Mean daily hot water use occupied dwellings					
Period	**Mean Daily hot water use (liters)**				
	House A	**House B**	**House C**	**House D**	**House E**
Annual	145.1	74.9	18.6		
BREDEM-12 model estimate	138.0	163.0	63.0	113.0	63.0
Oct-Apr	153.8	87.1	15.0		
Jul-Aug	116.2	51.7	25.7	111.7	49.6

The Elm Tree Mews case study showed how important are the heat losses from party walls as well as the assumptions about the performance of the different building elements. Therefore, for a more precise prediction heat losses through party walls should be a part of the calculation procedure. Moreover, the actual instead of the nominal performance of the different elements should be taken into account and the substitution of materials should be careful and in line with the design.

Stamford Brook case study

For Stamford Brook the research was conducted by Leeds Metropolitan University in collaboration with University College London from 2001 to 2008 (Wingfield, et al., 2011, b). The Stamford Brook development consists of more than 700 cavity masonry dwellings. Even though the construction of all the dwellings was observed, only four of them were monitored, for a year, after their occupancy[13] and their details presented in Table 9 (Wingfield, et al., 2011, b).

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[13] Thermal images can be found in Appendix II

Table 9: Dwelling details for the Stamford Brook case study (Wingfield, et al., 2011, b)

Dwelling code	Dwelling type	Floor area (m^2)	Number of bedrooms	Number of occupants
House A	3-storey end terrace	105	3	3
House B	2-storey mid terrace	84	3	2-3[14]
House C	3-storey end terrace	105	3	2
House K	2-storey detached	129	4	2

This research, in contrast to the Elm Tree Mews, was more focused on the occupant's behavior and the reasons behind the different energy use patterns. The results on occupant's behavior are presented in Table 10 along with the annual energy consumption for heating and hot water. It becomes clear that the ventilation habits have a positive correlation with the energy use for heating. The same is true for the internal temperature preferences. For example, house A has the highest energy use for heating. This can be explained by the high internal temperatures, which in combination with high ventilation rates, lead to high heat losses through ventilation. As concerns their effect, the internal temperature preferences have a stronger effect on the energy consumption than the ventilation habits. For example, houses C and K have similar ventilation habits but house C has higher internal temperature thus the energy use for heating is higher for house C than for K.

Table 10: Occupant behavior patterns and their effect on the annual energy use for heating and hot water (Stamford Brook case study) (Wingfield, et al., 2011, b)

Occupant behavior patterns and effect on annual energy use					
House	**Ventilation during Heating Season**	**Internal Temperature during Heating Season**	**Domestic Hot Water Use**	**Annual Space Heating Energy Use (kWh/m2/yr)**	**Annual Domestic Hot Water Energy Use (kWh/m2/yr)**
A	High	High	High	81	37,4
B	Average	Average	Low	48	26,5
C	Average	Average	Average	42,8	29,2
K	Average	Low	High	35,7	31,5

The differences at the dwellings (as presented in Table 9) in combination with the various occupants' preferences (as presented in Table 10) can explain the variations in energy consumption between the households, as these are presented in Table 11**.** The highest gas use is observed for house A which is the result of the high internal temperature during the heating season and also the high ventilation rates. Next on gas consumption is house K which, in spite the fact that is bigger in size than A, it has significant less gas use. This results from the fact that house K has less occupants and the internal temperature during the heating season is low. The variations between B, C and K are not of the same magnitude as with A and they can be explained mainly by the size of each dwelling.

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[14] From April to September there were three occupants whereas for the rest of the year there were 2.

Table 11: Average annual gas and electricity consumption in the monitored dwellings in Stamford Brook case study (Wingfield, et al., 2011, b)

Mean annual energy consumption for monitored dwellings from meter readings				
	Dwelling A	Dwelling B	Dwelling C	Dwelling K
Annual Gas Use (kWh/a)	12835	6444	7938	8849
Annual Electricity Use (kWh/a)	3086	2506	3019	3020
Total Annual Energy Use (kWh/a)	15921	8950	10957	11869
Total Annual Energy Use per m2 (kWh/m2/a)	151,6	106,5	104,4	92

The outcome of the Stamford Brook case study showed that the SAP predictions are in good agreement with the actual energy use when factors related to occupants' behavior but also factors related to the differences, between design and actual building, are taken into account. This means that not only factors such as the temperature setting and the ventilation rate are important but also the party wall effect and the true efficiency of the installed systems (Wingfield, et al., 2011, b). The importance of these factors can be better understood if we compare the predictions with the actual consumption. The comparisons between actual and predicted hot water consumption as well as actual and predicted space heating are presented in the Figure 18 and Figure 19[15]. For space heating the SAP calculations are corrected, except for the actual occupancy, for internal temperature, party wall U-value, degree-days, thermal bridging and installations efficiencies (here is boiler efficiency). As it can be seen from the graphs the corrections for actual occupancy are not enough to bring the predictions in good agreement with the actual consumption. Thus factors related to the differences between design and actual building should be taken into account and the corresponding corrections are necessary to close the gap.

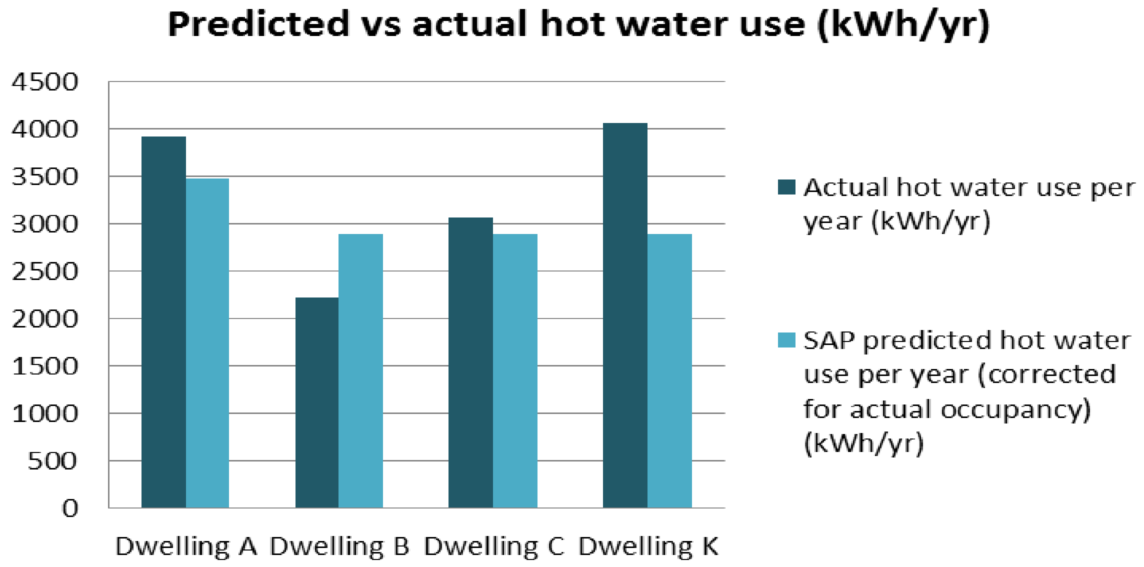

Figure 18: Comparison between actual consumption of hot water and the corrected for the actual occupancy SAP predictions.

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[15] The data are retrieved from the Stamford Brook report (Wingfield, et al., 2011, b)

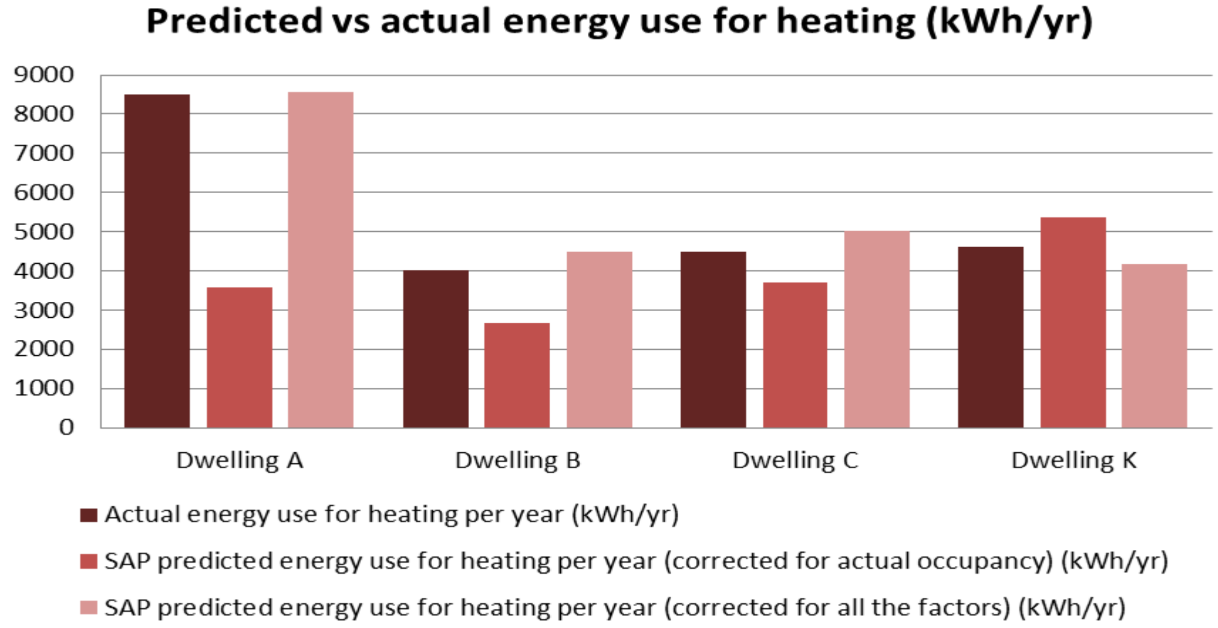

Figure 19: Comparison between actual energy consumption for heating and SAP predictions corrected for actual occupancy and for all the other factors.

3.3.2. Existing buildings

Until now the case studies have concerned new buildings. However, the existing buildings constitute a great share of the building sector. Therefore, the last case study is focused on the renovation of existing building. The renovation concerned the Number 67 Temple Avenue, York, and it was focused on improving the fabric followed by improvements in heating and ventilation systems[16]. The research was carried out by the Leeds Metropolitan University from July 2009 to March 2010 (Richards Partington Architects, 2012).

The situation with existing buildings is more complex than the one for new buildings. Existing buildings have the same issues, during their renovation as new buildings (i.e. substitution of material, construction techniques etc.) but they also have issues during the design phase. Every existing building is unique due to the specific alterations that took place on it over time. These alterations lead to a building that is different from the average building of the same era. Therefore, during the design phase there is high uncertainty on the thermal properties of the building fabric and consequently the efficiency of the building which can reduce the savings from the implemented measures.

For the Temple Avenue the predictions for the performance of the building were carried out using SAP calculations. The U-values of the fabric, for the SAP calculations, were taken from the inspection of the building and air permeability tests. However, the measured performance of the building was better than the predictions, probably due to lack of understanding of the construction, which led to underestimation of the building performance (Richards Partington Architects, 2012). Moreover, the first stage of improvements (Standard retrofit) following the underestimation of the building performance, overestimated the benefits from the undertaken measures. The same is true for the second stage of improvements (Radical retrofit) as well (Richards Partington Architects, 2012). An overview of the Temple Avenue project can be seen in Table 12**.**

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[16] Thermal images can be found in Appendix II

Table 12: Overview of the Temple Avenue Project (Richards Partington Architects, 2012)

67 TEMPLE AVENUE	EXISTING CONDITION	STANDARD RETROFIT	RADICAL RETROFIT
SAP BAND A-G	D	C	B
SAP SCORE 0-100	59	77	89
PREDICTED HEAT LOSS W/K	341,4	238,7	107,2
PREDICTED HEAT LOSS REDUCTION W/K	0	102,7	234,2
PREDICTED HEAT LOSS PARAMETER W/m2K	3,05	2,13	1,15
MEASURED AIRTIGHTNESS $m^3/(h.m^2)$@50Pa	15,76	9,83	5,42
MEASURED HEAT LOSS W/K	324,7	249,2	159,0
MEASURED HEAT LOSS REDUCTION W/K	0	75,5	165,7
MEASURED HEAT LOSS PARAMETER W/m^2K	2,90	2,22	1,42

The comparison of the predictions with the actual measurements (see Table 12) shows that the actual heat losses of the building were 4,89 % less than the SAP predictions. This led to overestimation of the possible improvements both in the first and the second stage of the renovation. The result was 26,48 % smaller heat loss reduction in the first stage (Standard retrofit) and 29,25 % smaller heat loss reduction in the second stage (Radical retrofit).

The values added to SAP calculations and therefore the predictions for the initial status of the building depend on the survey carried out at the beginning of the project. The predictions after the improvements also depend on the values added to the calculations. Usually the values added to the calculations are theoretical U-values of the various elements, which are based on laboratory performance, and also ideal installations are assumed. These assumptions are not achieved in practice and therefore the predictions over- or underestimate the actual performance (Richards Partington Architects, 2012).

From the results in the Temple Avenue case study has been verified that every existing building is unique and requires different improvement measures. Before the renovation, an extensive survey is required, which will include also all the alterations that have been done to the building, in order to discover which is the current state of the building. Furthermore, the efficiency of the improvements depends on the precision of the installation. This means that the construction workers should be careful with the implementation of the improvements (e.g. accurate placement of the insulation material) in order to have the expected saving results.

3.4. The Netherlands

In the Netherlands the research on the difference between actual and predicted energy use is young and small. Therefore, the magnitude of the problem is unknown since the collected data are few and they cannot be considered as statistical data for the whole country. The aim of their presentation here is to give a first insight to the problem and highlight the need for further research.

The case studies and the corresponding data for the Netherlands have been retrieved from BouwTransparant[17]. BouwTransparant is a project in which newly constructed houses are tested against their actual energy performance. It helps municipalities, environmental and constructing parties in the realization of the EPC, as specified in the building permit. BouwTransparant gives the different parties an insight into the actual realized Energy Performance Coefficient of the house and shows the abnormalities.

There are more than 80 houses tested after the construction in order to investigate if they are in compliance with the design and the legal requirements. The process starts with the original EPC calculations and any equivalent statements. After that an inspection takes place during which different components of the building are monitored such as thermal capacity of the shell, thermal bridges, heating, hot water ventilation, solar collectors etc. The last step is the recalculation of the EPC using the observed values for the different components. The tests do not consider the occupant's behavior but only the performance of the building itself. A general representation of the results can be seen in Figure 20 and Figure 21. Figure 20 shows the difference between actual and predicted energy use for each house, while Figure 21 shows the Energy Performance Coefficient (EPC) difference as a percentage.

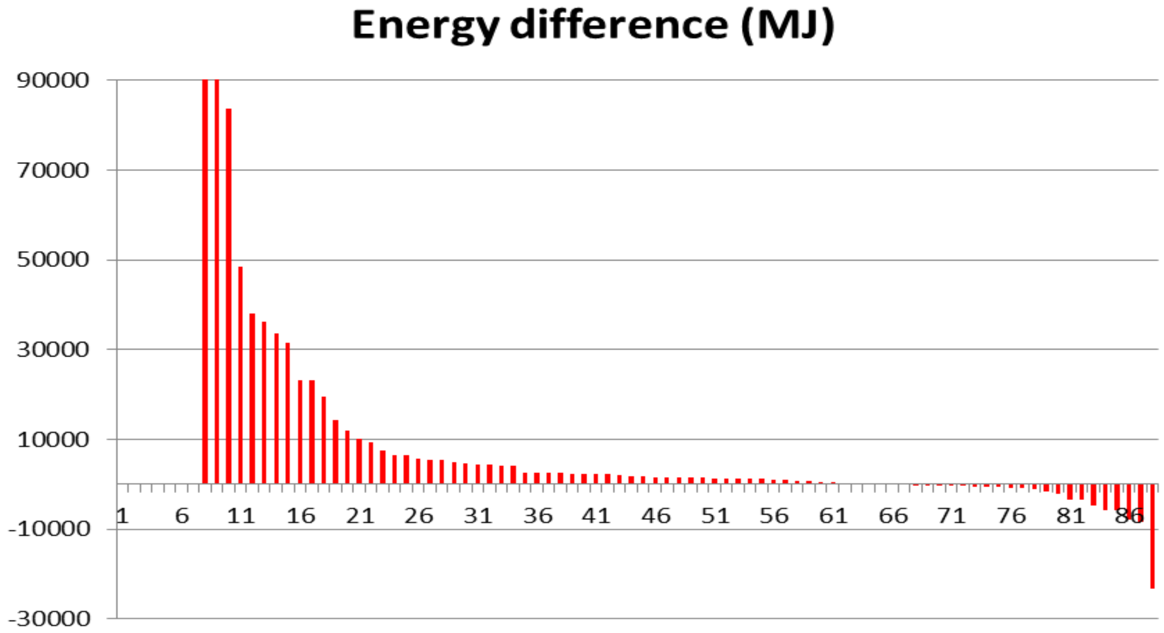

Figure 20: Difference between actual and predicted energy use for the tested houses in the Netherlands.

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[17] BouwTransparant web-site: http://www.bouwtransparant.nl/

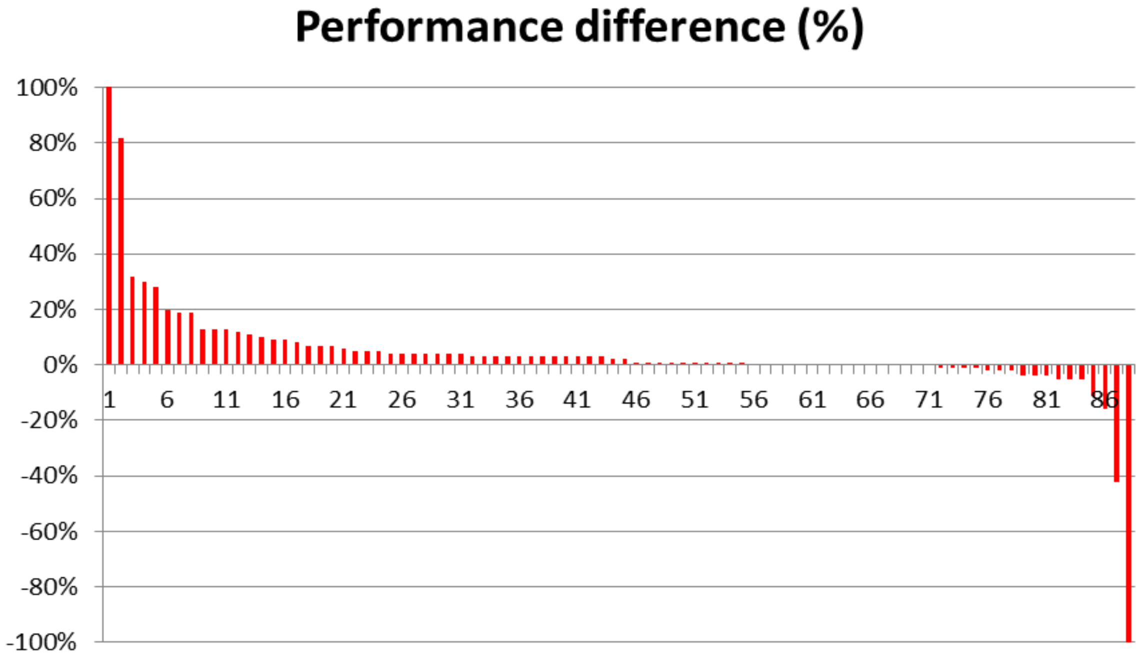

Figure 21: Performance difference as a percentage for the tested houses in the Netherlands. (88 tests)

It should be noted that, in Figure 20 the first seven houses are not zero but unknown values. This resulted from the fact that these houses had been built in accordance with the design; however, there are differences, between prediction and actual measurement, in the energy consumption for the various systems (heating, ventilation, lighting, cooling etc.) and therefore it is unknown if their total energy consumption is the same or differs from the predictions. In addition, the houses 8 and 9 (the first two lines in Figure 20) have an extremely large variation from the prediction (approximately 262000 MJ and 237000 MJ respectively) thus their values cannot be seen in the graph. Furthermore, attention should be paid not to compare the two graphs directly since a large energy difference does not correspond to a large performance gap. For instance, the two former mentioned houses (house 8 and house 9) are not represented by the first two lines in Figure 21 but they come later with a performance difference 13% and 11% respectively. This results from the fact that the houses are built in different years and therefore with different requirements and different standards. Also the first house in Figure 21 has a performance difference of 126% thus it is out of the axis range.

The previous graphs show the size of the difference in total. However, it is also interesting to see which the origin of the energy differences is. In other words, where the biggest energy difference is coming from? As it can be seen in Figure 22, the most frequent sources of energy difference are the heating (42% of the houses) and the summer comfort[18] (25% of the houses). It is also worth to note that there are houses, which have been built according to the design, and they do not have any deviation at the energy use (7%). However, there are also houses in compliance with the design which still exhibit small energy differences. This is due to the fact that installed systems require more and/or less energy than the predictions. For example the heating system uses less energy than the predictions but the summer-comfort requires more energy than the predictions. However, it is unknown if these two variations equilibrate each other and bring the total energy consumption of the house to the same level as the predictions or not. Therefore, there is an “Unknown” part which can fall in any of the other categories.

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[18] “summer comfort” refers to the energy that is required in order to maintain comfortable indoor conditions during the summer. This can be energy for fans, air conditioners or heating systems that also provide cooling.

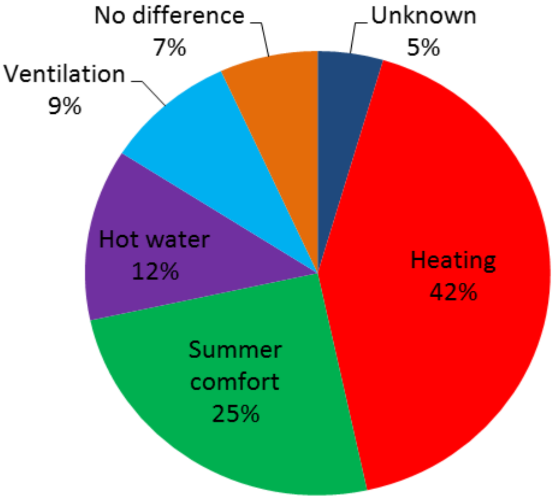

Figure 22: Reasons behind the largest energy difference in houses in the Netherlands presented based on their frequency.

The data analysis showed that in the most cases the factors causing the deviation, between predicted and actual energy consumption, affecting negatively the energy use. For instance, the bigger glazing, the increased U-values for frames and insulation as well as the incorrect installation of the insulation and the connections between the various building elements cause unwanted heat losses. Moreover, the smaller efficiency or the bigger capacity of the installed systems as well as the incorrect installation of these systems and the orientation of the building increase the energy demand. On the other hand, factors were also observed which decrease the energy use. The observed factors can be found in Table 13 ranked according to the number of houses they have been observed in. This means that 15% of the houses had more glazing than the design where as 5% had less glazing. As is it mentioned earlier there were houses which were built exactly as the design and therefore these houses are not included in the results in Table 13. Furthermore, there is possibility that both negative (factors increasing the energy use) and positive (factors decreasing the energy use) factors to be observed in the same house. This means, for instance, that a house might have more glazing than the design but also insulation with lower U-value.

Table 13: Factors influencing the energy use in the Dutch houses ranked based on the percentage of houses in which they were observed.

Factors increasing energy use		Factors decreasing energy use	
More glazing	15 %	**Lower U-values for insulation**	11 %
Higher U-values for frames	13 %	**More efficient installed systems**	9 %
Higher U-values for insulation	10 %	**Less glazing**	5 %
Less efficient installed systems	10 %	**Installation of systems with smaller capacity**	3 %
Incorrect installation of windows and doors	8 %		
Implementation errors	8 %		
Improved systems not found or incorrect installed	6 %		
Orientation	6 %		
Incorrect installation of insulation	5 %		

Factors increasing energy use		Factors decreasing energy use
Thermal bridges	5 %	
Different length or width of pipes	5 %	
Incorrect installation of the various systems	3 %	
Installation of system with bigger capacity	1 %	
Wrong assumptions at the original calculations	1 %	
Leakages from the pipes.	1 %	

There is no available information on the influence that the occupants' characteristics and behavior have on the energy use and therefore the gap between actual and predicted energy use.

In order to have a better understanding of the problem two case studies (new houses) have been chosen to be presented here as examples.

House A

The dwelling consists of three floors (total 114 m^2). The building was inspected during the construction and also tests were carried out after the completion of the construction[19]. The predicted EPC was 0,49 and the re-calculated EPC (after the inspection and the tests) was 0,89[20]. Thus it has a performance difference of 82% and its energy consumption is 23163 MJ higher than the predictions.

The performance of the dwelling is highly influenced by the heat losses through the various elements of the building. In House A the observations and the measurements showed that the predicted U-values were lower than the actual U-values. Therefore, the actual heat losses were higher than the predicted. Table 14[21] shows the predicted and the actual U-values as well as the corresponding heat losses from the various elements of the building calculated using the "as-designed" and "as-built" U-values. The differences between predicted and actual heat loss as well as the percentage increase of heat loss are also shown in the same table.

It should be noted that in some of the elements there is no increase in the heat losses or the increase is significantly small. This results from the fact that the size of some elements was smaller at the constructed building than in the design. Therefore, the smaller size outweighs the increase in the U-values. It should be noted also that the U-values are the average for the frames for the specific floor. This means that not all of the elements have different U-values. More specific, the doors have the same U-values whereas all the windows have higher U-values. The U-values for the walls are also average values but in this case all of the walls have insulation with a higher U-value.

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[19] Thermal images of the building can be found in Appendix II

[20] Data obtained from BouwTransparant - http://www.bouwtransparant.nl/

[21] Data obtained from BouwTransparant - http://www.bouwtransparant.nl/

Table 14: Predicted and actual U-vales and heat losses for House A

Predicted and actual U-values and heat losses					
Heat loss elements	U-values (W/m^2K)		Heat losses (W/K)		
	As-designed	As-built	As-designed	As-built	Difference (%)
First floor					
Walls	0,20	0,21	7,16	7,53	0,37 (5,2%)
Frames	1,57	1,62	25,63	26,85	1,22 (4,8%)
Floor	0,11	0,11	5,20	5,20	0,00
Second floor					
Walls	0,21	0,21	7,91	7,92	0,01 (0,1%)
Frames	1,06	1,13	14,34	14,73	0,39 (2,7%)
Roof	0,19	0,19	2,15	2,15	0,00
Third floor					
Walls	0,20	0,21	2,92	3,07	0,15 (5,0%)
Frames	1,40	1,50	2,10	2,10	0,00
Roof	0,19	0,19	9,63	9,63	0,00
Total			77,05	79,18	2,14 (2.8%)

The increased heat losses are not the only reason behind the increased energy use of the dwelling. Table 15[21] presents the predicted and the actual energy consumption for the various operations of the building. As it can be seen the increase in the energy use for heating is greater than it would be expected based on the differences in heat losses. This is due to the fact that the heating system is not as efficient as it was assumed to be in the original calculations. The generation efficiency of the heating system is 60% lower than it was assumed. This can be caused by an incorrect installation of the system or the substitution of the system with another without considering the efficiency. Moreover, the energy use for ventilation is much higher than the predictions. The reason behind this difference is the substitution of the predicted ventilation system with a bigger one. More precise, the installed system has 230% more fan power than the system in the original calculations and thus it consumes much more energy during its operation. Thus, as it is presented in section 3.2, the construction methods, the material and the systems use are important contributors to the gap between predicted and actual energy consumption.

Table 15: The energy use for House A as it was calculated at the design calculations and after the inspection.

As-designed and as-built energy use for House A		
	Predicted energy use (MJ)	Actual energy use (MJ)
Heating	10129	25694
Hot water	4768	4768
Ventilation	3118	10667
Lighting	6425	6425
Summer comfort	3192	2983

This case study showed that the insulation, the windows and the doors used in the building are important for the energy consumption. Also the size of the different elements is important as it can influence the heat losses. However, the installed systems have a greater influence on the energy consumption of the building. Therefore, the various installed systems should not be altered during the construction face without considering the efficiency. This means that the substitute systems should have the same efficiency as the ones considered in the design calculations. Furthermore, all the systems should be installed carefully in order to achieve the maximum efficiency and therefore the predicted energy consumption.

House B

The dwelling consists of three floors (total 179 m^2). The building was inspected during the construction and also tests were carried out after the completion of the construction. The predicted EPC was 0,39 and the re-calculated EPC (after the inspection and the tests) was 0,88[22]. Thus it has a performance difference of 126% and its energy consumption is 48573 MJ higher than the predictions.

Similar to House A, House B is another example of higher U-values and less efficient installed systems. For this house the inspection showed that the "as-built" U-values for the frames (windows and doors) are higher than the "as-designed". For this reason differences in the heat losses can be seen only for the windows and doors and thus their influence on the energy consumption of the house can be seen easier. Table 16[23] contains the "as-designed" and "as-built" U-values and the corresponding heat losses for the various elements of the building. In addition, the differences in the heat losses and their percentage representation are contained in this table.

From the presented data it can be seen that due to the higher U-values for frames only, the heat losses have been increased approximately 10%. Therefore, one can easily understand the importance of the correct selection for material substitution and their correct implementation. However, it should be noted that the insulation was not checked during the inspection due to lack of opened butt joints; thus there is an uncertainty for the walls U-values.

Table 16: Predicted and actual U-vales and heat losses for House B

Predicted and actual U-values and heat losses					
Heat loss elements	**U-values (W/m^{2}K)**		**Heat losses (W/K)**		
	As-designed	**As-built**	**As-designed**	**As-built**	**Difference (%)**
Ground floor					
Walls	0,21	0,21	18,52	18,52	0,00
Windows	1,39	1,57	45,18	51,03	5,85 (12,9%)
Doors	1,50	2,27	7,95	11,30	3,35 (42,2%)
Floor	0,11	0,11	8,16	8,16	0,00
First floor					
Walls	0,19	0,19	16,45	16,45	0,00
Frames	1,39	1,57	23,91	27,00	3,10 (12,9%)
Floor	0,31	0,31	2,54	2,54	0,00
Second floor					
Walls	0,26	0,26	4,77	4,77	0,00
Frames	1,39	1,57	11,95	13,50	1,55 (12,9%)
Roof	0,26	0,26	24,35	24,35	0,00
Total			139,44	153,29	13,85 (9,9%)

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[22] Data obtained from BouwTransparant - http://www.bouwtransparant.nl/

[23] Data obtained from BouwTransparant - http://www.bouwtransparant.nl/

The heat losses through the various elements of the building are significant contributors to the energy consumption and therefore to the gap between actual and predicted energy use. However, they are not the only reason for the energy difference. Similar to previous house, House B has also an installed system which efficiency is not in agreement with the original calculations.

Table 17 presents the predicted and the actual energy consumption by the various systems in the house. From these results it becomes obvious that the system for hot water consumes much more energy than it was predicted. This results from the fact that the installed system has 8% worse efficiency than the system used in the original calculations. The reason for this efficiency difference can be the substitution of the assumed system with a less efficient one but also the incorrect installation of the system. Furthermore, the energy use for heating is significantly higher than the predictions. The higher U-values for frames contribute partly to this increase, however, due to the great difference and the uncertainty about the insulation level one cannot exclude the possibility of a worse insulation than the one assumed.

Table 17: The energy use for House B as it was calculated at the design calculations and after the inspection.

As-designed and as-built energy use for House B		
	Predicted energy use (MJ)	**Actual energy use (MJ)**
Heating	13132	55932
Hot water	4464	10366
Ventilation	6939	6939
Lighting	10097	10097
Summer comfort	1801	1671

From the results of this case study one can understand that when comparing the actual and the predicted energy use the observed differences are one of the parts of the answer to the question where the excess energy is consumed. The other part is the factors that cannot be confirmed during the inspection and therefore there is an uncertainty about their accuracy. This means that the inspection should be carried out very carefully and also when a difficult at measurements occurs should be noted.

At this point it should be mentioned that the differences in the energy use for summer comfort result from the variations between design and actual building. The presence or absence of elements such as the shadings for the windows can influence the amount of energy that is used for summer comfort. In most of the cases the energy used for summer comfort was higher than the predictions due to absence of shading for the windows.

In general, the case studies in the Netherlands showed that a significant number of the houses are built according to the design or in good agreement with it. The U-values, the efficiency of the systems and the construction procedures are among the most often observed, as well as the most important, reasons behind the energy difference between actual and predicted consumption. These results are in line with the results presented in section 3.2. Apart from the above mentioned, the case studies in the Netherlands indicated the degree of accuracy and detail level that are necessary in order to have a complete picture of the constructed building.

3.5. Greece

The situation in Greece is unknown because it was not possible to find any information concerning the difference between actual and predicted energy use in the residential sector or the compliance of the constructed houses with the current legislation. This is probably due to two reasons. The first reason is that the legislation and the regulations about the energy performance of the houses in Greece are relatively new. They only have been introduced after the EU Directive and they came in force in 2010. The second and probably the most important reason, behind the lack of data, is the economic situation of the country which led to extremely low rates of constructions and renovations. Therefore, the opportunities for such a research are limited. Having in mind the short time frame and the limited opportunities one can understand that the possibilities for such a research to been completed are significantly low. However, it is not possible to say with confidence if any research has been done or if any research is in progress at this moment since every attempt to communicate with experts was failed.

The fact that no data, concerning the performance gap of the buildings in Greece, were available should not lead to the conclusion that no research has been conducted. The relation between the occupants' behavior and the energy consumption, as well as the relation between the climatic conditions and the energy consumption, have been studied (see also: Santamouris, et al., 2001; Sardianou, 2008). Moreover, the energy consumption of the buildings, the corresponding emissions and the potential energy savings as well as the type of the building in relation to its energy performance have also been studied (see also: Balas, et al., 2007; Dascalaki, et al., 2011).

3.6. Comparison between the countries

In this part the data and the results from the countries under investigation are compared. Their similarities and differences are highlighted. The results of each country are also compared with the reasons behind the gap presented in section 3.2.

The performance gap for the United Kingdom and the Netherlands has been discussed in detail. The data for these two countries present some differences and therefore it is not possible to compare them directly and in detail. Their differences are due to the nature of the collected data (i.e. occupants' behavior is missing for the Netherlands) and also due to the different size of the sample.

Figure 17 and Figure 21 present a general representation of the performance gap for the United Kingdom and the Netherlands respectively. From the first sight one might compare them and conclude that the performance gap is smaller for the Netherlands. However, this is not the case because the data for the Netherlands do not contain any information on the occupants. Therefore, Figure 17 gives the performance gap in all the phases of the buildings life while Figure 20 gives the performance gap only for the "design-calculation" and "construction" phases. Despite the differences in the size of the gap, the reasons behind the gap are the same for both countries and in line with the results in section 3.2. The most important reasons are the heat losses from the building shell (i.e. different U-values for walls, insulation, windows, doors etc.), the incorrect installation of the various systems as well as the variations in efficiency of materials and/or installed systems.

As concerns the building shell, in the United Kingdom the results showed that in most cases the heat losses were 50% or more, higher than the predictions. The causes of this variation are the installation of insulation with higher U-value or its incorrect installation which can lead to heat losses and infiltration of air through the shell. Moreover, wrong connections between various elements of the building (e.g. windows-walls, roof-walls etc.) and incorrect installation of the various systems (e.g. heating, ventilation etc.) lead also to increased losses. In line with these results are the findings from the case studies in the Netherlands. Namely, the U-values for walls, windows and doors have showed to be of crucial importance for the total heat losses and therefore for the total energy use. In addition, the case studies in the Netherlands showed that the selection of the proper substitute system is of equal importance as its correct installation.

A significant finding, from the English results, is that the party walls contribute a great share to the total heat losses of the house even though they were not taken into account during the design calculations of energy use. This finding was not included in the data for the Dutch houses and therefore the magnitude of its contribution is unknown. On the other hand, an interesting result from the Dutch case studies, which is not investigated for the English houses, is the size of the windows and the doors. From the data analysis for the Netherlands it has been seen that the size of these elements is frequently different than in the design; which influences the energy consumption even if the U-values are the same as in the design.

The energy gap also concerns existing buildings which undergo major renovation. The results for existing buildings in the United Kingdom are in good agreement with the findings for newly constructed buildings. This means that the incorrect installation of the new elements as well as their U-values also cause differences in the energy consumption for the existing buildings. However, in this category there is also another important reason behind the gap and this is the underestimation of the performance of the dwelling. The condition of the house before the renovation was not known in detail and therefore the design calculations contained several assumptions which often underestimate the performance of the existing construction. Even though the existing buildings are a significant fragment of the building sector there are no available data concerning the existing buildings in the Netherlands. Therefore the situation is unknown and the comparison is impossible.

Another source for the gap between actual and predicted energy use, which also contains uncertainty is the occupants. The results from the United Kingdom made it clear that the occupants' characteristics (e.g. age, number, presence time in the house etc.) as well as the occupants' preferences and behavior (e.g. heating temperature, ventilation rates, frequency of showering etc.) also influence the energy consumption and in most cases they have a negative influence on the energy use. This means that these factors most often increase the energy use of the house creating a bigger difference between actual and predicted energy use. Unfortunately, case studies analyzed for the Netherlands do not contain any data for the occupants. Therefore, it is not possible to compare the behavior of the residents and also the magnitude of influence that these factors have on the energy consumption.

Table 18: Reasons behind the gap, which have been confirmed for the countries under investigation

Buildings' life	Reasons behind the gap	Countries		
		UK	NL	GR
"Use" phase	***Occupant characteristics***			
	Number of occupants	✓		
	Age of occupants			
	Income of occupants			
	Occupant behavior			
	Heating preferences	✓		
	Ventilation peferences	✓		
	Time at home	✓		
	Shower/bath frequency			
	Use of appliances			
"Construction" phase	***Technical aspects of building***			
	Different U-values	✓	✓	
	Incorrect installation	✓	✓	
	Building differ from design		✓	
	Knowledge of the industry			
	Understanding of the design			
	Understanding of the technologies	✓	✓	
	Experience of the constructors	✓	✓	
	Control of the construction	✓	✓	
"Design-Calculation" phase	***Calculation processes***			
	Standardized occupant behavior	✓		
	Use of nominal instead of actual efficiencies	✓		

In section 3.2 the reasons behind the gap were discussed. When comparing them, in Table 18, with the results from the data analysis, for the countries under investigation, one can see that a great share of them has been confirmed. Attention should be paid not to jump to conclusions since the available data do not cover all the aspects of the building life. This means that the reasons which have not been confirmed can still be true but additional research is required in order to verify their validity. For instance, the reasons within the category "occupants' behavior" have not been confirmed for the Dutch households (based on the current available data) but it is common sense that they have an influence on the energy consumption. Indeed it has been suggested that the occupants have a greater influence on the energy use compared to the physical characteristics of the building (Brounen, et al., 2011). Therefore, further research into the relation between the occupants' behavior and the building compliance is required in order to verify their influence. From Table 18 can be concluded that the results for the United Kingdom and the Netherlands are in good agreement and they confirm the reasons concerning the technical aspects of the construction and the knowledge of the construction sector. The reasons concerning the occupants are confirmed for the United Kingdom however, the lack of data for the Netherlands does not allow any conclusions to be made.

4. Conclusions and Recommendations

The gap between actual and predicted energy use, for the residential sector, has been investigated. The unavailability of data was the main problem during this research. Moreover, the uncertainty of the results in some case studies led to an even smaller sample since those results were not taken into account. However, the available analyzed data gave a first insight to the size of the gap as well as to the reasons that create this gap. Furthermore, they gave answers to the sub-questions which lead to the answer of the main research question. The answers to the sub-questions are present below.

1. *Which factors determine the actual energy use of a household?*

The actual energy use takes into account the dwelling characteristics but also the occupants' behavior. Therefore, factors such as the type, the age, the insulation and the installed systems of the dwelling; but also factors such as the number and the age of the occupants as well as their heating and ventilation preferences, are taken into account when the actual energy use is determined. (See section 3.1.2)

2. *What is the actual energy consumption of residential buildings in Greece, the Netherlands and the United Kingdom?*

Based on the European Statistics it has been found that the electricity consumption in households in 2008 for the Netherlands was 24.798 GWh (89.273 TJ), for the United Kingdom 119.800 GWh (431.280 TJ) and for Greece 18.126 GW*h* (65.254 TJ) (European Statistics, 2012 e). The energy used for heating in households in the same year for the Netherlands was 308.449 TJ, for the United Kingdom 1.174.115 TJ and for Greece 115.193 TJ (European Statistics, 2012 b; European Statistics, 2012 c; European Statistics, 2012 d). The energy consumption variations can be explained by the weather conditions, the type of heating used in the households and the use of air conditioning. (See section 3.1.2)

3. *Which factors are missing or differ between design and actual energy use?*

The factors that are missing or differ between actual and design energy use are the reasons behind the gap between these two values. These reasons can be divided into five categories; and these are a) the occupants' characteristics, b) the occupants' behavior, c) technical aspects of building, d) knowledge of the industry, e) calculation processes. Each category contains a number of reasons; however, some of them stand out. For instance, the age of occupants and the heating habits dominate the first two categories. Whereas the correct installations, the understanding of technologies and building methods, as well as the assumptions in the models are among the most important factors for the last three categories. (See section 3.2)

4. *What are the similarities and the differences between these countries?*

From the comparison of the data for each country with the reasons behind the gap from section 3.2 (see Table 18) it has been found that reasons with in the categories c) technical aspects of building and d) knowledge of the industry, have been observed in both the United Kingdom and the Netherlands. Moreover, in the United Kingdom reasons within the categories a) occupant characteristics and b) occupant behavior have also been detected to have influence on the gap between actual and design energy use. However, the same cannot be concluded for the Netherlands due to lack of data on the occupants behavior. Furthermore, the lack of data for the Greek residential sector does not allow any conclusions or comparisons to be made. (See section 3.6)

5. *What are the possible options to close the gap between design and actual energy use?*

It is clear by now that the possibilities to fully close the gap, between actual and predicted energy use, are limited since the human behavior is one of the variables. However, it is possible to make improvements in order to assure that this difference is as small as possible.

The significant lack of obtained data highlights the need for further research. This means that it should be obligatory all the houses to be tested after the construction in order to assure that the required standards have been achieved. In addition monitoring of the building after the occupancy is needed in order to complete the energy profile of the building. The design calculations should be separated into two parts. The first will contain the technical requirements for the construction and the second the energy consumption calculations based on occupants behavior. In the energy consumption calculations the standardized occupant behavior should be replaced by scenario calculations. This means that three scenarios are needed. The first one based on low energy use behavior, the second based on average energy use behavior and the third based on high energy use behavior. This will bring the predictions closer to the actual consumption since the range of the expected consumption will be bigger.

Furthermore, the difficulty to obtain data for this research revealed the need to create databases. These databases should contain the technical requirements as well as the results from the conducted tests after the construction. They should also contain the energy consumption calculations and the monitoring results. In addition to the new constructions, the existing buildings that undergo major renovation should also be included in the databases. In this category the design calculations are substituted by a pre-renovation survey in order to discover the current condition of the dwelling. Therefore, an extensive survey is required, which will include also all the alterations that have been done to the building, in order to understand in detail the current state of the building. The use of data bases will provide the necessary statistical information to recognize which are the main reasons behind the gap in each country and will reveal behavioral patterns of the occupants. In this way policy makers will be able to create targeted action plans with clear objectives.

This research revealed the possible targets for the policy makers. These are the designers, the constructors and the occupants. Below are presented improvement options for each of the target groups which can bring the predicted energy use closer to the actual energy use.

- The designers should make less complex designs and also communicate all the details to the constructors in order the latters to have a better understanding of the design and be able to assure more accurate constructions. To fewer inaccuracies can also contribute the regular monitoring of the construction and the corresponding feedback by the designers to the constructors.
- The constructors should be better educated on the new technologies and their correct implementation, in order to achieve the maximum efficiency of the various building elements as well as of the various installed systems. Constructors should also be better informed about the relation between heat losses and energy use. In this way they will be aware of the consequences their carelessness has on the energy use of the building. This means that they will be aware of the fact that higher heat losses lead to higher energy consumption which then lead to higher energy bills for the occupants. This can also be used as an incentive for higher quality work if connected to their personal lives and houses.

- The last target is the occupants who can also be considered as the general public. As occupants of a house people should be informed in detail how the installed systems are operating and which is the proper way of their maintenance. This information should be provided by the constructors or the engineers to the residents when the latter move into the building. In addition, manuals for all the installed systems should be provided. It should be noted, however, that it is necessary these manuals to be written in a simple way in order to be comprehensive from people without special knowledge. Such information can lead to more efficient operation of the dwelling and therefore less energy consumption. Furthermore, people should be informed on energy saving measures and conscious use of energy through campaigns which will highlight not only the environmental benefits but also the economic benefits.

5. References

Agentschap NL. (2012). *Handbooek gemeenten - Energie prestatie gebouwen.* Utrecht: Agentschap NL.

Atanasiu, B., Despret, C., Economidou, M., Maio, J., Nolte, I., & Rapf, O. (2011). *Europe's building under the microscope.* Building Performance Institute Europe (BPIE).

Balas , C., Gaglia , A., Georgopoulou , E., Mirasgedis, S., Sarafidis , Y., & Lalas, D. (2007). European residential buildigns and empirical essessment of the Hellenic building stock, energy consumprio, emissions and potential energy savings. *Building and Environment 42*, 1298-1314.

Bell, M. (2010). *Carbon compliance for tomorrow's new homes: (Topic 4) Closing the gap between designed and built performance.* London, UK: Zero Carbon Hub.

Bell, M., Wingfield, J., Miles-Shenton, D., & Seavers, J. (2010). *Lessons from Elm Tree Mews.* York, UK: Joseph Rowntree Foundation.

Brounen, D., Kok, N., & Quigley, J. (2011). *Residential energy use and conservation: Economics and Demographics.*

Centraal Bureau voor Statistics. (2012, July). *Historie woningbouw*. Retrieved November 22`, 2012, from CBS - STATLINE: http://statline.cbs.nl/StatWeb/publication/?DM=SLNL&PA=71527NED&D1=10&D2=a&HDR=T&STB=G1&VW=T

Dall'O, G., Sarto, L., Galante, A., & Pasetti, G. (2012). Comparison between predicted nad actual energy performance for winter heating in high-performance residential buildings in the Lombardy region (Italy). *Energy and Buildigns 47*, 247-253.

Dascalaki , E., Droutsa, K., Balaras, C., & Kontoyiannidis, S. (2011). Building typologies as a tool for assessing the energy performance of residential buildings - A case study of the Hellenice building stock. *Energy and Buildings 43*, 3400-3409.

de Groot, E., Spiekman, M., & Opstelten, I. (2008). Dutch research in to user behaviour in relation to energy use of residences. *25th Conference on Passive and Low Energy Architecture.* Dublin: PLEA.

Department of Energy and Climate Change UK. (2012). *Other current policies*. (UK) Retrieved August 2012, from Department of Energy and Climate Change: http://www.decc.gov.uk/en/content/cms/tackling/saving_energy/community/policies/policies.aspx

Department of Energy and Climate Change, UK. (2011). *The Government's Standard Assessment Procedure for Energy Rating of Dwellings.* Watford, UK: Building Research Establishment (BRE).

European Commision. (2011). *A roadmap for moving to a competitive low carbon economy in 2050.* Brussels.

European Statistics. (2012 a, March 6). *Heating Degree-days*. Retrieved Novenber 1, 2012, from EUROSTAT: http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_esdgr_a&lang=en

European Statistics. (2012 b, May 24). *Supply, transformation, consumption - heat - annual data*. Retrieved November 1, 2012, from EUROSTAT: http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_106a&lang=en

European Statistics. (2012 c, May 24). *Supply, transformation, consumption - oil - annual data*. Retrieved November 1, 2012, from EUROSTAT: http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_102a&lang=en

European Statistics. (2012 d, May 24). *Supply, transformation, consumption - gas - annual data*. Retrieved November 1, 2012, from EUROSTAT: http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_103a&lang=en

European Statistics. (2012 e, May 24). *Supply, transformation, consumption - electricity - annual data*. Retrieved November 1, 2012, from EUROSTAT: http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_105a&lang=en

European Statistics. (2012 f, May 24). *Supply, transformation, consumption - all products - annual data* . Retrieved November 16, 2012, from EUROSTAT: http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_100a&lang=en

European Statistics. (2013, January 31). *Supply, transformation, consumption - all products - annual data*. Retrieved February 10, 2013, from EUROSTAT: http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_100a&lang=en

Fokaides, P. A., Maxoulis, C., Panayiotou, G. P., Neophytou, M. K., & Kalogirou, S. A. (2011). Comparison between measured and calculated energy performance for dwellings in a summer dominant environment. *Energy and Buildings 43*, 3099-3105.

Guerra Santin, O. (2010). *Actual energy consumption in dwellings - The effect of energy performance regulations and occupant behaviour.* Delft, NL: Delft University Press.

Hellenic Statistics. (2008, July 24). *El.STAT. Database*. Retrieved November 22, 2012, from EL.STAT.: http://www.statistics.gr/portal/page/portal/ESYE/PAGE-database

Minister of Finance & Minister of Environment,Energy and Climate Change. (2010). Regulation for the energy efficiency of buildings. *Government Gazette of the Hellenic Republic*.

ODYSSEE-MURE. (2011). *Energy efficiency profile: Netherlands.* ODYSSEE.

Owen, P. (2011). *Powering the nation - Household electricity - using habits revealed.* London, UK: Energy Saving Trust.

Palmer, J., & Cooper, I. (2011). *Great Britain's housing energy fact file.* Department of Energy and Climate Change.

Pan, W., & Garmston, H. (2012, a). Building regulations in energy efficiency: Compliance in England and Wales. *Energy Policy 45*, 594-605.

Pan, W., & Garmston, H. (2012, b). Compliance with building energy regulations for new-build dwellings. *Energy*.

President of the Hellenic Republic. (2008). Measures to reduce energy consumption in buildings and other provisions. *Government Gazette of the Hellenic Republic*.

Richards Partington Architects. (2012). *Temple Avenue Project: Energy efficiency refubrished homes for the 21st century.* York, UK: Joseph Rowntree Housing Trust.

Santamouris, M., Papanikolaou, N., Livada, I., Koronakis, I., Georgakis, C., Argiriou, A., et al. (2001). On the impact of urban climate on the energy consumption of buildings. *Solar Energy 70*, 201-216.

Sardianou, E. (2008). Estimating space heating determinants: An analysis of Greek households. *Energy and Buildings 40*, 1084-1093.

Schoonvelde, G. (2010). *Constructing energy efficient dwellings in the Netherlands - The effect of energy efficiency measures through the lifecycle of a dwelling.* Utrecht, NL: Master Thesis Utrecht University.

Stafford, A., Bell, M., & Gorse, C. (2012). *Building Confidence - A working paper.* UK: Center for Low Carbon Futures.

Sunikka Blank, M., & Galvin, R. (2012). *Introducing the prebound effect: the gap between performance and actual energy consumption.* Cambridge, UK.

Tigchelaar, C., Menkveld, M., & Daniels, B. (2011). *Obligations in the existing housing stock: Who pays the bill?* ECN.

van Raaij, W., & Verhallen, T. M. (1983). A behavioral model of residential energy use. *Journal of Economic Phychology 3*, 39-63.

Vringer, K. (2005). *Analysis of the energy requirement for household consumption.* Utrecht, NL.

Wingfield, J., Bell, M., Miles-Shenton, D., & Seavers, J. (2011, a). *Elm Tree Mews Field Trial - Evaluation and monitoring of dwellings performance - Final Technical Report.* Leeds, UK: Centre for the Built Environment, Leeds Metropolitan University.

Wingfield, J., Bell, M., Miles-Shenton, D., South, T., & Lowe, B. (2011, b). *Evaluating the impact of an enhanced energy performance standard on load-bearing masonry domestic construction. - Understanding the gap between designed and real performance: lessons from Stamford Brook.* London, UK: Queen's Printer and Controller of Her Majesty's Stationery Office.

Appendix

I. Personal Communication with Malcolm Bell (11/10/2012)

In general the size of the gap is not really known. The difference between expected and achieved energy performance of the building is in the range of 10% - 120%. The underperformance of the heating system is as important as the performance of the building itself.

1. <u>How important are the changes on the design during the construction phase and how important is the human behavior for the gap?</u>

   It would be more wised to separate the different types of the gap i.e. the gap that refers to the heat loses and the actual performance of the building and the gap that refers to the use of the house and the total energy that is consumed. This is due to the fact that the differences occurred from the construction can be controlled and changed whereas the differences due to the residents cannot be controlled or changed. Therefore there are bot important in different aspects of the gap. However the heat losses contribute significantly to the energy use whereas the energy consumed by the residents will be the same until one point even if they have a conservative attitude. Also if the residents try to change their behavior in order to save energy this savings will be much smaller than the savings coming from the limitation of the heat losses. Moreover for the human factor more important is the time someone is spending at home and their heating habits than their income or their education level.

2. <u>The differences that are observed with the design are only due to complex design or due to bad habits of the constructors as well? - The mistakes during the construction concerning the insulation and the junctions are mainly due to lack of knowledge or due to limited attention on details?</u>

   The designs are usually complex and the level of details is really high. Despite the fact that there is communication between the design and the construction is not at the right level in order all the details to be explained and thus the construction doesn’t really know what is design and what is expected.
   The confusing design process in combination with the lack of knowledge and lack of cultural concern about the checking leads to differences between design and construction as well as mistakes during the construction. The construction industry is not used to check what is expected to be their final product so they just do their work as they used to. This culture is really difficult to change.

3. <u>Is the gap between design and actual energy use different for different types of houses e.g. privately owned and social housing?</u>

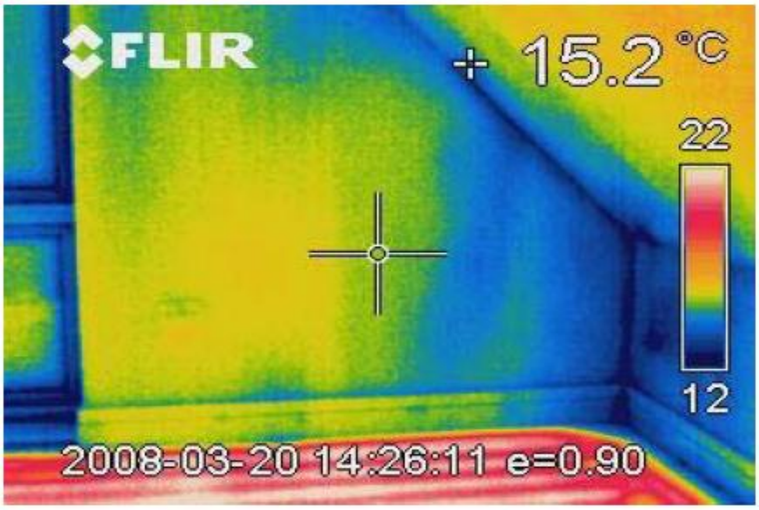
   There are no data on this because usually social houses are investigated since they are easier to access than privately owned. However, if the two researches, the one for Stamford brook (private – 100% higher heat losses) and the one for elm trees (social – 70% higher heat losses), are taken into account then there are no significant differences. Also the observed differences can be explained by the different technologies that are used in the construction. It should be noted that there are no data or research on this thus the conclusions are assumptions and expectations.

4. Renovated houses have the same issues as new houses?

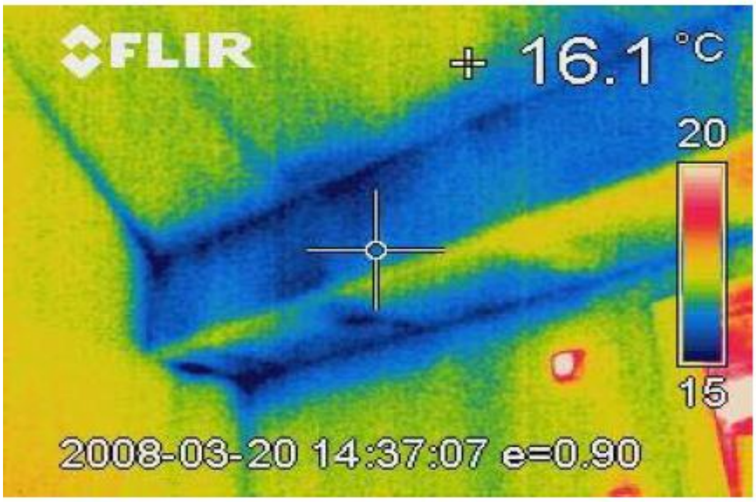
Renovated and new buildings have the same issues and in addition the renovated houses also have issues with the predicted heating losses (U-values). In several cases the calculated U-values are different than in practice. For example the calculated U-values may be in a range of 1,9 – 2 whereas the measured U-values are in the range of lower than 1 or 1 – 2 . This is due to the fact that it is not precisely known how the walls are constructed and in most cases there is a thin layer of air between the bricks which improve the insulation level significantly. Therefore, designs based only on calculated values might be wrong and the anticipated results might be much higher than what it is achieved.

II. Thermal images of the presented houses

United Kingdom – Elm Tree Mews

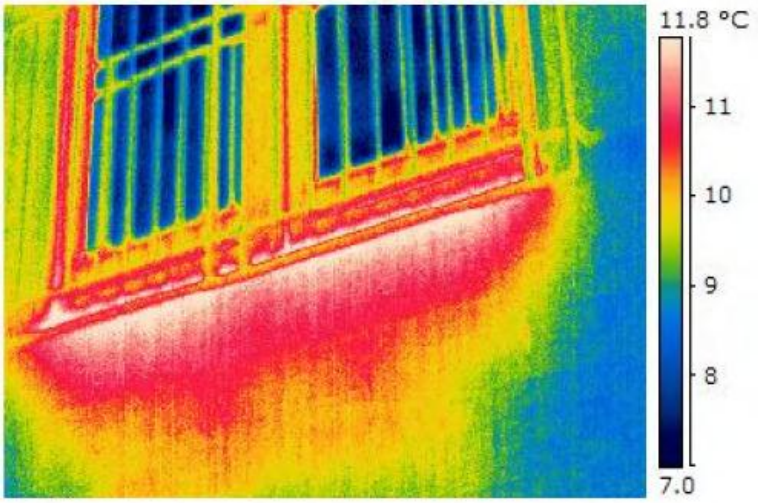


House D: Infiltration of cold air

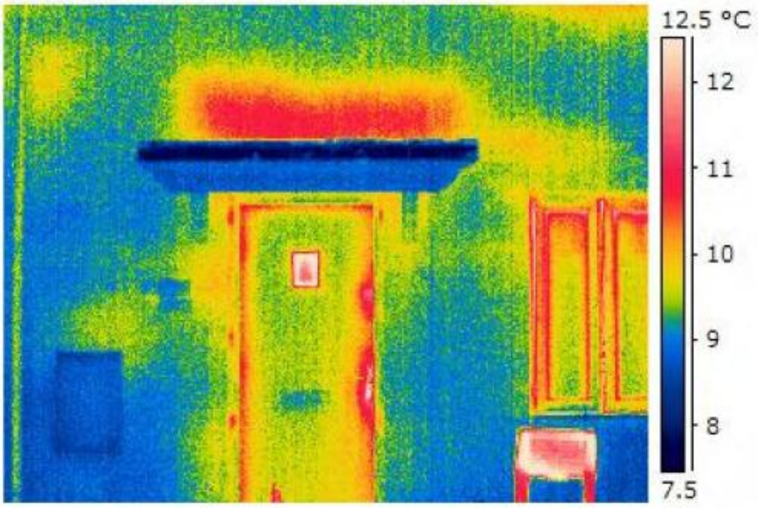


House D: Infiltration of cold air

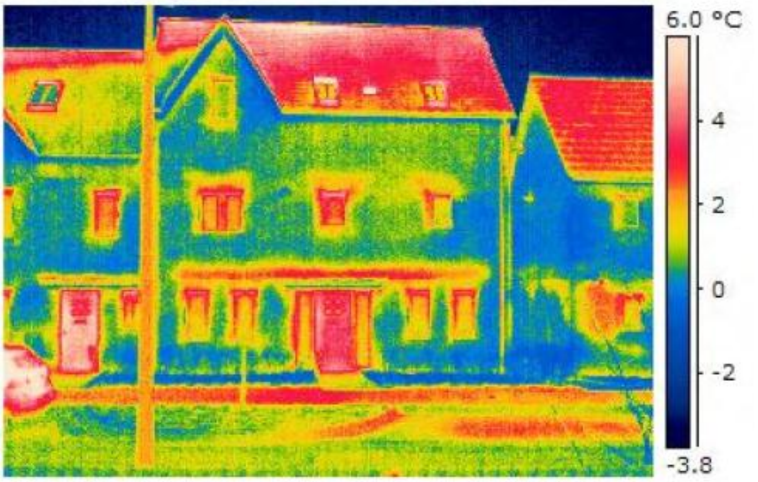
United Kingdom – Stamford Brook



Heat loss at the balcony threshold

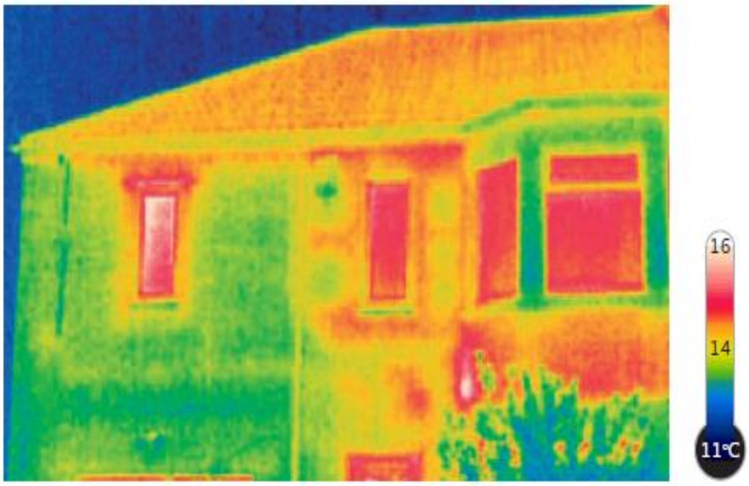


Heat loss at the door head



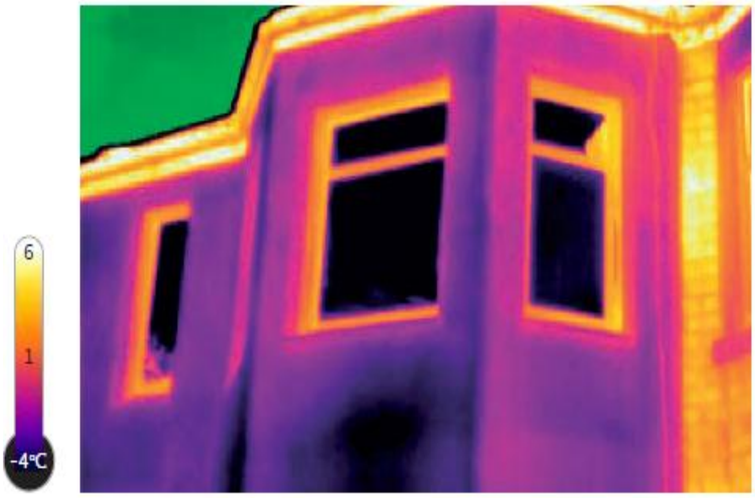
Continuous line of heat loss across door and windows head

United Kingdom – Temple Avenue



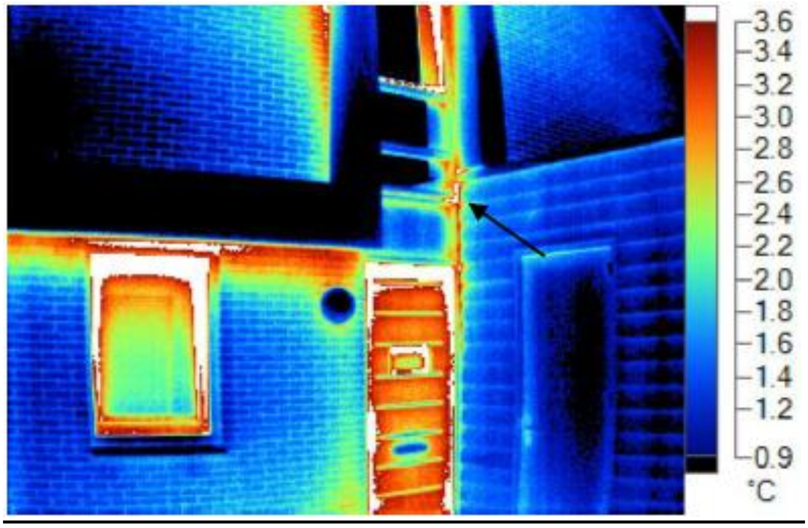
Existing condition: Heat leakage through uninsulated walls and windows

Standard retrofit: Heat losses through the walls and the bay window

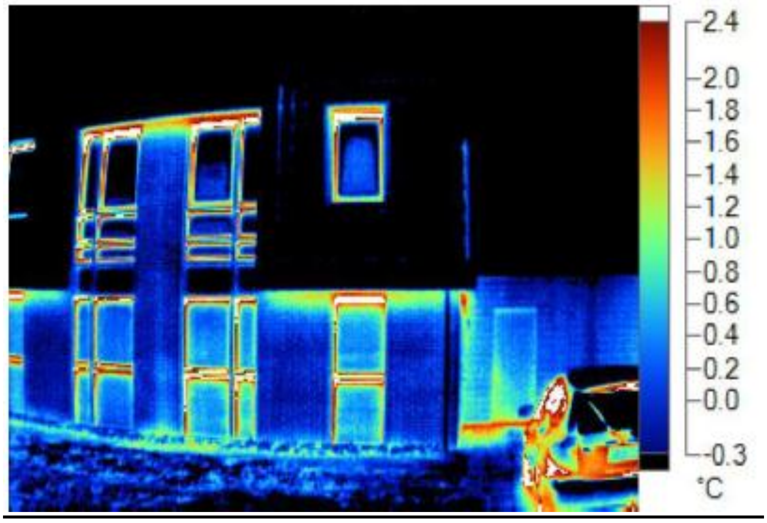


Radical retrofit

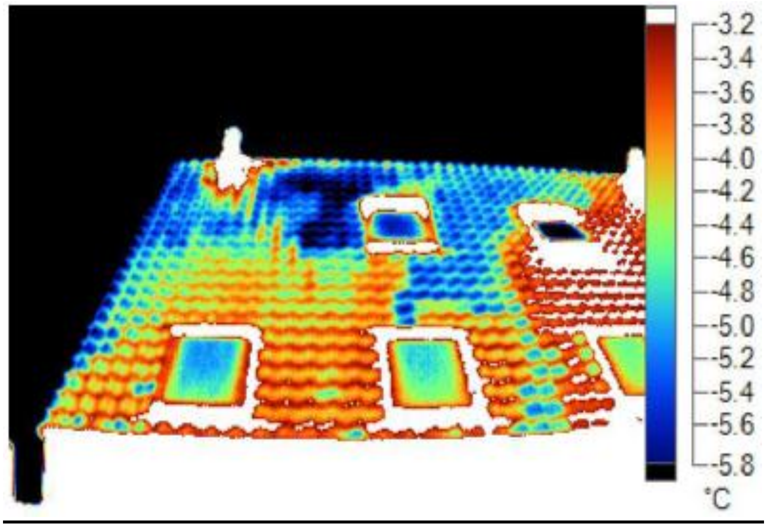
Netherlands – House A



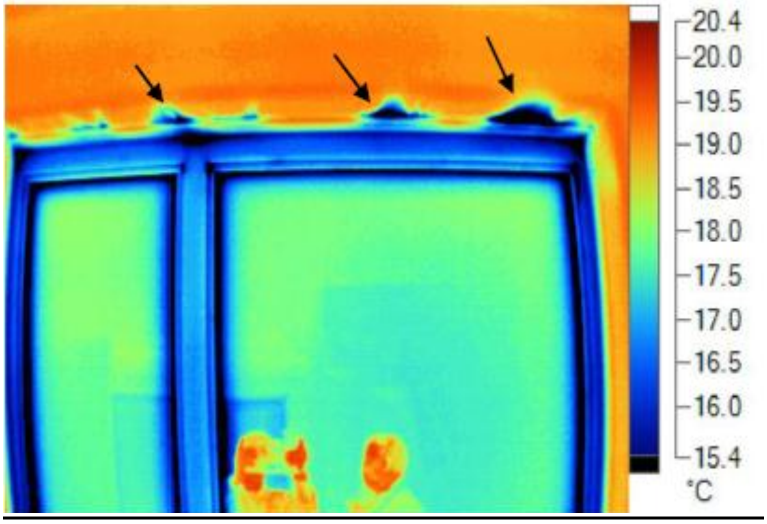
Small heat leak at the connection



No abnormalities



Small heat losses around the roof ducks



Air leakages from the frame at the front side